Irrigation in Mediterranean Agriculture: challenges and innovation for the next decades

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SERIES A: Mediterranean Seminars
2008 - Number 84

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OPTIONS
méditerranéennes
Head of Publication: Bertrand Hervieu

2008 | Series A: Mediterranean Seminars | Number 84

Centre International de Hautes Etudes Agronomiques Méditerranéennes
International Centre for Advanced Mediterranean Agronomic Studies

L'édition technique, la maquette et la mise en page de ce numéro d'Options Méditerranéennes ont été réalisées par l'Atelier d'Édition de l'IAM de Bari (CIHEAM)

Technical editing, layout and formatting of this edition of Options Méditerranéennes was by the Editorial Board of MAI Bari(CIHEAM)

Tirage / *Copy number* : 300

Ideaprint - Bari, Italy
e-mail: ideaprint@virgilio.it

Fiche bibliographique / *Cataloguing data :*

Comment citer cette publication / *How to quote this document* :

Irrigation in Mediterranean Agriculture : challenges and innovation for the next decades - IAM Bari : CIHEAM (Centre International de Hautes Etudes Agronomiques Méditerranéennes), 2008 - 329 p. (Series A : Mediterranean Seminars N° 84, Options Méditerranéennes)

Catalogue des numéros d'Options Méditerranéennes sur /
Catalogue of Options Méditerranéennes issues on :
www.ciheam.org/publications

ISSN : 1016-121X– ISBN : 2-85352-408-6

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Foreword

During recent years there has been much progress in understanding soil hydrological processes and their parameterisation in the management of water resources. The advances in research has produced the innovative methodologies which are ready for being transferred to operative applications of great impact on the management of water and land resources. In the same time, technological developments of new generation of measurement methods provide the opportunity for new observational and modelling perspectives.

The aim of this International Conference is to provide a link between *operational applications* and *future trends* in water and soil management for improving the sustainability of irrigation, also considering the indication of U.E. Water Directive n.2000/60.

The Conference is organised in the framework of activities of **GRU.S.I.** (Gruppo Studio Irrigazione/ Irrigation Study Group), with the sponsorship of Italian Association of Agricultural Engineering (AIIA- Section 1), European Association of Agricultural Engineering (EurAgEng), Italian Society of Agronomy (SIA) and Italian Committee of ICID (Ital-ICID).

We would like to express to all the organizers and participants our deep gratitude for the invaluable job they have been carrying out for long time within the framework of the GRU.S.I..

Alessandro Santini
Professor at Napoli University - Federico II

Cosimo Lacirignola
Director of IAMB

Introduction

This special issue of *Options Méditerranéennes* collects selected contributions presented at the International Conference "*Irrigation In Mediterranean Agriculture: Challenges And Innovation For The Next Decades*", organised by the University of Naples Federico II and the *Italian Group for Studies on Irrigation*. The conference has taken place at the Congress Centre "Partenope" of the Naples University on 17^{th} and 18^{th} June 2008.

The Italian Group for Studies on Irrigation (Gru.S.I.) has been founded in 1962, starting as an initiative of the National Research Council (C.N.R.) undertaken by a group of academic from different Universities: Angiolo Crocioni (Torino), Raffaele Barbieri (Sassari and later Napoli), Giampiero Ballatore (Palermo) and Luigi Cavazza (Bari and later Bologna). This group, originally formed by scientists working in agronomy coordinated by Prof. Cavazza, has focused his activity on the organisation of scientific meetings and conferences, which have been attracting throughout the years a larger interdisciplinary audience. Following the solicitations of the chairs of the National Committee of Agricultural Sciences of C.N.R., Franco Scaramuzzi and Gian Tommaso Scarascia Mugnozza, the group has been extended with the participation of researchers from different organisations and scientific areas i.e. agricultural hydraulics, chemistry, economy and pathology among others.

At the very beginning, the group, named GRUCARAI and later on GRUSI, has held regular annual meetings for coordinating the research activities financed by the C.N.R. in the field of irrigation and for presenting the results of these researches. Later on, a second meeting has been added, every time in a different location around Italy and recently in Mediterranean countries with technical visits to irrigation areas and farms. During each meeting, invited seminars on agronomical and engineering aspects of irrigation are followed by presentations of most recent research results and projects output.

The participation to these scientific meetings has always been opened to researchers not directly involved in C.N.R. funding; as such, the role of the group, initiated as a research coordination, has evolved in a large interdisciplinary forum on irrigation research. Throughout the years, the GRUSI has became an informal scientific association gathering, on a voluntary basis, many researchers and technicians dealing with all different aspects of irrigation and related issues. Even during a period of critical restrictions on funding, the GRUSI has kept his dynamism and enthusiastic participation, thus representing an example of motivation based on genuine research interests, which is in itself a guarantee of success and knowledge advancement.

Presently, the GRUSI involves a participation of about 70-80 people to each meeting, belonging at 20-30 different Institutions and Organisations, from University to Agricultural Ministry Research Departments, C.N.R., public and private research and technological centres, all of them dealing with irrigation and water management in agriculture. Besides the two regular annual meetings, the GRUSI has also organised 5 larger conferences, with the publication and distribution of proceedings: in 1967, the conference on "Irrigation problems" (publication on "Quaderno n.50 C.N.R. Problemi dell'Irrigazione"); in 1969, in Bari, on the "Soil water flow" (publication on "Quaderno n.80 Ricerca scientifica del C.N.R.") ; in 1974, in Rome, the "3^{rd} Workshop on Agronomical problems in Irrigation (publication on "Quaderno n.99 Ricerca scientifica del C.N.R."); in 1988, in Bologna "Irrigation and Research" (2 proceedings volumes); in 1998, in Bari, the "5^{th} National Conference on Irrigation Research: progresses on the usage of water resources (publication of key-note presentations on the journal "Irrigazione e Drenaggio", 4, 2001; publication of proceeding volume).

The research topics have evolved during the GRUSI life. During early years, the focus was on the production response of herbaceous crops and orchards to different irrigation volumes throughout the season, and the influence of irrigation methods and scheduling application at different phenological stages. With the progress of knowledge on this issue and the assessment of definitive results, the interest of GRUSI has been progressively dedicated to more complex problems, such as a deeper understanding of evapotranspiration process and the influence of groundwater circulation, the operation of new irrigation equipments, the utilisation of alternative water resources for irrigation with lower quality, the drainage problems deriving from the irrigation practices, the management of collective distribution networks, the environmental implications of irrigation, the modelling of soil water flow and the modern concepts of porous media, the delineation of new concepts for the assessment of water use efficiency, and many other topics.

During the last decade (1998-2007), I had the honour to coordinate the GRUSI, following the path indicated by Prof. Luigi Cavazza, and maintaining the traditional meeting schedule. Two meetings have been organised abroad, in Tunisia in 2002 and in Spain in 2007, thanks to the dedication of Ing. Lamaddalena, of CIHEAM-Bari, Prof. N.Ben Mechlia of INRAT (Tunisia), Prof. Giuseppe Provenzano of Palermo University and Drs. Herminia Puerto of Elche University (Spain).

The latest event organised by the GRUSI is the conference "*Irrigation In Mediterranean Agriculture: Challenges And Innovation For The Next Decades*", held in Naples. This conference, with a participation of more than 100 attendees, has confirmed, once again, the vitality of the GRUSI after more than 40 years from his start. The organisation efforts of the Agriculture Faculty of the University of Naples, with the support and the collaboration of CIHEAM for the publication of this special issue of *Options Méditerranéennes*, have resulted in an event of high scientific quality, presenting the state of the art in three major issues of broad interest:

1) the impact of U.E. Water Directive n. 60/2000 on the irrigation in Southern Europe;
2) management, physiological and genetic aspects for a better efficiency in agricultural water use;
3) the usage of alternative water resources for irrigation.

In this volume the papers have been ordered progressively in accordance with these issues.

The conference has also been the opportunity to hand over the leadership of the GRUSI to Pasquale Steduto, Chief of the Water Unit at F.A.O., and to Guido D'Urso, Professor of Agricultural Hydraulics at the University of Naples "Federico II". I am sure that under their guidance the GRUSI will continue to represent the ideal community for debating the challenging and emerging issues of irrigation and water management in an open, highly-qualified and at all time interdisciplinary forum.

Angelo Caliandro
Coordinator of Gru.S.I.

Going from rain to gain: blue and green water management practices

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Abstract. For many decades, the irrigation sector has enjoyed a privileged situation being supplied with liberal volumes of subsidized water on a priority basis. The contemporary situation is quite different. The urban centres and their industrial-service sectors are now perceived as engines of economic growth and innovations. The question is: *"how to provide the growing urban centres with their water demands and combine the tremendous challenges to ensure food and environmental security?"* The answer to this question implies that our efforts should be directed to the management of both the blue and the green water. Indeed and for various reasons, in many countries effective conservation and use of rainwater are seldom seen as a water resource management task. The conventional conceptualisation has neglected a large unnoticed resource: the green water source, i.e. the infiltrated rain in soil that supports all plant production, including rainfed agriculture. On the contrary, current institutional and technological responses are mostly focussing on the blue water and surface water in particular, which is indeed only a small part of precipitation. Even though countries must continue to improve management of blue water, the path of making better use of green water should be fully explored. A better use of green water – as a substitute for further pressure on blue water - is thus a win-win governance option. Green water can yield positive returns in crop production beside its potential of freeing up blue water that can be used for non-agricultural economic activities as well as for maintaining required stream flows to sustain the aquatic ecosystem. To govern water from rain to gain, focus should be on more efficient use of rainwater through integrated land and water resources management, conservation farming, watershed management and rainwater harvesting.

Keywords. Rain – Green water – Blue water – Management – Rainwater harvesting.

Valorisation des eaux de pluie par la gestion de « l'eau verte » et de « l'eau bleue »

Résumé. *Pendant des décennies, le secteur de l'irrigation a eu le privilège de disposer de volumes d'eau importants sous des formes subventionnées. Actuellement, la situation a beaucoup changé. Les centres urbains et les secteurs des services et de l'industrie sont devenus des moteurs de croissance économique et d'innovations. "Comment satisfaire les besoins en eau croissants des centres urbains tout en tenant compte des défis énormes pour assurer la sécurité alimentaire et environnementale?" La réponse à une telle question doit être recherchée dans la gestion intégrée de l'eau verte et de l'eau bleue. En réalité, et pour différentes raisons, en de nombreux pays la conservation et l'exploitation efficace des eaux de pluie sont rarement considérées comme des tâches qui entrent dans la gestion des ressources en eau. La conceptualisation conventionnelle a négligé une grande ressource inaperçue: l'eau verte, à savoir, l'eau de pluie qui s'infiltre dans le sol et qui est à la base de toute production végétale et de l'agriculture pluviale aussi. Au contraire, les politiques et les technologies actuelles sont focalisées surtout sur l'eau bleue, et l'eau de surface en particulier. Etant bien entendu qu'il faut poursuivre une meilleure gestion de l'eau bleue, il faudrait explorer pleinement le chemin de l'eau verte. Une meilleure utilisation de celle-ci – servant à alléger la forte pression exercée sur l'eau bleue – est une option de gouvernance gagnante-gagnante. L'eau verte peut engendrer une rentabilité intéressante au niveau de la production des cultures, et soulager l'eau bleue d'une quantité qui serait ainsi utilisée pour des activités économiques non agricoles et pour le maintien du débit minimal nécessaire pour l'écosystème aquatique. Pour la valorisation des eaux pluviales il faudrait assurer une exploitation plus efficace à travers la gestion intégrée des terres et des ressources en eau, la culture de conservation, l'aménagement des bassins versants et la récupération des eaux de pluie.*

Mots-clés. *Pluie – Eau verte – Eau bleue – Gestion – Récupération des eaux de pluie.*

I – Introduction

Nowadays, in many river basin, the water resources are already close to or already over-committed in the sense that the stream-flows have been depleted beyond what is needed for flushing, dilution and sustaining aquatic eco-systems. Such over-commitment has already spread over 15% of the land area hosting 1.4 billion inhabitants those are already suffering the water shortages (Smakthin *et al.*, 2004). Under such situation, one consequence is that further expansion of irrigated agriculture can only be very limited which makes the food security an alarming issue. Indeed, food needs are increasing and food consumption is moving towards more water-intensive items.

Today, consumption drives food production which is changing the consumptive use of water and impacting already stressed water resources, eco-systems and the water available for other societal uses. However, food production will always be highly water consuming from both the green and blue-water perspectives. Therefore, for arid and semi-arid regions, where rain-fed smallholders farming dominates agriculture, it is needed a new agricultural revolution calling for harvesting the potential of green-water in the soil through conservation farming and rainwater harvesting. Equally, water harvesting has to shift its focus from the blue-water and incorporate, also, green-water linked to land use and see rainfall as the manageable freshwater resource.

The blue and green water of the continental global precipitation, some 65% forms green-water in the soil (soil moisture) to be consumed in biomass production by forests, grasslands, wetlands and crop lands. The remaining 35% generates blue-water (surface and groundwater), i.e., the water that is available in rivers, lakes and aquifers out of which only 10% is withdrawn to meet societal needs for settlements, industry, irrigation and hydropower (Fig.1).

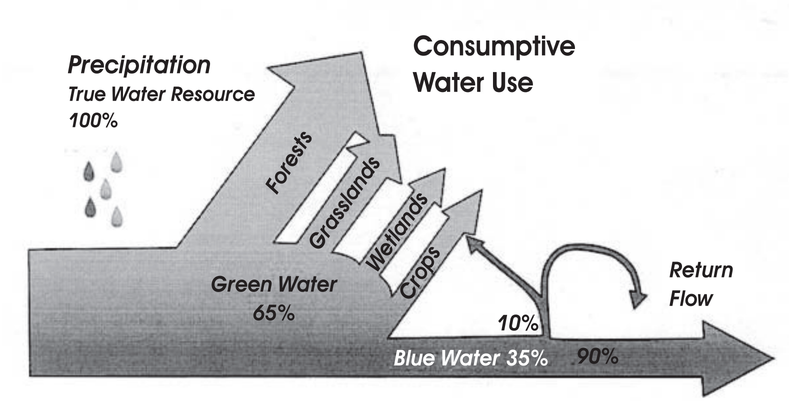

Figure 1. Green and Blue Water.

Discussions concerning food production and food security have invariably focused on the blue-water resources, while the significantly larger green-water resources, i.e. the water invisible to the naked eye, is overlooked.

The long standing emphasis on irrigated agriculture has largely had the side-effect of neglecting potential and substantial improvements of the productivity of rain-fed agriculture.

With blue-water resources, already heavily over-reported in many parts of the world, it is time to revisit and revitalise green-water based food production. This is most obvious in the Middle East and North Africa regions. Indeed, those regions ran out of water for food self sufficiency already in the 1970s (Allan, 2002). For arid and semi-arid countries, using the green-water more productively within rain-fed agriculture, can have, on one hand, yield positive returns in crop production and, on the other hand, increase the potential of freeing-up blue-water that can be used to meet the increasingly water demands in the other sectorial water uses as well as maintaining required stream-flows to sustain aquatic eco-systems.

II – Green-water management: the challenge

Today there are several driving forces pushing towards up-grading the green-water management, among those the following:

- intensified blue-water competition

During the last century, the rate of withdrawals of blue water resources was about 2-2.5 times more rapid than overall population increase (Fig. 2).

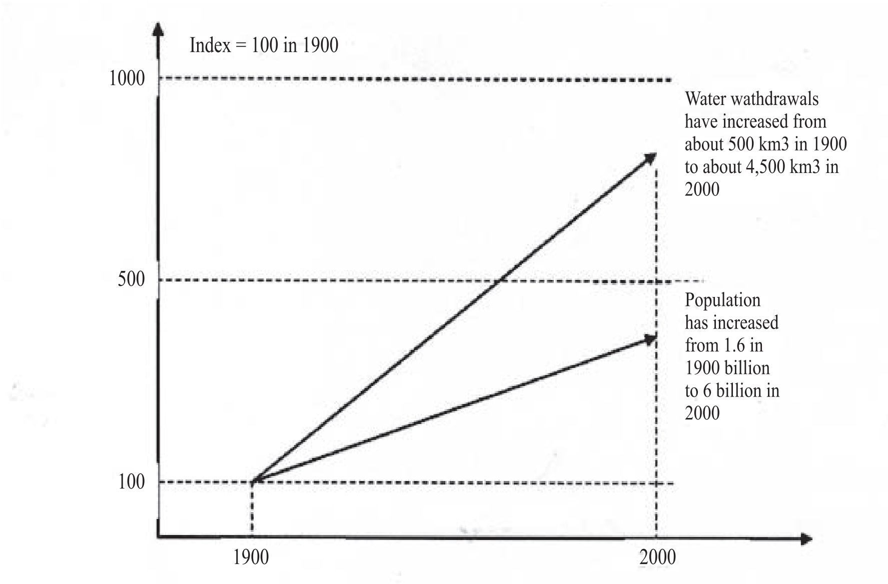

Figure 2. Rate of water withdrawals and demographic change in previous century.

Water withdrawals have increased from about 500 km^3 in 1,900 to about 4,500 km^3 in 2.000. This means that it is primarily the water in rivers, lakes and aquifers, referred as “blue-water” that has been exploited. The demonstrated figure indicates clearly that an extrapolation in the withdrawal of water is neither possible nor desirable whereas the demographic curve will continue to grow and by 2050 a most likely scenario is that another two billion people will be added to the world’s population. The fact that the available water is more or less constant overtime, the competition and conflicts among the sectorial water uses has naturally increased and it will continue to increase.

No doubt the water situation under such notable demographic increase is alarming in many countries of the world and the situation is also worsening in some respects in terms of water management and water quality. The question is: *“how can the increased competition be handled and how to avoid the increasing tensions and conflicts between water users?”*. The direct answer could be through improving water productivity in both irrigated and rain-fed agriculture, following an appropriate integrated land and water resources management approach for the two agriculture systems (Hamdy, 2008).

III – Rainfall partitioning and its losses in farming systems

One of the crucial questions to be clearly identified is: *"where does the rainwater go?".*

In arid and semi-arid regions, a large proportion of the arable land are subjected to shortages in available water, recurrent dry spells, as well as recurrent periods of drought during crop growth, those are harmfully reducing the yield production.

In such areas, the majority of land users depends on rainfall for their livelihood, i.e. green water not on irrigation based on blue water. However, for arid and semi-arid regions, rainfall is highly erratic and most rainfalls as intensive, often convective storms with very high rainfall intensity and extreme spatial and temporal rainfall variability. In fact, in such regions, the poor distribution of rainfall overtime often constitutes a more common cause for crop failure than absolute water scarcity due to low cumulative annual rainfall.

Figure (3) gives an indication of the partitioning of rainfall into different water flow components in rain-fed agriculture in semi-arid zones of Sub-Sahara Africa.

Soil evaporation accounts for 30 to 50% of rainfall (Cooper *et al.*, 1987; Wallace, 1991; Rockstorm, 1997) a value that can exceed 50% in sparsely cropped farming systems in semi-arid regions (Allen, 1990).

Surface runoff is reported to account for 10 to 25% of rainfall (Casenave and Valentin, 1992; Penning de Vries and Ditèye, 1991). The characteristics in dry lands of frequent, large and intensive rainfall event result in significant drainage, amounting to some 10-30% of rainfall (Klaji and Vachaud, 1992).

The results is that productive green water flows as transpiration, in general, is reported to account for merely 15-30% of rainfall (Wallace, J. pers. comm.). The rest between 70-85% of rainfall is lost from the cropping system as a non-productive green water flow, as soil evaporation and as blue water flow (deep percolation and surface runoff).

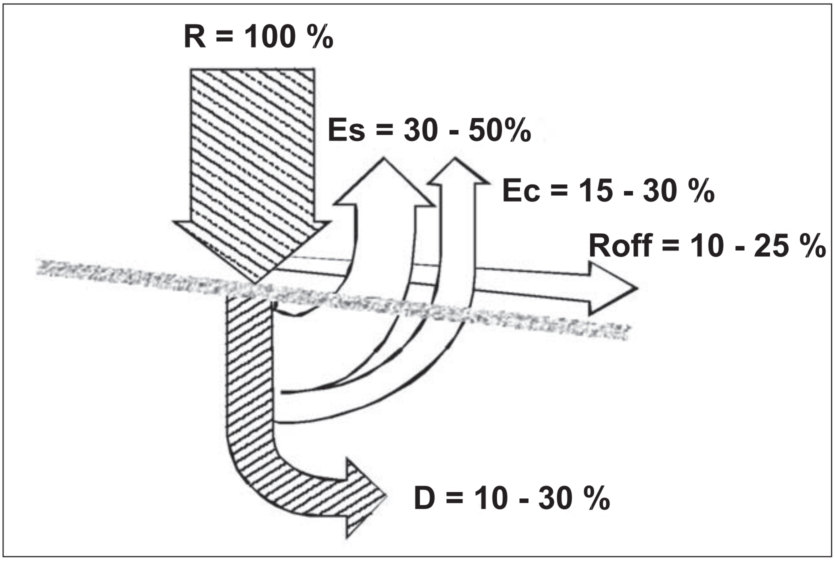

Figure 3. General overview of rainfall partitioning in farming systems in the semi-arid of sub-Saharan Africa. R = rainfall, Ec = plant transpiration, Es = evaporation from soil and through interception, Roff = surface runoff, D = deep percolation.

As shown in Fig. (3), it is quite apparent that there is a high risk of soil water scarcity in crop production irrespective of spatial and temporal rainfall variability. Rainfall varies from 400-600 mm in semi-arid zone and has an approximate range of 200-1000 mm from the dry semi-arid to the dry sub-humid zone. The productive green water flow component returned to the atmosphere as transpiration, being with values accounting to only 15-30% of rainfall means that over 2/3 of the rainfall is lost. This lost water and its conversion from evaporation to transpiration would be sufficient to produce 4-5 reasonable crop yields, assuming roughly 100 mm of transpiration flow for a grain yield of 700 - 1000 $kgha^{-1}$ if the totality was allocated as plant transpiration.

IV – From rain to gain: effective conservation and use of rains

Blue water is only a small part of the precipitation that falls over a country. For various reasons, an effective conservation and use of rains is seldom seen as a water resource management task. One reason is probably that it is much more easy, although quite expensive, to exploit blue water resources.

Another more interesting explanation is that green water management, i.e. harvesting the rains and better use of the water that is stored as soil moisture, requires an integration and land/soil and water management. In rainfed agriculture the potential to better utilize the green water resource must be explored. There is a large potential to upgrade rainfed agriculture in arid and semi-arid regions (SIWI *et al.*, 2005). It has been shown that just by meeting the soil and plant deficiency challenges, crop yields may be doubled or even tripled (Rockstrom, 2003).

It is therefore fundamental to realize that in such zones the crop production potential is considerable. For this purpose, the water-related problematic, typical for arid and semi-arid zones, has to be properly understood. The situation in those areas could be characterized in terms of four challenges that have to coped with (Falkenmark and Rockstorm, 2004):

- long dry period and a wet season interrupted by dry spells (green water challenge)
- infiltration problems linked to crust forming soils (green water challenge)
- low run off production, leaving small water courses empty, except during heavy rains (blue water challenges)
- recurrent drought years (both green and blue water challenges
- measures and management practices for improving rain water use.

The green water production potentials have yet to catch the eyes of most water managers and have only marginally been subject to legislative measures or other types of political and managerial responses. In the meantime, there is currently increasing focus linked to conservation farming, watershed management and rain water harvesting in rural areas. Studies in India by ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) showed that increased productivity in rainfed agriculture was largely due to reduced run-off and increased rainwater use efficiency (65 per cent). In addition, it has been shown that conservation farming can lead to improved plant production through decreased run-off as well as improving groundwater recharge. Moreover, the integrated watershed management programme showed a potential of doubling the productivity on farmers' fields in rainfed areas while sustaining the natural resource base (Wani *et al.*, 2003).

These findings show that improved rainfed agriculture can involve many environmental and economic gains that have the potential to be sustained in the long run, that is: going from rain to gain. It is also of interest to indicate that such studies demonstrated clearly the interface between blue water and green water that measures of improving rainwater use has positive impacts on ground water recharge and irrigated agriculture.

Regarding green water management, it is well recognised that not all the management practices applied to blue water are relevant to green water. For example, the application of various pricing regimes will be ineffective since the green water is coming from the rain which falls directly onto the land. It is basically the size of land and soil characteristics that determine the availability of green water and, therefore, it is irrelevant to use economic incentives for allocating water.

For the green water economic incentives can be in the form of micro-credit schemes for introducing new soil/water management technologies such as rainwater harvesting and supplementary irrigation to protect the growing crops against prolonged periods of drought. In our opinion, to improve the use of green water focusing should be on integrated approaches and strong focus must be put on local processes of participatory approaches, decentralization and national legislations and institutions that can facilitate inclusiveness and access to the needed tools to improve the use of green water to achieve the most possible gain from each drop of rain. In addition, major emphasis should be given to the water and land/soil interface due to its critical impact on improving the use of green water for increased food production. Indeed, a land use decision is also a water decision since land use changes can influence the partitioning of the rainfall, beside it will also affect various components of the hydrological cycle such as runoff, infiltration and evapotranspiration.

From an administrative point of view, land and water are normally separated. Within the water sector, the concept of integrated water resources management (IWRM) is well established, even though its implementation, in practice, has been difficult. There is a need to integrate land and water resources issues. This has been captured by Duda (2003) who in the context of fragmented environmentally related international conventions proposes that the proper terminology should be "*integrated land and water resources management" (ILWRM)*. This means that governance responses to green water will need to shift the focus from blue water allocation to more efficient use of rainwater and intensify the integration of water and land/soil management.

V – Getting the most out of blue water availability: needed research

In arid and semi-arid zones, the main challenge should be: *how to increase green water productivity making the most of green water availability, i.e. the soil moisture.* The production potential is large, provided that plant productivity problems, due to dry spells, etc., can be alleviated by soil/water management measures (green water problems). Affordable small scale technologies and approaches that farmers' capacities could assimilate hold tremendous promise in getting the most out of the falling rains.

Governance and technologies responses should be directed towards making better use of the green water in rainfed agriculture; even though focus should shift from blue water allocation to more efficient use of rainwater, such as through conservation farming and watershed management.

Technically and politically, major efforts are nowadays directed to the improvement of rainfed agriculture. It is well recognised that achieving food security in developing countries of arid and semi-arid regions implies better use and management of both green water and blue water. Improving the rainfed agriculture and increasing the availability of green water (soil moisture) is fundamentally depending on the different approaches we are already implementing in the collection of the falling rains with maximum reduction in water losses which are extremely high lying between 70 to 85% of the total rainfall. In this regard, rainwater harvesting technique is the one widely practiced in most arid and semi-arid zones.

VI – Rainwater Harvesting

Water harvesting may be the most pertinent entry point to farming systems improvements in water scarce regions. The reason for this is the reduced risks for crop failures due to dry spells, which in turn will increase the willing among farm entrepreneurs to invest in other inputs.

However, albite the vast knowledge and experience accumulated in the field of water harvesting, there are still large gaps in research that need to be filled. Fields identified as primary constraints for the successful transfer or innovation and technologies are within the socio-economic domain and relate to the flexibility of concepts introduced so as to fit into the social context. Often lack of education, is a primary constraint, but, sometimes, the proper understanding of underlying social factors can make a difference between a success or failure in introduction/implementation of water harvesting systems.

Research is also needed regarding technical solutions, taking into account the catchment requirements and dynamics as well as the design of the system as such. The main issue is to reduce water losses by evaporation and seepage.

At present, very little is known on socio-economic, environmental and hydrological impact of up-scaling small-scale water harvesting technologies. This requires understanding of complex biophysical processes at different time and spatial scales, as well as inter-sectoral dynamics between, for example, processes in the agro-ecosystem and driving forces behind human land-use decisions. Furthermore, this understanding has to span over a broad scale spectrum from the farm level to the river basin scale, in order to anticipate impacts between upstream and downstream water uses and users.

VII – Conservation tillage: need for systems research

Conservation tillage (CT) may be the most interesting water harvesting option available in order to achieve quick improvements in rainfall partitioning and crop yield on a large scale. Indeed, CT focuses on maximizing infiltration and the improvement of soil productivity by abandoning the inversion of the soil through conventional ploughing.

However, it could be argued that the low adoption of CT among small-holder farmers may be linked to the lack of systems research, studying all the components: tillage, timing, livestock management, fertilization, soil conditions, farm management, etc., which together from the basis of a successful conservation tillage system. There is research gap on system oriented adaptive on-farm research on the design, functioning, bio-physical criteria and implication of CT-production systems.

VIII – Dry spell occurrence and mitigation

This issue should deserve further research as the manageable challenge for the farmer is to mitigate the effects of dry spells which occurs frequently in semi-arid farming systems.

There is very little research carried out studying the occurrence of dry spells from a management perspective, and the potential of planning for dry spells mitigation using water harvesting. Planning tools have to be developed from fundamental science that enables the assessment of water requirements to mitigate dry spells and the potential of harvesting required water.

IX – To convert evaporation to transpiration

An interesting win-win option is to convert non-productive evaporation to productive transpiration.

However, from a water harvesting perspective, all the possibilities of using water harvesting as a method for improving the crop environment in favour of: (i) lower saturation deficit (VDP, Vapour Pressure Deficit) and (ii) increasing the T/ET ratio can be of large importance for the water availability on a watershed scale. The know-how on the ways water harvesting could contribute to lower VDP and higher T/ET is still limited. Research is required to study the actual potential of water harvesting to affect VDP, WUE_{ET}, WUE_{T} and T/ET ratio.

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European water directive evaluation and decision support system to improve irrigation management: RISP-IDRIC Project

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Abstract. The safeguard of water resources is becoming a major environmental priority, because water is an essential mean of production for agriculture and a basic element for the survival of all human activities. The recent reform of the Common Agriculture Policy is oriented towards an ecologically-sound agriculture and to a reasonable use of the production factors (technical features, including water), without waste, without releases of pollutants in water, soil and products. In this context, the Water Directive n. 60/2000 introduces in the water resources management new principles such as "polluter pays", the full cost and volumetric pricing. Implementation of the directive could have important effects on the agricultural sector and management.

The "Consorzio della Bonificazione Umbra", authority, located in Central Italy, is responsible for soil reclamation and conservation, protection of land and the environment, with special reference to water resources for the improvement and transformation of production systems. The "Consorzio" comprises 128.000 hectares with a total irrigated area of 4.181 hectares and 64.700 farms.

The RISP-IDRIC is a research project, funded by Italian Ministry of Agricultural, Food and Forestry Policies (2007-2010) and it will achieve two main goals:

– To find the most efficient solutions (and less expensive) to meet the targets set by European Water Directive n. 60/2000, giving a methodological support for application of national and regional water directives, testing the impact of different scenarios of contributory systems, consortia remediation and, consequently, agricultural system.

– To develop a web irrigation decision system to improve the efficiency of irrigation technology, streamline procedures for irrigation and optimization of the use of water resources, providing specific guidance to farmers for irrigation supply (time and amount) offering them a tool that exploits the advantages of new technologies.

In the paper a description of the project and the methodology that will be used has given.

Keywords. Water directive – Irrigation water management – Software – Water cost.

Evaluation de la directive européenne de l'eau et développement d'un système d'aide à la décision pour améliorer la gestion de l'irrigation : projet RISP-IDRIC

Résumé. *La sauvegarde des ressources en eau est l'une des priorités environnementales majeures, car l'eau, essentielle pour les productions agricoles, est un élément base pour la survie des activités humaines. La réforme récente de la Politique Communautaire de l'Agriculture est orientée vers une agriculture respectueuse de l'environnement et raisonnable dans l'utilisation des facteurs de la production, sans gaspillage et sans la pollution de l'eau, du sol et des produits agricoles. Dans ce cadre, la directive de l'eau n. 60/2000 introduit de nouveaux principes de gestion de la ressource : « le polluant paye », « le coût complet » et le « prix volumétrique ». L'application de la directive peut avoir des effets importants sur l'agriculture et sa gestion. Le « Consorzio della Bonificazione Umbra » de l'Italie centrale est responsable de la conservation du sol et de la protection de l'environnement, avec une attention particulière à le ressource eau et à la transformation et l'amélioration des systèmes de production. Le « Consorzio » de 128.000 hectares comprend une superficie* *totale irriguée de 4181 hectares et 64700 exploitations. Le projet de recherche RISP-IDIRC est financé par le Ministère Italien de l'Agriculture (2007-2010) et a deux objectifs principaux:*

- *Trouver les solutions plus efficientes (et moins chères) pour respecter la directive de l'eau n. 60/2000, en donnant un support méthodologique pour l'application des directives nationales et régionales, tout en évaluant l'impact des différents scénarios de systèmes agricoles et de contribution*
- *Développer un système de support à la décision sur web pour améliorer l'efficience de l'irrigation et les systèmes de flux, optimiser l'utilisation de la ressource, guider les agriculteurs dans le pilotage de l'irrigation et évaluer les avantages des ces nouvelles technologies.*

Cet article décrit le projet et la méthodologie utilisée.

***Mots-clés.** Directive de l'eau – Gestion de l'eau d'irrigation – Logiciels – Coût de l'eau.*

I – Introduction

The preservation of water resources is becoming a major environmental priority, because water is an essential mean of production for agriculture and a basic element for the survival of all human activities.

The recent reform of the Common Agriculture Policy is oriented towards an ecologically-sound agriculture and then to a reasonable use of the production factors (technical features, including water), without waste, without releases of pollutants in water, soil and products. In this context, the Water Framework Directive (WFD) n. 60/2000 introduced a new philosophy in the water resources management, such as to protect and improve the quality of aquatic ecosystems, to promote a rational and sustainable use of the water based on a long term management of the water resources, to adopt specific measures to monitor the pollution (local discharges, emissions and losses of priority substances etc.), to reduce the pollution of the groundwater and to mitigate the effects of floods and droughts through the monitoring of waters.

1. The Water Directive

The innovative elements of the WFD are a water management based on the river basin districts, a monitoring of the water pollution, based on the limits to the emissions and on reaching the goal of water quality, an integration of all the uses, functions and values of the water, an attribution to the final user of the "full cost recovery of water", an integration of economic and financial tools with price policies for a rational use of water and a consultation of the civil society and the stakeholders in the process of water utilization. The new aspects of the directive are:

- full recovery cost of water ("polluter-pays" and "user-pays");
- incentives to the water pricing.

Basically, only the activities that cause significant impacts on water bodies and therefore pose a risk to achieving good status are covered by the definition of water uses. General experience shows that navigation, hydropower generation, domestic, agriculture and industrial activities are important water uses which may cause significant impacts and therefore have to be taken in consideration.

The WFD wants to be the reference point of the water policy in the next decades across the slimming of the European legislative framework in subject of water, the inspiration to the principles of sustainability, a very binding policy on the plan of the costs, either direct (es. new nets, expansion services) or indirect (renouncements to use the water) and with a very ambitious timetable (Tab. 1).

The "water" resource must be managed at basin level, with an approach no more sectorial, but shared by all the sectors and the allocation cost has to follow the principles of efficiency and equity.

The final objective of the directive is to reach a "good state" of the superficial and underground waters within 2015.

Most European countries provided incomplete reports on the Article 5 economic analysis. Regarding the sectors to be covered for cost recovery, the sector of households was addressed most often, followed by industry and then agriculture (Fig. 1).

Member States that have provided information on households have indicated a cost recovery rate of services for households between 70 and 100%, for industry between 40 and 100% and for agriculture between 1 and 100%. Italy is late in comparison to different fulfillments foreseen by the directive. The main crucial point concerns the incomplete transposition of directives preceding the WFD, the nitrates directive (91/676/CEE) and the directive on the treatment of urban waste water (91/271/CEE), the missed or partial realization of some key aspects of the WFD, for examples the identification of the water bodies strongly modified, the diffused pollution, the guardianship of the groundwater, the economic analysis (Fig. 2).

Table 1. Timetable of realization of Water Directive

Year	Issue	WFD Reference
2000	Directive entered into force	Art. 25
2003	Transportation in national legislation	Art. 23
	Identification of river basin districts and authorities	Art. 3
2004	Characterization of river basin: pressures, impacts and economic analysis	Art. 5
2006	Establishment of monitoring network	Art. 8
	Start public consultation (at the latest)	Art. 14
2008	Present draft river basin management plan to public	Art. 13 & 14
2009	Finalize river basin management plan including program of measures	Art. 13 & 11
2010	Introduce pricing policies	Art. 9
2012	Make operational program of measures	Art. 1 1
2015	Meet environmental objectives, first management cycle ends	Art. 4
2021	Second management cycle ends	Art. 4 & 1 3
2027	Third management cycle and last extension of deadlines ends	Art. 4 & 13

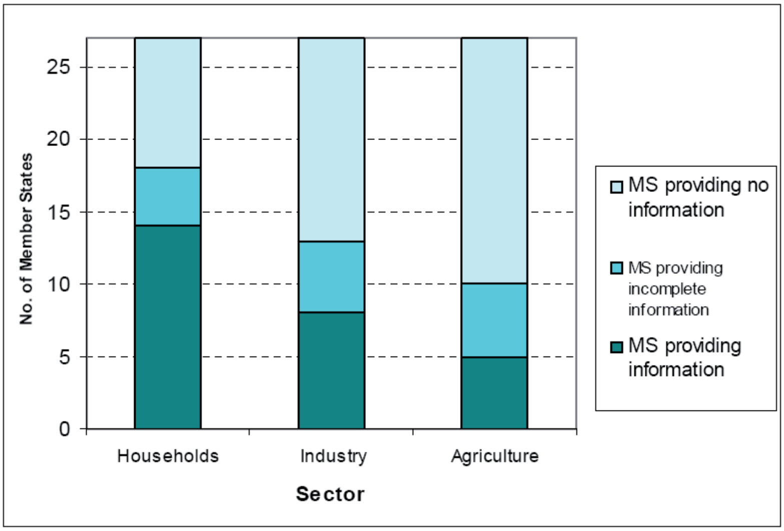

Figure 1. Level of information provided by Member States on sectors to be covered in cost recovery of water services.

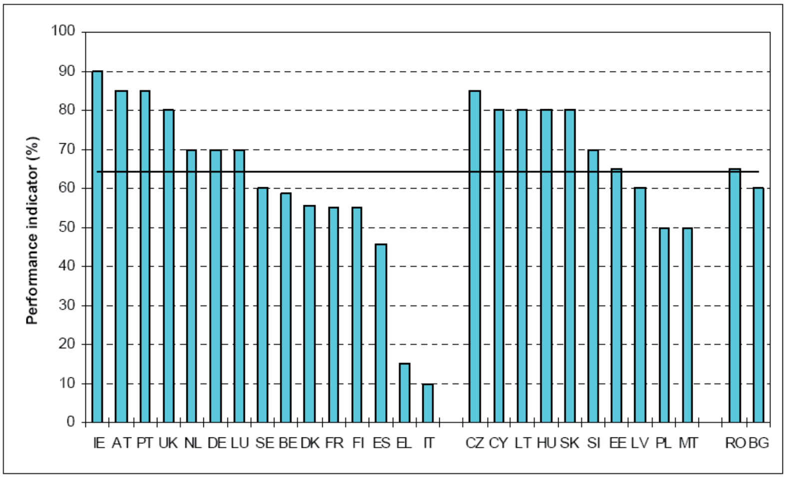

Figure 2. Indicator per Member State regarding its reporting performance and the EU-27 average (based on Member States' reports).

2. The "Consorzio della Bonificazione Umbra"

In this context, the RISP-IDRIC project wants to give **a** contribution to the realization of the WFD, verifying the applicability of some aspects related to the distribution of the water for irrigated use in the "Consorzio della Bonificazione Umbra", central Italy.

It is located in Spoleto (Umbria region) (Fig. 3) and it is responsible for soil reclamation and conservation, protection of land and the environment, with special reference to water resources for the improvement and transformation of production systems.

The "Consorzio" performs the functions and duties assigned by the Act and the activities that are still necessary for the achievement of its institutional tasks. It comprises 128.000 hectares with a total irrigated area of 4.202 hectares (on 3100 ha sprinkler method is used and on 1102 surface one) and 64.700 farms. The costs for the implementation, maintenance and operation of land reclamation projects, as well as those relating to the other purposes of the "Consorzio" are allocated on the basis of specific plan standings.

The "Consorzio" substantially applies from 2007 two ways of tariff method: a base fee (65 €/ha) for all the field in the consortium area, and supplemental fee for irrigated field only (65 €/ha), declar by farmers and controlled by consortium's employers.

The Law n. 183 (1989) for soil preservation in the Umbria region created three basin authorities:

- Tevere river, 95% of the territory;
- Arno river, 3% of the territory;
- Marche region, 2% of the territory.

This law was finalized to the defense of the hydrogeological risk and it has been set up to assess three main aims:

- guaranteeing the maintenance of the hydraulic defense system to avoid that the deterioration could reduce the efficiency of the actual hydrographic network;
- preventing the flood events, using systems of monitoring in real time to notice the risk in its initial phase, in order to put on alert the competent authorities and to apply the necessary measures of safeguard.

The Hydrogeologic plan of the Tevere river has been adopted in 2000, while in 2007 the definitive plan by the Umbria Region has been approved; the plan of the Marche region has been approved in 2004 and the plan of the river Arno (Tuscania region) has been adopted in 2008.

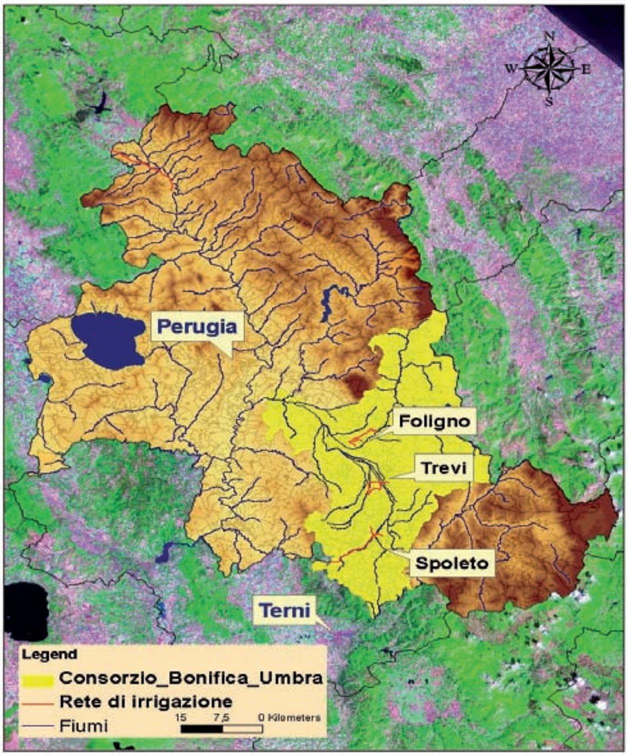

Figure 3. Umbria region, with the indication of Consorzio's area (yellow area) and the three main irrigation districts.

II – The RISP-IDRIC Project

The RISP-IDRIC project has been funded by Italian Ministry of Agricultural, Food and Forestry Policies (2007-2010), coordinated by "Consorzio della Bonificazione Umbra" and in cooperation with CRA-SCA of Bari and several research institutes. It is a research project and it will achieve the following main goals:

- To find the most efficient solutions (and less expensive) to meet the targets set by European Water Directive n. 60/2000;
- To give a methodological support for application of national and regional water directives, testing the impact of different scenarios of contributory systems, consortia remediation and, consequently, agricultural system.
- To develop an analysis method to validate operational criteria for quantification of the cost (full) of water in agriculture.
- To assess the effects of changes in the contributory system on the agricultural sector and consortia.
- To analyze all the possible strategies of sustainable application of the directive and drafting the final report.
- To develop a web irrigation decision system to improve the efficiency of irrigation technology, streamline procedures for irrigation and optimization of the use of water resources, providing specific guidance to farmers for irrigation supply (time and amount) offering them a tool that exploits the advantages of new technologies.

For a correct application of FWD the quantification of the "Full cost recovery of water" needs to be carried out. It derives by the sum of financial, environmental and opportunity costs.

"Financial costs" of water supply are the current or operating costs, and all the expenses for staff, consumable material, motive power, ordinary maintenance of the buildings, etc. should be taken into account. The quantification of the "Financial current costs or operating costs" presents several problems. They are usually the costs that the administration support yearly to supply the water to the users. Usually these data can be collected from the economic balance sheets of the consortium administration. Costs for the depreciation of immobilized capitals and all the costs of the extraordinary maintenance of the buildings, equipment, needed for water utilization, should be taken into account. In this case, the monetary quantification is more difficult, because it's needed to define:

- which investments to consider;
- which time to consider for the depreciation;
- how to share the costs among the different activities of consortium.

The cost of use of the capital (or opportunity cost, when own money are used) requested for the distribution of the water, should be also considered. In this case, the monetary quantification is quite easy, because in the presence of loans or debts, the rates will be related to the interest rates paid by the consortium; in the case of own resources, the cost of capital will be determined on the base of the "opportunity cost"; the subdivision of the cost of capital in the different sectors of the consortium administration is still a problem.

Environmental cost of the water subtraction, the environmental impact (quantitative and qualitative), that the resource water produces as a function of its utilization, should be quantified in monetary terms. Different matters it needs to face:

- if environmental costs should or not include social costs;
- if costs and benefits "upstream" or "downstream" of the point where water is available have to be considered;

- if environmental benefits of water use should be subtracted from the total cost;
- which methodologies could be adopted for the monetary evaluation of environmental externalities.

The opportunity cost of alternatives water uses, or, in other terms, the cost of the resource if, in presence of specific demand, it is devoted to alternative uses, should be evaluated in monetary terms. It needs to be defined: when the water is really scarce? How much value the water for the alternative uses? Must the alternative uses of the water be real or potential? How the marginal opportunity cost of the water vary? How can we determine the payment based on the real consumption? How can we measure the consumed amounts (and at what price)?

1. Impact of the water pricing on irrigated agriculture

This last question, about measuring of water consumed amount, is crucial in FWD application (the principle “user pays”). Few consortia in Italy apply a correct rate based on real water consumption. The most of them use a fixed fee per field area, but in this way no increase in water productivity could be expected.

In the Project oral and written question forms will be submitted to the farmers, in order to evaluate the reaction of the agricultural users to a payment criterion different by the present one.

Probably, the new pricing policies will determine an increase in the water costs for irrigated agriculture. The marginal farms will incur the main economic damages and the introduction of other restrictions to the production should be avoided. In this case another question rises up: should the economic, social and environmental effects caused by the reduction of agricultural activities in marginal areas be considered in the “full cost recovery of water”?

The correct quantification of water price is fundamental in marginal areas, to maintain agriculture, environmental care and to avoid depopulation.

2. Technical support to irrigation management

The scientific and technical support in the Project is guaranteed by Agricultural Research Council of Bari (CRA-SCA), “Consorzio per la Sperimentazione e la Divulgazione delle tecniche irrigue” (Vasto, CH) and University of Milano Department of Agriculture Production institutions: meeting and training courses will be carried out, with the aim to improve the technical knowledge of the farmers about irrigation management and, in particular, the irrigation systems and the time and amount of irrigation supplies.

The project will provide the creation and implementation of web software for irrigation management at field level. It calculates daily water balance including the following items:

- Rainfall;
- Water table arising, as a function of root depth, soil and crop;
- Crop water use (ETa) is estimated by daily weather data (temperatures), by mean of ETref (Hargreaves model) multiplied by crop coefficients to estimate ETa. If meterological network allows for solar radiation, wind and relative humidity data, Penman-Monteith approach is used;
- Drainage, the water that overflows below root depth;
- Rain intercepted by the crop;
- Runoff;
- Water stored in the soil, as a function of hydrological soil characteristics.

From water balance, a daily estimation of soil moisture is calculated; then water deficit is obtained as difference from soil field capacity. From water deficit the suggestion to irrigate or not derives and how much water the crop needs, according to full satisfaction of crop water demand, or a different water saving strategies. The software is feed by input data: a crop database is available, for both field and tree crop, but a new one can be also added.

For field crops, the database has the following information:

– Base temperature [°C];
– Optimal temperature [°C];
– Heat units to emergence [°C];
– Heat units to flowering [°C];
– Heat units to harvest [°C];
– Crop coefficients at maximum LAI [-];
– Critical value of soil water below which the plant transpiration is reduced [% of crop soil water];
– Maximum root depth [m];
– Capability of the crop to use water table [-].
– For the tree crops, the database has the following information.
– Crop coefficients in specific growth stages;
– Plant spatial disposal and size of canopy projection [m];
– Shape of tree canopy [-].

The soil key variables are the field capacity and the wilting point in different soil layers. If they are not available a set of pedo-transfer function can be used using the textural composition, and, optionally, organic matter contents and bulk density.

Irrigation management: the user has to define for each "field/crop" combination the following information:

- irrigation criteria;
- irrigation system;
- size of irrigated field;
- irrigation height;
- initial soil moisture.

The final information to the user will be the time and amount of irrigation water to apply, considering the weather, the soil, the crop, the previous irrigation supplies and the irrigation system.

The possibility to indicate the real amount of water supplied, and to change the irrigation from the scheduled one are implemented. Graphical tools a possibility of "what-if" analysis is also implemented, to check the effects of water saving strategies.

The software can run stand alone, but with a weather daily data population from web (a database of climatic station of the consortium). Similarly, it could be feed from a database of soil characteristics, or, in alternative, it could run directly on the consortium web server.

III – Conclusion

In this paper a research project about the application of European Water Directive 60/2000 in a consortium of Central Italy is reported; the methodology and the main questions that will be faced are analyzed and described.

The problematic of quantification of cost of water, the reaction of users to a different water pricing and the research effort to support a better water use are the main aspects that characterize the RISP-IDRIC project.

Acknowledgements

Project supported by the Italian Ministry of Agriculture, Food and Forestry Policies (contract n. 288/7303/06).

Agronomical aspects of the paper have been developed by Rinaldi, Ruggieri and Acutis, water framework directive and CBU description by Marcucci and Loreti, the economical aspects of WFD and water cost evaluation by Malagoli.

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The irrigation advisory plan of Campania Region: from research to operational support for the water directive in agriculture

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Abstract. The Irrigation Advisory Plan of Campania Region is an initiative of the Assessor for Agriculture and Productive Activities, through the Research and Development Service (Se.S.I.R.CA); it consists of an innovative advisory service for irrigation, based on the combined use of Earth Observation data, GIS and Information Technology to provide crop water requirements information from the field scale (>1 ha) to the irrigated basin scale (3000 ha). This initiative, which is perfectly aligned with the recommendations of European Union through the Water Directive n. 60/2000 has been tailored to improve the water use efficiency not only at farm level, but also at the district scale, with tangible benefit for the economy of primary sector and environmental protection. The personalized information provided to farmers and irrigation managers consist of the maximal irrigation volumes to be applied on a weekly basis and the duration of irrigation. This information is sent within 36 hours from the satellite acquisition to each farmer via SMS, MMS and E-mail; in addition a dedicated Web-GIS has been developed to monitor irrigation advice at district level.

Keywords. Crop water requirement – Earth Observation – Advisory service in irrigation.

Plan d'Assistance de l'Irrigation dans la Région Campania : exemple de transfert des résultats de la recherche pour supporter l'application de la Directive Européenne sur l'Eau en agriculture

Résumé. *Le Plan d'Assistance de la Région Campania est une initiative du Secteur de l'Agriculture et des Activités Productives du gouvernement régional. Il s'agit d'un service d'assistance au pilotage de l'irrigation, utilisant des donnés d'Observation de la Terre, le SIG et les Technologies de l'Information. Ces instruments sont appliqués pour obtenir la demande en eau des cultures à l'échelle de la parcelle (>1 ha), jusqu'au niveau du secteur de distribution collectif (3000 ha). Ce projet, qui s'aligne aux indications de l'Union Européenne – Directive n. 60/2000, a été conçu pour améliorer l'efficacité de l'irrigation, avec effets positifs sur l'économie de l'entreprise agricole et l'environnement. L'information fournie est personnalisée et indique la quantité maximale d'eau à appliquer en une semaine et la durée de l'application. Cette information est distribuée par SMS, MMS et E-mail dans 36 heures après le passage satellitaire.*

Mots-clés. *Evapotranspiration – Observation de la Terre – Assistance à l'irrigation.*

I – Introduction

During recent years, Earth Observation techniques are more and more transferred to applications for supporting land and water management. In this paper, we present an operational procedure for improving the efficiency of irrigation at farm and district level, built on the integrated use of Earth Observation data and Information Communication Technologies (I.C.T.). By using irrigation advices based on the actual development of the canopy, it is possible to monitor the maximum water demand for irrigation and to achieve an improvement in the application efficiency. The prototype of this methodology has been developed by a consortium of European research institutions in three irrigated areas in Spain, Italy and Portugal within the EU-funded project "DEMETER" (http://www.demeter-ec.net/) and further extended to other areas within the "PLEIADeS" project (http://www.pleiades.es).

Since 2007, the procedure has been implemented operationally in 4 irrigation districts in the Campania Region, Italy; during 2008, it has reached 150 farmers with an irrigated surface of over 3000 ha. This project represents a further step for the implementation of E.U. Directive n.60/2000 in the agricultural sector of this region.

II – Modeling approach

The theoretical background for the estimation of crop water requirements from satellite data adopted in this study is based on the standard method of F.A.O.-Paper 56 (F.A.O., 1998), i.e. the so-called "one-step" approach. This method calculates the maximum evapotranspiration of ETp of a canopy under stardard conditions i.e. unlimited soil water availability, pest and disease-free crop, by using appropriate values of canopy variables such as the surface albedo α and the Leaf Area Index (LAI). In this c ase, assuming a minimum stomatal resistance of 100 sm-1 (Monteith *et al.*, 1990; Kelliher *et al.*, 1995) the value of ETp can be calculated from the following equation:

$$ET_p = \frac{86400}{\lambda}\left[\frac{s\left(1-0.4e^{-0.5LAI}\right)(1-\alpha)\left(K^{\downarrow}+L^{*}\right)+c_p\,\rho_a\,(e_s-e_a)U/124}{s+\gamma\,\left(1+U/0.62\,LAI\right)}\right]\ \text{(mm/d)} \qquad (1)$$

where $K^{\downarrow}$ is the incoming solar radiation and U the wind speed. The other variables, namely L^* (net longwave radiation), c_p (air specific heat), ρ_a (air density), (es−ea) (vapour pressure deficit), λ (latent heat of vaporisation of water) and γ (thermodynamic psychrometric constant) are calculated from measurements of air temperature and humidity at a ground-based meteo station. Equation is valid under conditions of high solar irradiance (typical summer condition in Mediterranean climate) and for LAI>0.5; adaptations might be needed under different climatic conditions. This equation can be applied by using ground-based meteorological data and satellite-based estimation of the two canopy parameters needed for the calculation, namely the surface albedo α and Leaf Area Index (D'Urso *et al.*, 1995; 2006).

Simplified methods are available to estimate surface albedo α and Leaf Area Index from satellite-based surface reflectance with satisfactory accuracy for the present application. Broad-band sensors in the visible and near-infrared, i.e. Landsat, SPOT, IRS, Terra-Aster, have been intensively used for deriving maps of α and *LAI*. A combination of different satellites can be found to define a "virtual constellation"; so doing it is possible to achieve a revisit time of 7-10 days, in order to adequately follow the phonological development of crops during the irrigation season.

For the estimation of α from Earth Observation data we need to solve three main problems: the directional integration of spectral radiance detected by the sensor, the spectral integration to obtain the planetary albedo, that is at top-of-atmosphere height, and the correction of atmospheric effects in each spectral band for deriving the surface albedo. The current sensor capabilities (broad-band, near-nadir view) impose several simplifications. Considering that radiance measurements are performed at different wavelengths, the spectral integration is approximated in discrete form, as expressed by the following relationship (Menenti *et al.*, 1989):

$$\alpha = \pi\int_0^{\infty}\frac{K^{\uparrow}(\lambda)}{K^{\downarrow}(\lambda)}d\lambda \cong \pi\sum_{\lambda_1}^{\lambda_n}\frac{K_{\lambda}\left(d^0\right)^2}{E_{\lambda}^0\cos\vartheta^0} \qquad (2)$$

In Eq. (2) the spectral radiance reflected from the surface, $K^{\uparrow}_{\lambda}$ (W m^{-2}), and the extraterrestrial solar irradiance, E^0_{λ} (xW m^{-2}), are integrated values over the width of each spectral band λ_i; θ^0 and d^0 are respectively the solar zenith angle and the sun-earth distance in Astronomical Units. By grouping these quantities in a set of band-coefficients (which are sensor-dependent), Eq. can be simplified in the following expression:

$$\alpha = \sum_{\lambda} w_{\lambda}\rho_{\lambda} \qquad \lambda = 1,2,....,n \tag{3}$$

where ρλ represent the spectral reflectance (corrected for atmospheric effects) in the generic band. The coefficients wλ can be calculated for each sensor type and applied to calculate α for the given image acquisition (D'Urso *et al.*, 2006).

Simple and feasible approaches based on empirical relationships between *LAI* and nadir-viewing measurements in the red and infrared bands has been have been defined by several authors. These methods implicitly assume that all other factors, except *LAI*, influencing the spectral response of canopy are fixed. In the DEMETER and PLEIADES projects, we have used the model CLAIR (Clevers, 1989), based on the *Weighted Difference Vegetation Index* (*WDVI*) which is defined as follows:

$$WDVI = \rho_i - \rho_r \frac{\rho_{si}}{\rho_{sr}} \tag{4}$$

where ρ_r and ρ_i indicate the reflectance of observed canopy in the red and infrared bands respectively, while ρ_{sr} and ρ_{si} are the corresponding values for bare soil conditions; the ratio ρ_{si}/ρ_{sr} can be takes as a constant, in analogy with the "soil line concept" (Baret *et al.*, 1993). The WDVI index has the advantage to reduce to a great extent the influence of soil background on the surface reflectance values; diversely, it is quite sensitive to the atmospheric effects, thus it requires a reliable radiometric correction. The LAI is related to WDVI of the observed surface through the expression:

$$LAI = -\frac{1}{\omega}\ln\left(1 - \frac{WDVI}{WDVI_{\infty}}\right) \tag{5}$$

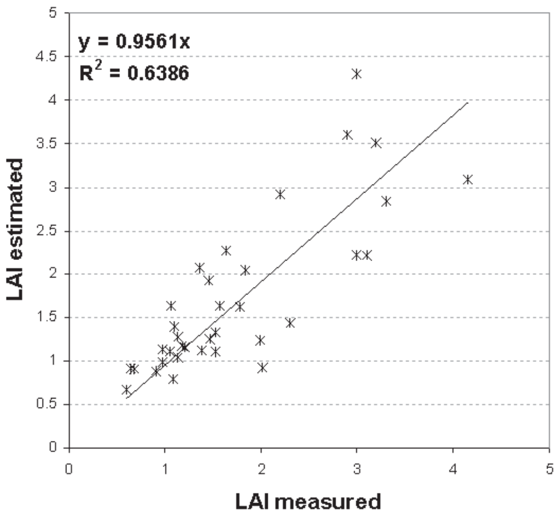

Figure 1. Validation of empirical estimation of LAI on the basis of field measurements on different crop types, Sele River Plain, Italy. Eq.(6) has been applied with ω =0.33; $WDVI_{\infty}$ =0.55 and ρ_{si}/ρ_{sr} =1.11.

In Eq.(5), ω is an extinction coefficient to be determined from simultaneous measurements of LAI and WDVI; WDVI∞ is the asymptotical value of WDVI for LAI→∞. This approach has been validated by field measurements and by means of numerical models simulating the reflectance of leaf and canopy in a wide range of conditions in different sites (D'Urso *et al.*, 1995). By using independent measurement data-sets collected during several field campaigns, calibration and validation of Eq.(6) has been carried out (fig.1).

When a more complete radiometric information is available, i.e. by using TERRA-ASTER data or new generation of satellite with super-spectral capabilities, it is possible to apply physically-based model of vegetation radiative transfer to estimate canopy albedo and LAI, without strong restricting assumptions as in the semi-empirical models. A possibility is offered by a fast and robust inversion techniques based on the construction of a look up table (LUT) (Weiss *et al*., 2000) from the widespread SAIL – model (Verhoef, 1984) combined with PROSPECT (Jacquemoud & Baret, 1990) to "PROSAILh" (e.g., Baret *et al.*, 2007; Weiss *et al.*, 2000). This combined model takes into account the effect of soil background, the optical properties of the leaves, which are related to pigments and leaves water content. As such, diversely from Eqs. throug , an higher amount of spectral information is required to achieve a satisfactory level of accuracy in the results (Richter *et al.*, 2007). A remarkable difference between the empirical methods and the physically-based PROSAILh model is the possibility of considering the influence of illumination and observation geometry on the canopy reflectance, otherwise considered as a Lambertian reflector.

The approach described here, based on the combination of canopy parameters estimated from E.O. data and the Eq.(2), has been validated by using independent measurements of ET_a obtained from micro-meteorological instrumentations during different field campaigns. For example, in the case of corn and alfalfa plots under well-watered conditions, the comparison between ET_a and ET_p derived from satellite-based data has evidenced a very high correlation (fig.2).

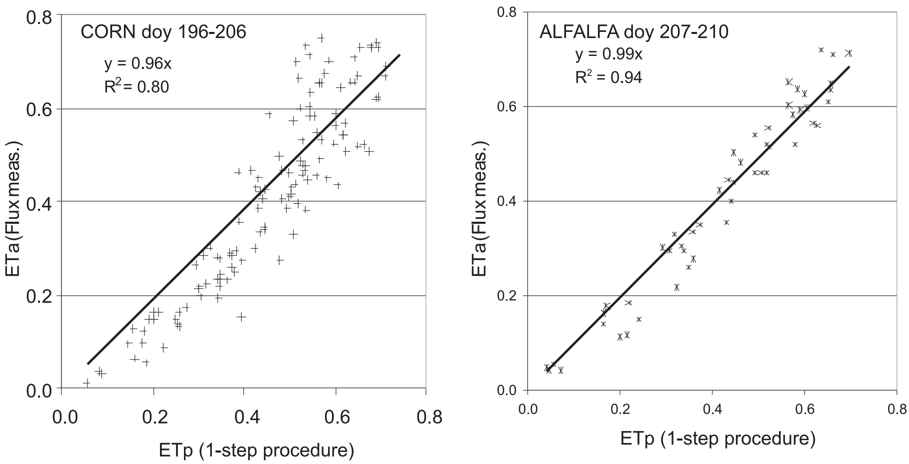

Figure 2. Comparison between ET_p values based on Eq. and field measurements of ET_a obtained by means of Eddy-Covariance techniques on corn and alfalfa plots fully irrigated; values are mm/h. Measurements refers to experiments carried out in the context of PLEIADeS project in the Nurra irrigation district.

Since the concept of crop coefficients K_c is still widely used in irrigation practice and it represents an information which can be easily transferred to final users, we can derive an analytical expression of K_c based on Eq., applied twice, a first time with canopy standard parameters for ET_0 and successively with the actual values for ET_p.

III – Processing and I.C.T. delivery of information to final users

Semi-automatic procedures have been developed in order to elaborate ET_p maps from E.O. data in the minimum possible time. The key-points of this procedure are: a) personalised irrigation advice; b) timely delivery of the information. Once the data are acquired by the satellite, i.e. at 10:00 a.m. day 1, the raw image is available via FTP within 12 hours at the processing center. The following processing steps are then applied: geometric correction (based on Ground Control Points), atmospheric correction, calculation of canopy parameters (albedo, *LAI*, K_c).

This processing is generally completed within 24 hrs from image download, i.e. at 12:00, day 2. At the end of this processing phase, the following products are ready: 1) color combination maps, 2) Crop Coefficient maps – from both approaches, 3) meteorological data (Precipitation, Reference Evapotranspiration) and 4) crop water requirements data. These products are directly delivered to each farmer by using I.T. in two ways: (1) simple text report by using SMS; (2) standard report, by MMS and e-mail, including images of the fields in false colors combination and a Kc map. The entire process is completed around 15:00 hrs, day 2. An example of the derived product is shown in figure 3.

The total cost of the advisory service, based on weekly reports, has been evaluated on the basis of 6 images from Landsat-5 and SPOT per irrigation season (60 days), over an extension of approximately 10 000 ha of irrigated land. The resulting cost is on the order of 40 € per hectare per year, including personnel cost for data processing and product generation; however, this value is strictly dependent on the density of irrigated area within the image acquisition.

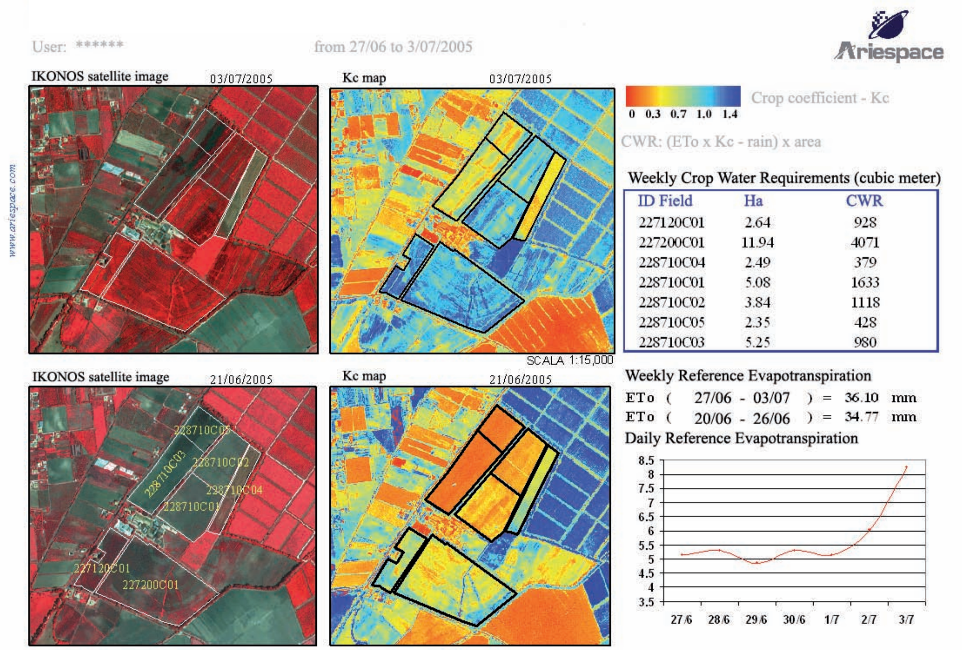

Figure 3. Example of information distributed to farmers via MMS (mobile phones) and E-mail: colour composite derived from high resolution satellite images and K_c map for a period of 4-7 days.

We have also carried out an evaluation survey among the final users. From this investigation, it has resulted that farmers have been able to recognize without difficulties their parcels on the images and they have scheduled the irrigations by taking into account the information provided. The crop heterogeneity captured by the high resolution images has been considered as a valuable add-on information to identify the variability of soil texture and fertility, plant nutrition, or different performance of irrigation systems.

If the actually given water volumes are known, it is then possible to evaluate the irrigation efficiency at different spatial and temporal scales. In a better way, crop water requirement information can be distributed to farmers in order to avoid the application of excessive amounts of irrigation water (and increase efficiency). An example is shown in Fig.4, where the suggested volumes are compared with the actual applied ones.

All the farmers evaluated positively the usefulness of the information provided, especially when it was made readily available by means of the MMS or e-mail weekly reports, and in most cases an increase of irrigation efficiency was achieved, because of the reduction of water volumes.

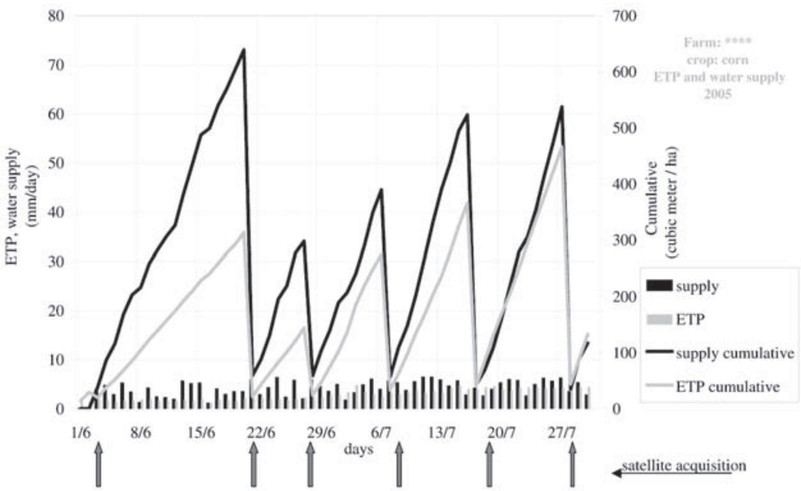

Figure 4. Comparison between the water volume supplied with irrigation and the crop water requirement estimated from E.O. data (bars:daily; lines: cumulate values). Data refer to a corn field with sprinkler irrigation. The farm has received weekly reports, for scheduling irrigation from the information provided.

IV – Conclusions

From the experience briefly presented here, it is possible to conclude that satellite remote sensing represent a mature technology ready to be transferred to operational applications in real-time (Calera *et al.*, 2005). Basic and advanced products, such as evapotranspiration and crop water requirements maps, based on satellite images and personalized for each farm and each parcel are delivered by using new Information Technology media (D'Urso *et al.*, 2006).

In the near future, thanks to improvements in the spatial and radiometric accuracy of new sensors, a more accurate estimation of this type of applications can be achieved. Due to the development of fast-access to Web resources, the time lag between satellite acquisition and availability of data to the final user has sharply decreased.

It is not difficult to positively assess the "cost-benefit" effectiveness of using E.O.data in operational contexts, with tangible benefits for a better management of water resources in irrigated areas.

Acknowledgements

This work is carried out in the framework of PLEIADeS project (Participatory multi-Level EO-assisted tools for Irrigation water management and Agricultural Decision-Support; Contract 037095 financed by U.E.- VI F.P.), with the support of Italian Ministry of University and Research (M.I.U.R.), National Research Project "Earth Observation and hydrological modelling for the study of crop water stress in the Mediterranean regions" (Prot. 2006070033/2006).

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An integrated solution for superficial water resources management based on complex distributed models and innovative web technologies

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Abstract. Action plans to reduce water pollution is a strategic task of European Countries (2000/60/CE) where water demand is steadily increasing, while water resources are limited. Action plans for water resource protection include monitoring activities, programming, identification of interventions, measures, constraints, and, in general, a variety of integrated actions for a water resource management policy. The advances in web-based technologies, computer simulation and high performance (GRID/CLOUD) computing in recent years have highly extended the possibilities in the environmental sciences, and have changed the ways in which land management systems operate. On this basis SAR, CRS4, ERA Progetti have started a collaboration to design tools, procedures and applications for the environment based on knowledge and easy access to up-to-date data and models for politicians, administrators and citizens. Here we present an innovative application accessible on the Internet, based on the web BASHYT portal (www.eraprogetti.com/bashyt), to simulate and analyze the water cycle.

The integrated software system will be tested to quantify agricultural drought periods for a Sardinian case history (San Sperate, South of Sardinia – Italy) produced with the weather data series of SAR meteorological stations for the period January 1995 - February 2008.

Keywords. SWAT – Water balance – Hydrological models – Sardinia – Drought.

Une solution intégrée pour la gestion des ressources en eau superficielle basée sur des modèles complexes et distribués et des techniologies web innovatives

Résumé. Les plans d'action pour la réduction de la pollution de l'eau constituent une tâche stratégique des pays Européens (2000/60/CE), où la demande augmente systématiquement, alors que les ressources en eau sont limitées. Ces plans d'actions incluent des activités de monitorage, de programmation, d'identification d'interventions, de mesures et de contraintes, et en général, une variété d'actions intégrées pour une politique de gestion de la ressource en eau. Grâce aux possibilités offertes par une plate-forme innovative basée sur le Web (BASHYT) et à la disponibilité de données météorologiques constamment ajournées, des modèles hydrologiques (principalement SWAT et QUAL 2K) et des procédures pour les rapports standardisés s'appliquent afin d'améliorer et d'intégrer la disponibilité d'informations à l'état de l'environnement.

Se basant sur ces hypothèses, SAR, CRS4 et ERA-Progetti ont entamé une collaboration pour créer et mettre à disposition, à l'appui des autorités responsables des ressources hydriques, un service de simulation du bilan hydrologique et des processus reliés (flux sortants ; transport de sédiments, de pesticides et de nutriments provenant des sources ponctuelles et diffuses) jusqu'au niveau de sous-bassin. À titre d'exemple, on a produit une application dans laquelle le contenu hydrique des sols permet d'évaluer l'intensité et la permanence des conditions de sécheresse dans le bassin de San Sperate, au Sud de la Sardaigne, produit avec la série Janvier 1995 - Février 2008 des stations météorologiques SAR.

Mots-clés. *SWAT – Bilan hydrique – Modèles – Sardegne – Sécheresse.*

I – Introduction

The complexity of the interactions between land use, soil, climate, anthropogenic stresses and quality of water in regions predominantly agro-livestock oriented (Sardinia is just one example), requires the use of reliable models to evaluate water resources vulnerability. The use of advanced ICT technologies, such as environmental models, GIS and web based applications, involves major investments, also in terms of acquisition of quality data, and the development of an interdisciplinary approach to the study. Such technologies can provide a significant contribution in the description of the water cycle and phenomena related to it.

The correct characterization of the spatial and temporal distribution of rainfall, of the land use, soil and anthropogenic pressures are strategic to represent the complex dynamic of surface and ground water resources and to design its sustainable use.

On these basis SAR, CRS4 and ERA-projects have started a collaboration by integrating data (in particular daily weather-climatic data), tools and expertise in the field of hydrological modeling, with the aim to organize and make available an operational service for the entire region, constantly updated, balanced and refined, which simulate the hydrological budget and related processes (e.g. sediment, nutrients and pesticides cycle). The objective of the work is to make available though a multi layered user-friendly web portal updated quality data, model outputs, visualization and processing tools to support the analysis and assessment of the water cycle.

II – The BASHYT framework

The latest computer technology offers computing and storage resources, distributed over a wide geographical domain, available from fast and secure networks, providing important services, applications and advanced visualization tools. The new paradigm is based on an integrated and collaborative approach where the complexity of the technology is transparent to the user, and interdisciplinary working groups and skills can be enhanced. On this basis, the development and use of enabling technologies (e.g. RDBMS with spatial extension, AJAX technologies, the GRID / cloud computing, etc..), allows to imagine new approaches for the management and the exploiting of data and physical resources available.

BASHYT (Basin hydrologic Scale Tool - http://www.eraprogetti.com/bashyt) is a web-based Collaboative Working Environment (CWE) for management and quantification of human and natural impacts on water bodies receptors, developed by ERA Progetti srl. The system has a modular structure built around the SWAT and Qual2K models. The portal permits to simulate and analyze the integrated water cycle (water balance and quality status of surface water bodies at different space and time scales), through a carefully rigorous methodology (DPSIR model) and to produce reports on environmental states by means of standardized procedures.

Data objects are natively digested by the CWE environment, allowing Web services to be exposed for data mapping, querying and sharing, processing and output distribution, using secure connections through the Web. The CWE framework can be thought as an easy to use Open development framework for constructing spatially enabled Internet- applications made available through the WEB browser.

The portal supports a WEB based live programming environment making the programming features available to developers with almost-zero learning curve. This increases developer productivity by reducing scaffolding code when developing web, GUI, database, GIS or applications.

III – The hydrological model SWAT

SWAT is a watershed-scale hydrological model, developed by the U.S. Department of Agriculture USDA-ARS and Texas A & M University, which allows to simulate the integrated water cycle and to assess the impact in the medium to long term of point and diffuse pollution. The application of the model requires specific information on weather, soil characteristics, topography, vegetation and land use.

The calculation of the water balance is carried out on Individual units (Hydrologic Response Units, HRUs), representing areas with a combination of land cover, soil type and management practice. From a computational, simulation of large basins also does not require too much investment of time and of computing resources. SWAT is an open source model, its use has further advantages: it's free, editable (it can be adapted to the particular needs), it is used by a large community of users around the world, and this encourages its continuous improvement. The model has been tested successfully in different geographical and climatic conditions.

The simplified equation of the water balance is summarized by the following:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_i - Q_{\sup,i} - ET_i - W_i - Q_{gw,i}) \qquad (1)$$

where SW_T is the final soil water content, SW_0 is the initial soil water content, t is the time in days, R_i is precipitation, $Q_{sup,i}$ is run-off, ET_i is real evapotranspiration, W_i is percolation and $Q_{gw,i}$ is baseflow.

Actual evapotranspiration is calculated on the basis of potential evapotranspiration. This can be quantified with the Hargreaves, Penman-Monteith or Priestley-Taylor methods. To calculate runoff SWAT uses both the Green & Ampt infiltration method and the Curve-Number method.

The model also includes additional routines that enable to quantify the outflow and soils moisture content, the sediment, nutrients and pesticides fate, channeled toward the main gages in each sub-basin. The different processes described by the SWAT model can help produce a wide range of information for a given basin, for various operational applications.

Among the various possibilities offered by the SWAT model, in this particular study we will focus on the evaluation of a drought indicator to assess the severity and duration of drought period. The development was carried out for the San Sperate catchment in the south of Sardinia, Italy, using meteorological data for the period January 1995 - February 2008, registered by the SAR stations.

IV – Example of application: an index for agricultural drought

1. The agricultural drought

Drought is a temporary condition of relative scarcity of water resource compared to values that can be considered normal for a period of time and on a region (Rossi, 2000). Regarding with the elements of the hydrological cycle we may distinguish between meteorological, agricultural, hydrological and operational drought. While the meteorological drought is identified on the basis of a deficit of precipitation, the agricultural drought depends on the soil moisture deficit which is dependent on the precipitation regime and weather, the soil characteristics and the evapotranspiration rate. The persistence of agricultural drought condition produces negative effects both on natural vegetation and agriculture. Drought periods have an important impact on water supply system causing water shortage, negatively affecting the economic and social system.

Regional water authorities (e.g. in Emilia Romagna, Piedmont, Calabria, Sicily and Sardinia) have organized operational systems to facilitate the collection, processing and dissemination of hydro-meteorological data to monitor drought periods. Several indexes and methods have been proposed since the Sixties to detect and monitor drought events. The most commonly used are essentially the Standardized Precipitation Index – SPI (McKee *et al.*, 1993), the Palmer index – PDSI (Palmer, 1965) and deciles method (Gibbs, Maher, 1967).

However, some authors have highlighted several shortcomings in the implementation of such indices especially if they are used for drought evaluation on a small spatial scale. To this end, agricultural drought indices may be more accurate to evaluate the water deficit on the basis of the available water on the soil profile. The use of hydrological distributed models can provide reliable estimates of the soil water content and help quantify its deficit taking into account the distributed soil and land use characteristics.

2. The San Sperate basin

The Flumini Mannu of S. Sperate basin is found on the south central part of Sardinia and is delimited by the Sarcidano plateau at north, the Sarrabus relief at east, the last layer of Iglesiente massif at West. The topography is characterized by a significant variation in terms of altitude (from 13 to 972 m a,s.l.). The main river is a tributary of Flumini Mannu of Cagliari river which discharges its waters into the Santa Gilla humid area near the gulf of Cagliari which is among the largest wetlands in Europe.

The climate of the area is Mediterranean with long hot dry breezy summers and short mild rainy winters. Average monthly temperature ranges from 8°C (January and February) to 25°C (July and August). Precipitations are largely confined to the winter months, the rainfall regime is characterized by a peak rainfall in December (83 mm) and a minimum in July (8 mm), with an average value of 591 mm/year. The S. Sperate river is characteristically fast flowing, with a relatively important water volume in winter, reduced to a trickle during the dry season. The monthly water volume is characterized by a minimum peak in August (0,16 mc/s) and a maximum in February (4 mc/s). Land is primarily used to satisfy agricultural needs with large areas destined to crop cultivation (Cereal is predominant – 9091 ha). On the south we find vineyards (1709 ha), olive groves (2383 ha) and orchards 1709 ha) mainly. At East, woods and pastures are mostly found.

The hydrological behavior of soil is related to a number of physical soil properties (USDA & NRCS Soil Survey Division, 1994). To obtain information about these soil properties of the S. Sperate basin, a 1:250 000 soil vector map (Arangino *et al.*, 1986) (Aru *et al.*, 1991) has been used, where each cartographic unit has been associated with one or two delineations corresponding to subgroups of USDA soil taxonomy (Cadeddu *et al.*, 2003). Land cover significantly affects the water cycle. In this study the CORINE Land Cover 1:100.000 vector map (Commissione Europea, Ministero dell’Ambiente, 1996) has been used. It consists of a geographical database describing vegetation and land use in 44 classes, grouped into three nomenclature levels. The CORINE covers the entire spectrum of Europe and gives information on the status and the changes of the environment (Cumer, 1999).

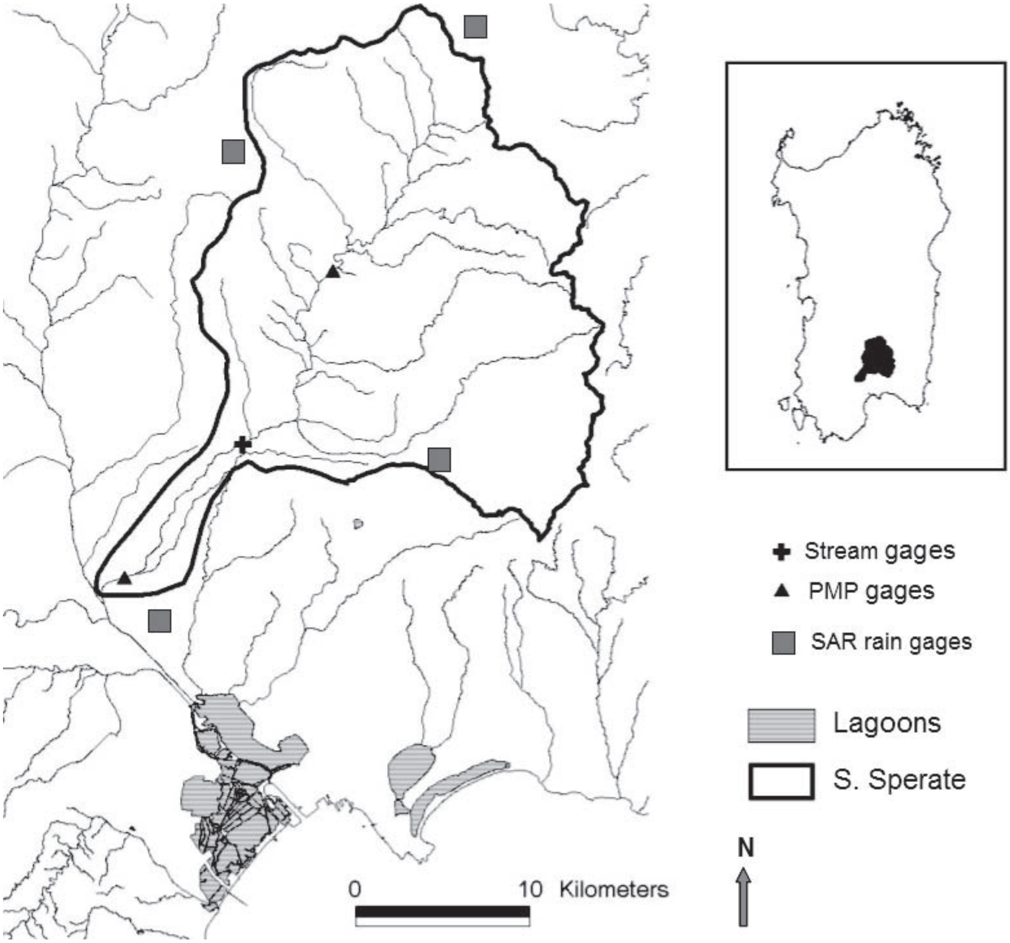

Figure 1. Location of the San Sperate basin.

Based on a 20 m digital elevation model, the 1: 100000 land use and the 1:250000 soil vector map, the S. Sperate has been subdivided in 23 Subbasins made of 444 HRUs.

The model was fed with air temperature and precipitation daily data for the period January 1995 – February 2008 recorded by monitoring network of Regional Agricultural Service for Sardinia (SAR). The climatic stations used for this application are those located in the area or localized in the surroundings: Decimomannu, Dolianova, Guasila, Siurgus-Donigala and Villasalto. Figure 1 shows the area of this study and the location of weather stations.

The model calibration/validation process followed a regional scale approach (Cau *et al.*, 2005). Monthly streamflows and reservoir water level historical records were used as control values. The soil and land cover parameterizations are not restricted to a single watershed, as similar soil and land cover types are found in different basins of the region. The parameters (Available Water Capacity, Curve Number, etc.) controlling the partitioning between baseflow, runoff, percolation, and evapotranspiration, as well as the transport of sediments, nutrients, and pesticides were changed within ranges suggested in the literature and according to the their uncertainty. Changes to the values of these parameters were accepted only if an overall improvement in streamflow was achieved compared to observed data. This was determined using as objective function the Nash-Sutcliffe index. The best-fit parameter values for our model implementation at a regional scale scored a Nash-Sutcliffe index of 0.77, suggesting a reasonably good match between simulated and observed streamflow rates.

3. The drought index

The daily-step run of the SWAT model allowed to estimate the various components of the hydrological balance for each HRU (potential evapotranspiration, actual evapotranspiration, runoff, soil water content, etc..). The SMD (Soil Moistures Deficit) agricultural drought index, a variation of the approach proposed by Narasimhan (Narasimhan, *et al.* 2002), has been calculated on a monthly basis as proposed in the formula (2). For the given month the index expresses the ratio between the anomaly of the monthly value compared to the average multi-annual data, and the difference between the maximum and minimum values for the entire time series available (in our case 1995-2008).

The SMD index reads as follows

$$SMD_i = \frac{SW_i - SW_i^{mean}}{SW_i^{\max} - SW_i^{\min}} \qquad (2)$$

SMD_i - deficit of soil water content for the months *i*

SW_i - monthly average soil water content for the month *i*

SW mean $_i$ – long-term average monthly soil water content for the month *i*

SW max $_i$ – long-term maximum soil water content for the month *i*

SW min $_i$ - long-term minimum soil water content for the month *i*

The index can be positive and negative, indicating for a given month a surplus and a deficit of water content respectively for a given soil (BASHYT automatically quantify the anomaly magnitude observed on a given month and to weigh it with respect to the variability of long-term estimated values to evaluate the SMD drought index).

V – The environmental reporting for the Case Study

The components of the hydrological balance, obtained on daily time step for each elementary territorial units (HRU), obtained by the SWAT model, were subsequently integrated and analyzed on sub-basin spatial scale and on a monthly time step, by means of the post-processing tools of the BASHYT portal. These outputs are then produced and presented on time series and spatial representations by means of dedicated interactive web pages within the portal. Figure 2 shows the hydrological balance for the whole basin.

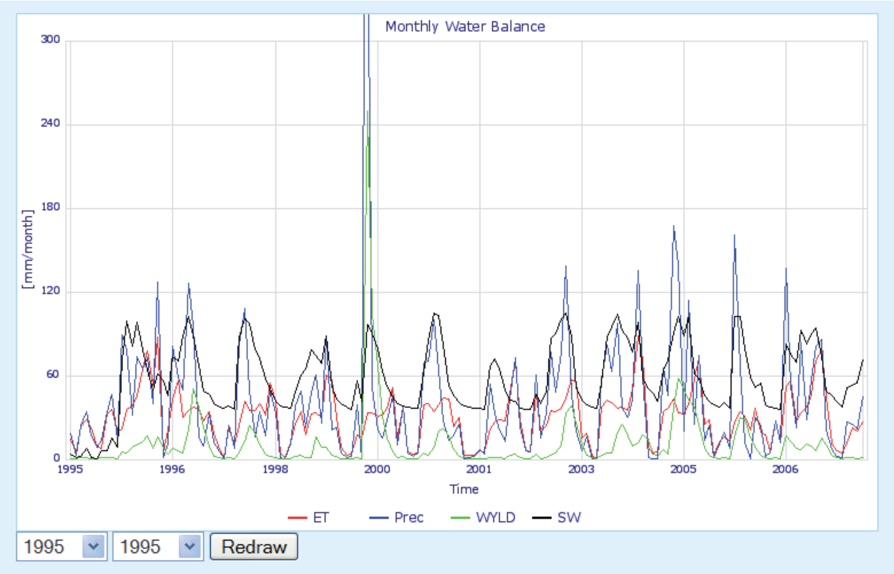

Figure 2. Prec - rainfall, ET - actual evapotranspiration, SW – soil water content, Wyld – water yield for the San Sperate basin, viewed on the BASHYT web portal.

Figure 3 shows the SMD index spatial distribution for the period Agost 2001 – January 2002, The web application permits to interactively monitor the intensity of the deficit condition and the duration of the drought period. In particular the period September - December 2001 is the longest drought period in the 15 years simulation while December 2007 is the one that showed the most sever intensity of the SMD index.

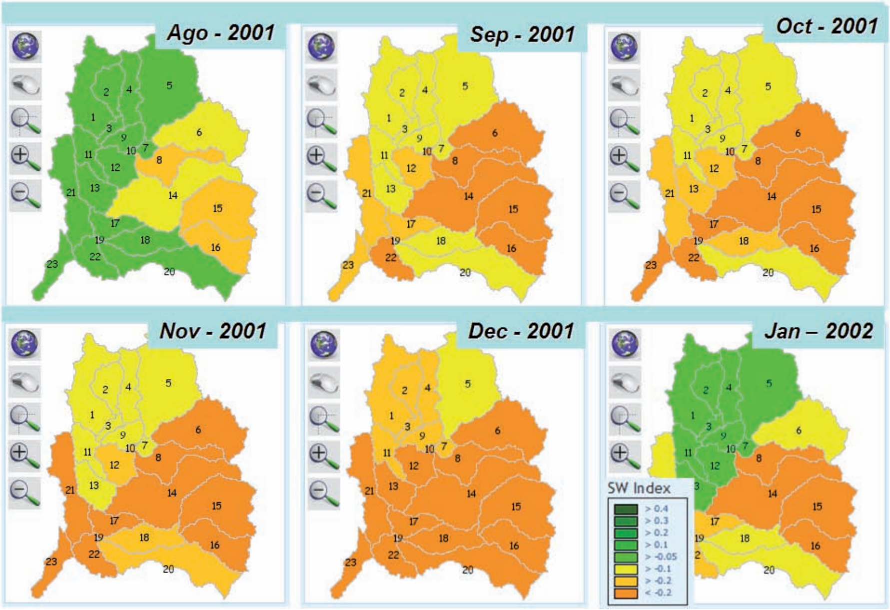

Figure 3. Spatial distribution map of the monthly SMD index (period August 2001 - January 2002).

VI – Conclusion

The proposed procedure for estimating the drought index SMD is based on a complex hydrological balance model which runs on a HRU spatial scale and on a daily time step. This approach has the advantage of examining the hydrological cycle at the correct scales of the hydrological phenomena involved. Subbasin monthly estimates are, as a matter of fact, derived from daily balances at the HRU scale.

Water authorities need to have substantial scientific tools to analyze complex phenomena of interest. BASHYT can represent an important contribution in the field of environmental reporting systems. This environment web-based decision support system is designed to meet the needs of administrations involved in integrating environmental reporting procedures (based primarily on GIS, tables, graphs) and analysis tools.

Finally, the case history briefly presented, although limited to the calculation of SMD on a complex Sardinian basin, allows to appreciate the potential of the proposed system. If extended to the whole region, such system, supplemented also with the assessments of other phenomena of interest (e.g. evaluation of the impact of point and diffuse pollution on water resources, etc..) offer operational tools highly useful for the management of water resources.

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The effects of mist irrigation on biological and productive behaviour of globe artichoke

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Abstract. Globe artichoke [*Cynara cardunculus* L. var. *scolymus* (L.) Fiori] is an important Mediterranean crop, producing edible immature inflorescences (heads or capitula). In Southern Italy, it plays a pivotal economic role, given its early ripening and potential to provide employment almost all the year-round. However, the critical summer conditions experienced by plantlets, often negatively affect crop establishment, yield and earliness. The goal of our study was to evaluate the opportunity to mitigate these drawbacks by means of mist irrigation, on three early-producing artichoke cultivars ('Spinoso di Palermo', 'Tema 2000' and 'Violet de Provence'). Mist irrigation reduced the maximum air temperature and increased the maximum R.H. within the crop. Such modifications had positive effects on crop establishment and yield, while reducing the production of unmarketable heads at the same time. This was positively reflected on final yield per unit area. Significant "genotype x mist irrigation" interactions were observed.

Keywords. Globe artichoke – Mist irrigation – Head atrophy – Earliness – Yield.

Effets de la nébulisation sur le comportement biologique et productif de l'artichaut

***Résumé**. L'artichaut [Cynara cardunculus L. var. scolymus (L.) Fiori] est une importante culture méditerranéenne, produisant des inflorescences immatures comestibles (capitules). L'artichaut joue un rôle crucial dans l'économie du sud de l'Italie, vues sa maturité précoce et sa capacité de fournir des emplois presque toute l'année. Toutefois, les conditions critiques auxquelles les plantules sont exposées l'été, ont souvent un effet négatif sur l'accroissement, le rendement et la précocité de la culture. L'objectif de notre étude était d'évaluer la possibilité de limiter ces inconvénients sur trois cultivars d'artichaut précoce ('Spinoso di Palermo', 'Tema 2000' et 'Violet de Provence') par la nébulisation. La nébulisation a réduit la température maximale et a augmenté la H.R. maximale au sein de la plante. Ces modifications ont eu des effets positifs sur l'accroissement et sur le rendement de la culture, tout en réduisant la production de capitules invendables. Cela a influé positivement le rendement final par unité de surface. Des interactions significatives "génotype x nébulisation" ont été observées.*

***Mots-clés**. Artichaut – Nébulisation – Atrophie du capitule – Précocité – Rendement.*

I – Introduction

Globe artichoke [*Cynara cardunculus* L. var. *scolymus* (L.) Fiori] is a perennial, Mediterranean crop, belonging to the Asteraceae family. The main product consists of immature inflorescences (heads or capitula), traditionally eaten in a multitude of Mediterranean dishes. Each plant produces several heads, with the earliest and most appreciated ones (the main capitula) formed at the apex of the central stem. Several smaller heads are formed later on the lateral branches. Currently, Southern Italian regions are the main artichoke producers worldwide, especially Apulia (17 Kha), Sicily (15 Kha) and Sardinia (13 Kha) (ISTAT, 2008), where this crop represents one of most important agricultural resources (Mauromicale 1984; 1988). This is due to the possibility of achieving early head productions (from early autumn), so markedly anticipating those coming from other Italian regions, i.e. in spring. This results from the interaction between mild winters and the characteristics of the locally grown germplasm, best adapted to forcing (summer implantation by "ovoli", followed by frequent irrigations) and with little chilling requirements (e.g. 'Violetto di Sicilia', 'Spinoso di Palermo', 'Violet de Provence' etc.) (Mauromicale and Ierna, 2000;

Mauromicale *et al.*, 2004). Nonetheless, as a consequence of such a crop scheduling, artichoke plantlets experience unfavourable summer climatic conditions (high temperatures and low air R.H.) in the juvenile stages, which frequently cause a significant reduction of crop establishment, as well as inducing head atrophy. These are the outcome of the alteration of both the water balance and the calcium allocation in the plant (Morone Fortunato *et al.*, 1981; Mauromicale, 1984; Magnifico *et al.*, 1984; 1985; Saure, 1998). All these phenomena have significant effects on the yield and earliness of marketable production, often persuading growers to shift the period of artichoke plantation. On the other hand, it has repeatedly been shown that mist irrigation is a suitable technique to modify the microclimatic conditions (temperature and R.H.) over the crop, so positively influencing the biological behaviour and yield components of several horticultural species (Mauromicale and Restuccia, 1987; 1989; Restuccia *et al.*, 1995). The aim of this study was to evaluate the opportunity to limit these drawbacks and to improve the earliness of heads production through mist irrigation on early-producing globe artichoke cultivars.

II – Materials and methods

The experiment was carried out during the 2005-2006 season, in a representative area for globe artichoke cultivation in Sicily, South-East of Palermo (37°58' N, 13°49' E), on a clay soil. A randomized split-plot experimental design with four replications was adopted to test the effects of mist irrigation (as main plot), compared with an untreated test, on three early-producing globe artichoke cultivars ('Spinoso di Palermo', 'Tema 2000' and 'Violet de Provence') as subplots. The 'ovoli' were transplanted on August 1, 2005, 0.80 m apart within row, with an inter-row spacing of 1.25 m (1.0 plant m^{-2}). Crop management (fertilization, weed and pest control) was ensured by following standard commercial practices. Drip irrigation was effected by supplying 100% of maximum evapotranspiration (ETM). The mist system consisted of sprinklers placed at 1.4 m above the soil at 6.5 m intervals (12 l h^{-1} at 4.0 atm). Five minute periods of mist irrigation were carried out three times per day between 12.00 and 14.00, from September, 1 (31 Days After Planting, DAP) until November, 15 (106 DAP). On the whole, 281 m^3 ha^{-1} of water were delivered with mist irrigation. Each net subplot consisted of 40 plants. Within the crop, meteorological measurements (daily maximum and minimum air temperatures, RH) were done through thermo-hygrometers Salmoiraghi® (Milano, Italy). The following parameters were measured: percentage of established plantlets, percentage of atrophic heads produced (until 151 DAP), fortnight's cumulative yield of heads $plant^{-1}$ and fortnight's cumulative yield of marketable heads ha^{-1} (from 118 until 268 DAP).

Data were submitted to Bartlett's test to check the homoscedasticity, then they were subjected to the ANOVA. When *F*-test was significant, means were separated through Fisher's LSD test. Percentage data were Bliss' transformed before the ANOVA (untransformed data are reported and discussed).

III – Results and discussion

Mist irrigation was able to modify the microclimatic parameters within the crop (Table 1). On average, an appreciable reduction was recorded for the daily maximum temperature, ranging from 1.5°C (1-30 September) to 2.2°C (1-31 October), i.e. during the transition of the apical bud and the initial growth of the head. Moreover, a reduction of the daily minimum temperature, from 0.8°C (1-15 November) to 2.6°C (1-30 September) was recorded and a contextual increase of the R.H., particularly during the 1-30 September period (+2%) (Table 1).

Table 1. Mean values of maximum temperature, minimum temperature and maximum R.H. recorded inside the globe artichoke crop during the mis t irrigation period.

	Maximum temperature		Minimum temperature		Maximum R.H.	
	°C				%	
	Test	*Mist*	*Test*	*Mist*	*Test*	*Mist*
September, 1 - 30	32.4	30.9	21.5	18.9	90	92
October, 1 - 31	26.9	24.7	17.8	16.7	94	95
November, 1 - 15	25.8	23.9	16.5	15.7	94	95

The microclimatic conditions determined by mist irrigation, compared with those of the untreated test, significantly increased the percentage of plantlets established, most of all in 'Violet de Provence' (+22%), followed by 'Spinoso di Palermo' (+10%) (Table 2). This was evident notwithstanding the treatment was started 1 month after planting. Our result is corroborated by the observation of Mauromicale (1984), who noted that dramatic decreases of crop establishment occur when plants must cope with high evapotranspiration rates at the 4-6th leaf stage (about 50 days old plants). He explained this with the initial slow growth of the radical apparatus, which is still unable to compensate the water loss of the well-developed epigeal apparatus. Moreover, the mist irrigation significantly reduced the number of atrophic heads. Its effectiveness in reducing head atrophy was directly proportional to the susceptibility of the cultivar.

Table 2. The effect of mist irrigation on some bio-agronomical variables of three globe artichoke cultivars.

Cultivar	Established Plantlets		Atrophic Heads (at 151 DAP)		N heads plant^{-1}		Marketable Yield	
	%						(000 heads ha^{-1})	
	Test	*Mist*	*Test*	*Mist*	*Test*	*Mist*	*Test*	*Mist*
Spinoso di Palermo	76	86	31	14	7.2	8.3	54.3	71.2
Tema 2000	75	78	13	7	7.9	8.4	57.8	64.9
Violet de Provence	66	88	17	12	5.6	5.9	36.5	51.4
				LSD $P \leq 0.05$				
Cultivar	NS		4.6		0.4		6.8	
Treatment	5.7		3.0		0.5		5.5	
Interaction	9.9		8.9		NS		NS	

Indeed, in 'Spinoso di Palermo', the most sensitive cultivar to head atrophy, the highest control of this physiological disorder by mist irrigation was recorded (-17%) as compared with 'Tema 2000' (-6%) and 'Violet de Provence' (-5%) (Table 2). A genotype-dependent response to mist irrigation was recorded for the final accumulated yield of heads per plant too (Table 2). Indeed, while no statistical differences were recorded in 'Violet de Provence' (5.9 *versus* 5.6 heads plant^{-1}), significant increases were recorded in 'Spinoso di Palermo' (8.3 *versus* 7.2 heads plant^{-1}), and in 'Tema 2000' (8.4 *versus* 7.9 heads plant^{-1}) (Table 2). Such increases, could be explicated by an appreciable improvement of the physiological response of the plants, such as the photosynthetic rate, the chlorophyll fluorescence parameters, or even by the level of endogenous growth-regulators, as in other vegetable crops (Saure, 1998). Nevertheless, further in-depth studies are needed to highlight the nature of this response.

The positive influence of mist irrigation on plantlets establishment, head atrophy and plant yield, was favourably reflected in the accumulated yield per unit area, as shown in Figure 1. Compared with untreated test, mist irrigation significantly improved the marketable earliness of the crop, particularly in ‘Tema 2000’ (9,745 *versus* 6,818 heads ha^{-1}, at 133 DAP), followed by ‘Violet de Provence’ (7,549 *versus* 4,018 heads ha^{-1}, at 163 DAP) and ‘Spinoso di Palermo’ (8,221 *versus* 6,789 heads ha^{-1}, at 163 DAP) (Figure 1). At the end of crop cycle (268 DAP), such differences among treatments reached their maximum values, since the marketable yield was increased, in response to mist irrigation, by 41, 31 and 12% in ‘Violet de Provence’, ‘Spinoso di Palermo’ and ‘Tema 2000’, respectively (Table 2).

IV – Conclusions

Although limited to one productive cycle, our results show the suitability of mist irrigation to regulate microclimatic conditions in the field crop, so positively influencing the agronomical behaviour of the globe artichoke. The main results obtained concerned the increase of the plantlets establishment and the partial control of heads atrophy, which together significantly increased the earliness and yield of marketable heads. The first aspect appears of key importance, since the implementation of mist irrigation might avoid the replacing of wilted plantlets, which is an expensive technique that, in any case, had no effects on the loss of earliness of the yields. With reference to the second aspect, according to Magnifico *et al.* (1985), mist irrigation did not totally prevent the onset of head atrophy. However, the containment of the phenomenon we recorded, suggests that this technique, by means of a better calibration, could be successfully implemented in the field, with the aim of improving the artichoke yields and expanding the locally grown germplasm, through an easier introduction of cultivars selected abroad (such as ‘Tema 2000’) (Mauromicale, 1984; Foti and Mauromicale, 1994). Moreover, the increase in the number of heads per plant, suggests the need for an in-depth understanding of the effects of mist irrigation on the photosynthetic machinery (e.g. gas exchanges, chlorophyll content and fluorescence, net photosynthesis), as well as on the level of endogenous growth-regulator substances, in order to better calibrate the technique in terms of crop management and water requirements.

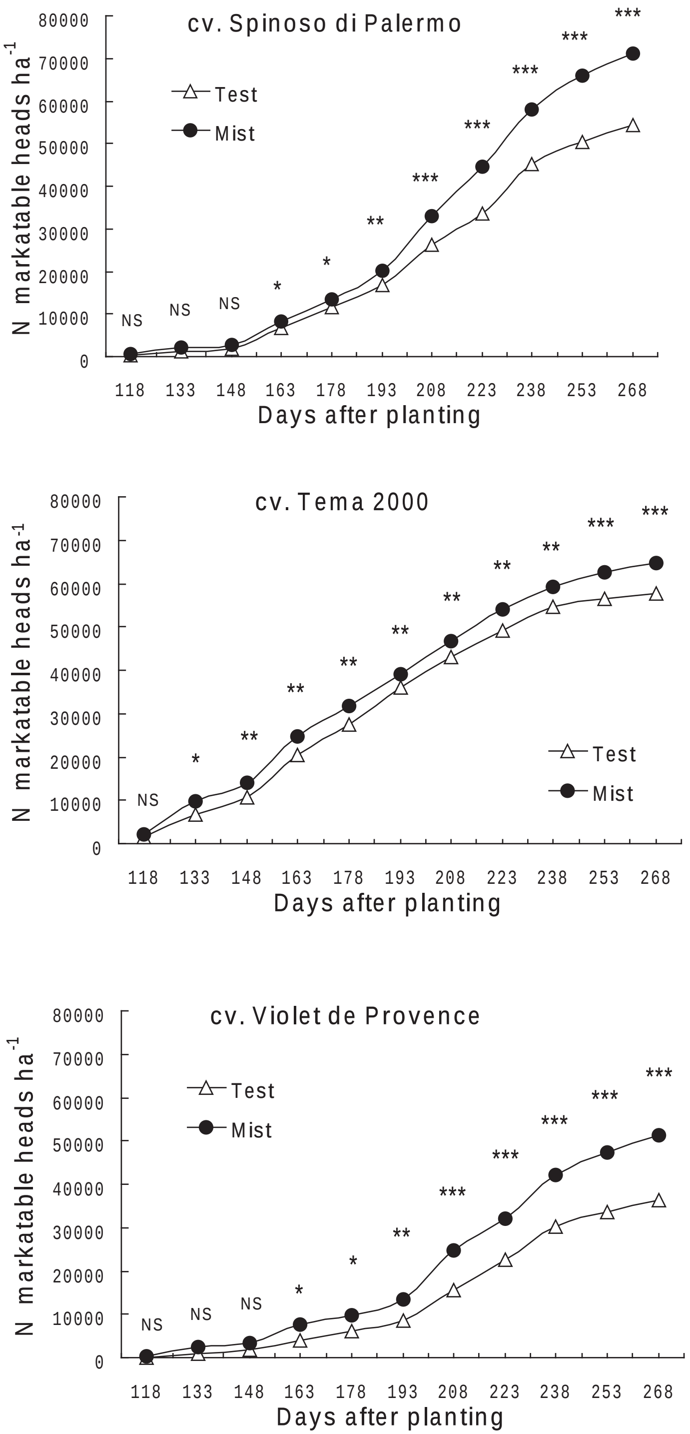

Figure 1. The effect of mist irrigation on the accumulated yield of three globe artichoke cultivars [NS = not significant; *, **, * significant at P ≤ 0.05, 0.01 and 0.001, respectively].**

Acknowledgements

The authors thank Mr. Antonino Russo and Miss Venera La Rosa for their excellent technical assistance.

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Ozone and water use efficiency

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Abstract. This study has been carried out in the southern Italy, under conditions favourable to ozone pollution, together with soil and atmospheric drought. Soybean was subjected to well-watered and water stress conditions, and three levels of ozone (filtered, low and high) in open top chambers during three growing seasons. Cumulated AOT40 values were zero, 3400 and 9000 ppb.h for filtered (control), low and high ozone concentration treatments, respectively. Under well-watered conditions, the increase of ozone concentration levels leads to a reduction in daily actual evapotranspiration (AET) and yield. On the contrary, under water stress conditions, the increase of ozone concentration levels does not affect the examined parameters. Compared to the control treatment under well-watered conditions, total AET reduction was 14% and 28% at low and high ozone levels, respectively. In well-watered conditions, at a high level of ozone concentration, a yield reduction of 47% was observed, whereas an increase in ozone had no effect on yield of plants in water-stressed conditions. Cumulated (during the soybean season) data of AET (ΣAET) and grain yield (Y) allow to calculate the water use efficiency (WUE) by the ratio WUE = Y/ΣAET. As a result, during the 3-year study, significant relationships were found between AOT40 and relative (low or high to control ozone treatments) water use efficiency.

Keywords. Mediterranean region – Soybean – Drought – Irrigation – Atmospheric pollutants – Yield.

Ozone et efficience d'utilisation de l'eau

Résumé. *Cette étude a été réalisée au sud de l'Italie dans des conditions, favorables à la pollution par l'ozone, combinées à la sécheresse du sol et de l'atmosphère. Le soja bien irrigué ou sous stress hydrique, a été soumis dans des enceintes découvertes, à trois niveaux d'ozone (filtré, bas et haut) pour trois saisons. Les valeurs cumulées du AOT40 étaient nulles, de 3400 et 9000 pp b.h, pour le traitement filtré (le contrôle), à basse et à haute concentration, repectivement. Dans le soja bien irrigué, l'augmentation de la concentration de l'ozone porte à une réduction, de l'évapotranspiration actuelle journalière (AET) et du rendement. Au contraire, sous stress hydrique, l'augmentation de la concentration de l'ozone n'affecte pas les paramètres examinés. La AET totale sous des conditions de basse et haute concentration d'ozone, a subi une réduction du 14% et du 28% respectivement, en comparaison avec le contrôle bien irrigué. Le rendement à été réduit du 47% dans le traitement bien irrigué à haut niveau d'ozone, alors qu'une augmentation de l'ozone n'a pas eu d'effet sur le rendement des plantes sous conditions de stress hydrique. Les données cumulées du AET (ΣAET) (pour toute la période de croissance du soja) et le rendement en graines (Y) permettent de calculer l'efficience d'utilisation de l'eau (WUE) par le rapport WUE = Y/ΣAET. En conséquent, pour les trois années d'étude, des rapports significatifs ont été trouvés entre AOT40 et l'efficience relative de l'utilisation de l'eau (par rapport aux niveaux d'ozone bas et haut).*

Mots-clés. *Région Méditerranéenne – Soja – Sécheresse – Irrigation – Polluants atmosphériques - Rendement.*

I – Introduction

The Mediterranean region is an area prone to the development of photochemical oxidants (Bussotti and Ferretti, 1998; Alonso *et al.*, 2001; Forlani *et al.*, 2005). The typical climatic conditions of this region (high temperatures and solar radiation combined with stable air masses and high emission of air pollutants) favour the formation of secondary pollutants such as ozone (O_3).

The objective of the study was to analyse, under natural conditions and for the entire growing season, the effect of ozone on the water use efficiency (WUE) of soybean. The effect was studied on soybean plants characterized by different conditions of water status.

II – Materials and methods

Field trials were conducted during three successive years (2003-2005), at the experimental farm of CRA-SCA (Agricultural Research Council-Research Unit for Cropping Systems in Dry Environments). This site is located in Rutigliano (lat 40° 59' N, Long 17° 59' E, 147 m a.s.l.). Soybean (cv. Casa) was chosen for the study because it grows during the occurrence of high ozone concentration levels, together with a reduction in soil water content (due to the high evaporative demand). The variety had a late maturity, that insures a relatively longer ozone exposure period. As a reminder, soybean is considered sensitive to ozone according to the classification made by Mills *et al*. (2002).

During soybean crop season, an hourly basis monitoring of ozone concentrations was carried out over the experimental plots at 1m height from soil level, using an ozone analyser. Figure 1 presents the daily maximum ozone values, as well as average values on a weekly basis.

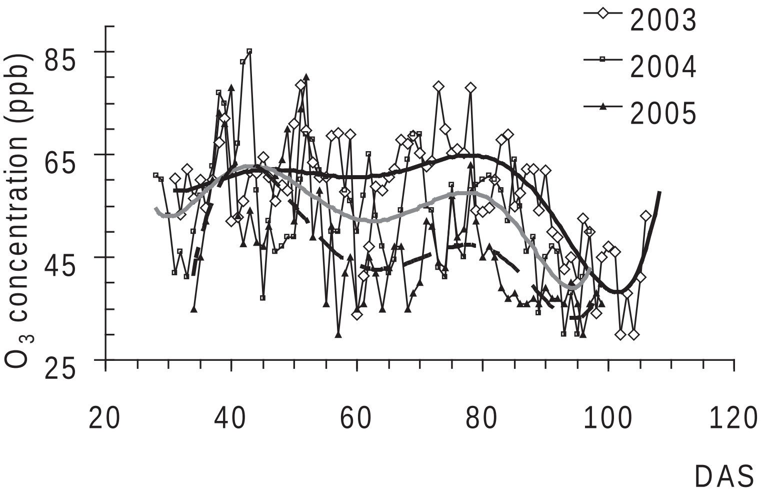

Figure 1. Daily maximum and mean values on a weekly basis of ozone concentration measured in the open field during 3 soybean growing seasons (2003, 2004 and 2005). DAS = Days After Sowing.

Maximum ozone values were generally higher during 2003, in comparison with the two following years. Ozone content in the atmosphere was evaluated through indices as AOT40, that is the accumulated hourly ozone values over the threshold of 40 ppb (Fuhrer at al., 1997). When AOT40 cumulated during 90 days is higher than the threshold of 3 ppm.h, according to the EU directive 3/2002), plant functions, mainly gas exchange, leaf growth and yield, are affected (*i.a.* see the review by Bou Jaudé *et al.*, 2008 a and b). Cumulated AOT40 over soybean crop season varied by a ratio of 1 to 3 between 2005 (3392 ppm.h) and 2003 (10237 ppm.h). Even during the season less favourable to ozone rise (2005), the thresholds limits indicate by the EU directive have been exceeded.

Four Open Top Chambers (Heagle *et al.*, 1973) were used in this study. The ozone treatments were: 1) Control (C) involves OTC's supplied with a charcoal filter. This filter can reduce the amount of ozone in ambient air up to 50%. In general, ozone concentrations in control treatments are lower than the 40 ppb threshold. 2) High ozone concentration treatments (H) involve OTC's equipped with an ozone generator OZOMATIC (mod. 4, VKAU147974, Wedeco). Air was enriched with ozone in order to reach a maximum value of 75 ppb whenever the hourly ozone concentrations were lower than 60 ppb. The objective was to reach an AOT40 value of about 10000 ppb.h, which corresponds to the highest value observed in the open field during the study period. 3) Low ozone concentration treatments (L) involve natural ambient air. The objective was to reach an AOT40 value close to 3500 ppb.h, which corresponds to the lowest value observed in the open field during the study period.

Ozone concentration measurements were performed by an ozone analyser (OZ 2000 G), at a 1m height above soil level, in ambient air as well as in the OTC's.

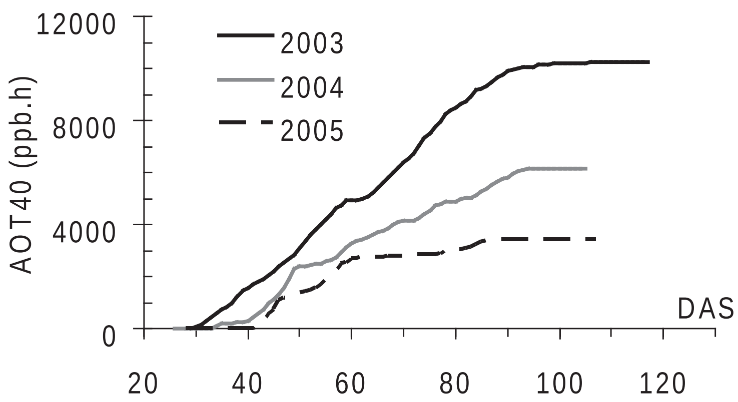

Figure 2. Daily cumulated AOT40 measured in the open field during 3 soybean growing seasons (2003, 2004 and 2005).

Ozone effects were studied in combination with the plant water status. The two conditions of plant water status were: 1) Well-watered (W); 2) Water-stressed (S). An original method was adopted for irrigation scheduling. It was based on the experimental relationship found between the predawn leaf water-potential and the stomatal conductance of soybean (Mastrorilli *et al.*, 1993). Irrigation was scheduled whenever the predawn leaf water-potential reached –0.4 MPa for the well-watered treatments (W) and –0.8 MPa for the water-stressed treatments (S).

The symbols CW and CS represent the control OTC groups, well-watered and stressed, respectively. The symbols HW and HS represent the OTC's with high ozone concentration levels, well-watered and stressed, respectively. The symbols LW and LS represent OTC's with low ozone concentration levels, well-watered and stressed, respectively.

Daily actual evapotranspiration was calculated for each OTC through a simplified soil water balance method as follows: AET = P $\pm$ ΔSw – Dr, where AET is the actual evapotranspiration in mm; P is irrigation (or rain) in mm; ΔSw is the daily variation in soil (root zone) water content measured by the time domain reflectometery method (TDR) in mm; Dr is drainage in mm. Drainage is the difference between soil water content (SWC) and field capacity (FC), when daily SWC>FC. The previous equation supposes that runoff is nil due to the use of a drip irrigation system and to the slopeless topography of the site; moreover capillary rise is nil due to the presence of a calcareous and impervious parent rock. The previous equation supposes that runoff is nil (due to the use of a drip irrigation system and to the level topography of the site) and the capillary rise is nil (due to the presence of a calcareous and impervious parent rocky layer). These hypotheses were verified by Mastrorilli *et al.* (1998), who showed coherence between the AET measured by the Bowen ratio method and that calculated through a simplified soil water balance method. Cumulated (during the soybean season) data of AET allow to calculate the seasonal evapotranspiration (ΣAET).

At harvest, yield was analyzed for all the plants grown within each OTC. According to the review of Katerji *et al.* (2008), the water use efficiency (WUE) was calculated as the ratio between the yield (Y = dry matter of the grains) and ΣAET (WUE = Y/ΣAET).

III – Results

Some reviews were addressed to evaluate the effect of ozone on crops cultivated under Mediterranean climate of Italy (Ferretti *et al.*, 2007), Australia (Muray, 2003), South Africa (Van Tinhoven and Scholes, 2003), and Egypt (Abdel-Latif, 2003). However these syntheses do not provide any information about the relationship between water use efficiency (WUE) and ozone exposure. Actual evapotranspiration is difficult to measure inside the Open Top Chambers (OTC) which have been conceived to analyze in field the ozone effect on crops.

In the following the measurements of AET realized in the OTC's are presented for each growing season. Successively the data on grain yield are reported, and finally the results on WUE.

1. Daily Evapotranspiration (AET)

Figure 3 shows the evolutions of AET measured in the 3-year experiment, inside the OTC's for the different ozone and irrigation treatments.

In 2004 season soybean was growing under well-watered conditions and each ozone treatment was repeated twice in the open top chambers (OTC1 and OTC2). Significant differences of AET values were observed between CW and HW treatments starting from 39 DAS (days after sowing). Daily evapotranspiration of HW treatments decreased progressively in comparison with CW treatments. Hence, cumulated AET values over soybean growing season were 386 mm and 274 mm for CW and HW treatments, respectively.

In 2005 soybean was growing under well-watered and stressed conditions. Cumulated AET values over soybean growing season were 389 mm and 285 mm for CW and HW treatments, respectively. These values were similar to the cumulated AET values obtained in 2004. Under water stress conditions, daily AET in 2005 shows a larger range of variation, between two irrigations. However, AET values for CS and HS treatments were similar over all the study period. Water stress minimized the effect of high ozone concentrations on daily AET. Cumulated AET values over the growing season were 291 mm and 272 mm for CS and HS treatments, respectively. These values showed a slight increase for the control treatment. The effect of water stress on plant water consumption is higher for the control treatment (-26%) than for the high ozone concentrations treatment (-5%).

The AET values cumulated over the 2003 soybean growing season were 344 mm and 295 mm for CW and LW treatments, respectively. The AET for LW treatments was reduced by 14% in 2003; whereas, reduction was 27% and 29% for HW treatments in 2004 and 2005, respectively. The daily AET values measured for water stressed treatments (LS, CS) during 2003 were similar to those observed for CS and HS treatments in 2005. Cumulated AET values during 2003 were 278 and 264 mm for CS and LS treatments, respectively. The difference between LS/CS treatments was 9%, a value very similar to HS/CS treatments in 2005.

2. Grain yield

In 2003 a low level of ozone concentration did not produce significant reductions in grain yield in either well-watered or water-stressed conditions (tab. 1). Differences between the ozone treatments under well-watered (CW and LW) or stressed (CS and LS) conditions were not statistically significant.

In 2004 (tab. 1), mean yield values obtained from the two ozone treatments (CW and HW) were significantly different ($P < 0.05$). The HW treatment shows a grain yield loss of 47%, which is the result of a reduction in the number of pods per plant and in the 1000 grain weight (Bou Jaudé *et al.*, 2008b).

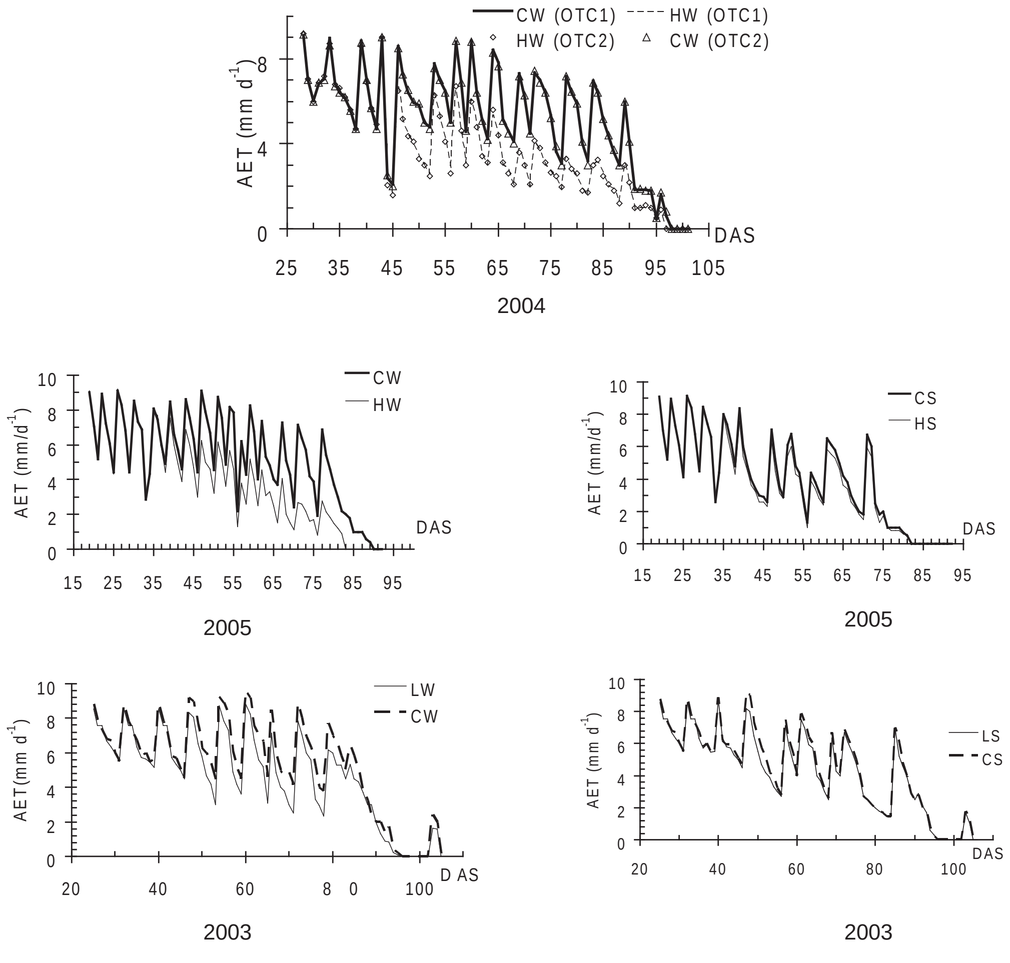

Figure 3. Time (in days after sowing, DAS) changes of daily actual evapotranspiration (AET). Values were measured during soybean growing seasons on well-watered (W) conditions in two open top chambers (OTC, high, H, and control, C, ozone treatments) in 2004, and on well-watered and stressed (S) conditions in 2003 (low, L, and C ozone treatments) and 2005 (H and C ozone treatments).

Table 1. Actual evapotranspiration (AET), yield, and water use efficiency (WUE) observed for different ozone treatments during the three soybean growing seasons.

Growing season	2003				2004		2005			
AOT40 (ppb.h)	0		3400		0	8979	0		8564	
$[O_3]$ + water-status treatment	CW	CS	LW	LS	CW	HW	CW	CS	HW	HS
AET m^3/m^2	0.34	0.28	0.30	0.26	0.39	0.28	0.39	0.29	0.29	0.27
Grain yield (kg/m^2)	0.30	0.32	0.27	0.31	0.28	0.15	0.28	0.19	0.15	0.18
WUE (kg/ m^3)	0.86	1.15	0.91	1.16	0.73	0.55	0.73	0.65	0.52	0.66

In 2005 (tab. 1), under well-watered conditions, the HW treatment significantly reduced grain yield (47%) in comparison with the control treatment (CW), which corresponds to a loss in the number of pods and 1000-grain weight (as found in 2004). In water-stressed conditions, control (CS) and high (HS) ozone treatments showed yield values which were not statistically different.

3. Water use efficiency

Table 1 summarizes for each treatment the seasonal AET, the grain yield and WUE.

In 2003, a low level of ozone concentration did not produce reductions WUE in either well-watered or water-stressed conditions.

In 2004, the WUE of the HW treatment was 25% lower than the control treatments.

In 2005, under well-watered conditions, the WUE of the HW treatment was 29% lower than the control treatment. In water-stressed conditions, control and high ozone treatments had similar WUE. WUE was characterised by a 11% reduction for the CS/CW treatments, and a 27% increase for the HS/HW treatments.

In synthesis (fig. 4), under well-watered conditions WUE was affected by the ozone. Notably, WUE decreased with an increase of AOT 40. In water-stressed conditions, yield and WUE were not affected by ozone and no correlation was found with AOT 40 values.

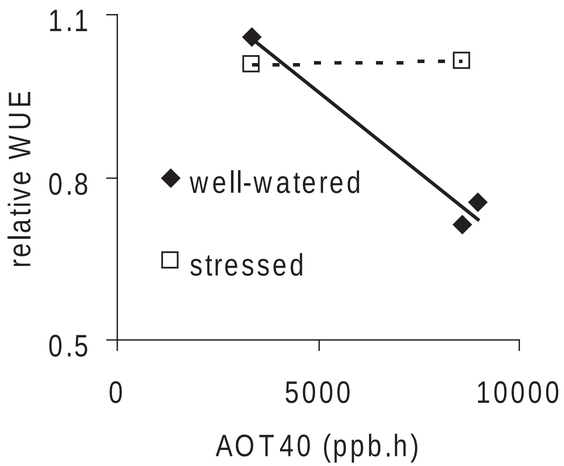

Figure 4. Relationships between AOT40 and relative values of WUE observed for well-watered and stressed soybean crops. Relative WUE was calculated as the ratios of WUE from the ozone treatments (low levels of ozone concentration in 2003, and high in 2004 and in 2005) and the corresponding control treatments (AOT40 = 0).

IV – Conclusions

Mainly in the Mediterranean region, AOT40 values observed during the growing seasons of winter and summer crops are rare. This represents an additional cause of the scarce knowledge concerning the effect of ozone on water requirements in the Mediterranean region, although this region is particularly interested by this kind of pollution.

Results here reported show that WUE of well-watered soybean subjected to high level of ozone during the vegetative cycle (cumulated AOT40 = 8500 pbb.h), decreased by 30% in comparison with a control treatment with air filtered (cumulated AOT40 = 0). Conversely, ozone had a not-significant effect on WUE of a soybean which was stressed by water rationing. According to the results reported by Bou Jaudé *et al.* (2008 a and b), the absence of effect on water-stressed plants is due to stomatal closure, which reduces ozone flux towards leaves (Karlsson *et al.*, 2000), and thus its action on plant functions. Drought induced stomatal closure has also been demonstrated to reduce ozone damages. In the presence of ozone, the smaller reduction in stomatal conductance observed in stressed compared to well-watered plants may be consistent with a protective effect of drought (Fagnano and Merola, 2007; Ferretti *et al.*, 2007), as well as of salinity (Maggio *et al.*, 2007), on ozone-induced stomatal closure. Nevertheless, this response should be considered only in relative terms since the water stress by itself reduced the stomatal conductance, independently on ozone stress.

These results agree with those observed on wheat (Khan and Soja, 2003), on cotton (Heagle *et al.*, 1988), and on white clover (Fagnano and Merola, 2007). The ozone level in the atmosphere is often a neglected parameter in studies on irrigation; however, it is susceptible to creating variability in WUE for irrigated crops in the Mediterranean region. The literature shows that few studies have been conducted on this subject, which is why the effect of ozone on plants needs to be analysed deeply in the future.

Acknowledgements

The Italian Ministry of University and Research (PRIN 2004 and PON funding to DIAAT of Naples University) is acknowledged for financial support.

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Tillage system effects upon productivity of *Menta* x *piperita* L.

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Abstract. The trial examined the cultivation of *Mentha x piperita* L. (variety Rubescens Camus). The experiment was carried out under Mediterranean climatic conditions. The experiment considered the adoption of three cultivation techniques: (P1) minimum tillage to a depth of 20 cm using a disk harrow, (P2) minimum tillage to a depth of 30 cm using a disk harrow, (P3) conventional tillage by mouldboard ploughing to a depth of 40 cm and then a tillage to a depth of 20 cm using a cutter. In 2006 and 2007 the following biometric parameters were determined: stalk length, number of leaves, total fresh weight, fresh weight of the root, fresh weight of the stalk, fresh weight of the leaves, total dry weight and LAI and weeding floristic mapping was performed. Considering the parameters most strictly linked to the economic results (total fresh weight, fresh weight of the leaves and total dry weight) for 2006 and 2007, we found that P2 treatment showed the best performance. P3 has higher values than P1, but in the case of the fresh weight of the leaves and the total dry weight these differences are minor. The results of this trial indicate that minimum tillage of 30 cm is more productive for M*enta x Piperita* L. Minimum tillage of 20 cm is less productive than conventional tillage.

Keywords. Mentha piperita - Minimum tillage – Yields - Mediterranean climatic conditions.

Les effets du labour sur la productivité de la Menta x piperita L.

Résumé. *L'étude examine la culture de la Mentha x piperita L.(Menthe poivrée variété Rubescens Camus) en milieu méditerranéen, conduite selon trois différentes techniques de labour du sol: (P1) tillage minumum à une profondeur de 20 cm., avec herse à disques, (P2) tillage minumum à une profondeur de 30 cm avec herse à disques, (P3) labour traditionnel avec charrue, suivi par un travail à la fraise à une profondeur de 20 cm. Pendant ces essais qui se sont poursuivis au cours de deux ans, on a examiné les paramètres suivants: longueur de la tige, nombre des feuilles, poids frais total, poids frais des racines, poids frais des tiges, poids frais des feuilles, poids sec total, LAI (Indice de surface foliaire) et présence de mauvaises herbes. En conclusion l'étude a mis en relief que, sur les deux ans, considérant les paramètres les plus importants pour le marché, la technique P2 est celle qui aboutit aux meilleurs résultats. P3 réalise des valeurs plus élevées que P1, sauf dans le cas du poids frais des feuilles et du poids sec total, paramètres pour lesquels la différence était moins sensible. Les résultats de l'étude mettent en évidence que le labour du sol à une profondeur de 30 cm. représente la solution la plus indiquée pour la culture de la Mentha x piperita L.*

Mots-clés. *Menthe poivrée – Tillage minimum – Productions – Milieu méditerranéen.*

I – Introduction

Soil water is the major limiting factor in dryland crop production in the Mediterranean region of Italy. Conservation tillage has been proposed as a promising strategy to improve soil and water conservation in these areas (Unger P.W., McCalla T.M., 1980; Lòpez M.V., Arrùe J.L., 1997; Hajabbasi M.A., Hemmat A,. 2000). Therefore, farmers need to manage crop residues and tillage to control soil erosion and effectively store and use the limited precipitation received for crop production (Hemmat A., Eskandari I., 2004; Hemmat A., Taki O., 2001). Tillage systems modify, in the short term, some of the physical properties of soil, such as soil porosity. Tillage has also an indirect effect on soil water content during the growth cycle of plants, particularly in areas with a Mediterranean climate. In several studies, minimum tillage has been reported to produce crop yields similar to (Carter M.R., Rennie D.A., 1984) or higher than (Tessier S. at all., 1990) conventional tillage.

II – Modeling approach

The trial examined the cultivation of *Mentha x piperita* L. (a variety of rubescens Camus) and was carried out in 2006 and 2007 in a field located near Segezia (FG) (41° 22' latitude N; 15° 18' longitude E). Table 1 presents physical and chemical properties of the soil.

Table 1. Physical and chemical properties of the soil.

	Depth 20 cm	Depth 30 cm	Depth 40 cm
pH	7.8	7.3	7.5
Total N (g kg^{-1})	1.6	1.5	1.4
Total C (g kg^{-1})	18	19	19
Available P (mg kg^{-1})	30	35	32
Sand (%)	57.9	59.5	61.7
Silt (%)	38	35.7	32.2
Clay (%)	4	4.8	6.1

The experiment was carried out under Mediterranean climatic conditions, characterized by rain mostly distributed in autumn and winter and a dry period in summer. Figure 1 presents the climatic conditions (precipitation and temperatures) from September 2005 to December 2007.

In 2006 a total rainfall depth of 739 mm occurred in late winter-early spring (from January to March). Usually spring crops can benefit from rain water stored in the soil.

In 2007 a total rainfall of 620 mm was recorded, but from January to March precipitation levels were half that of 2006. Temperatures for both years were similar.

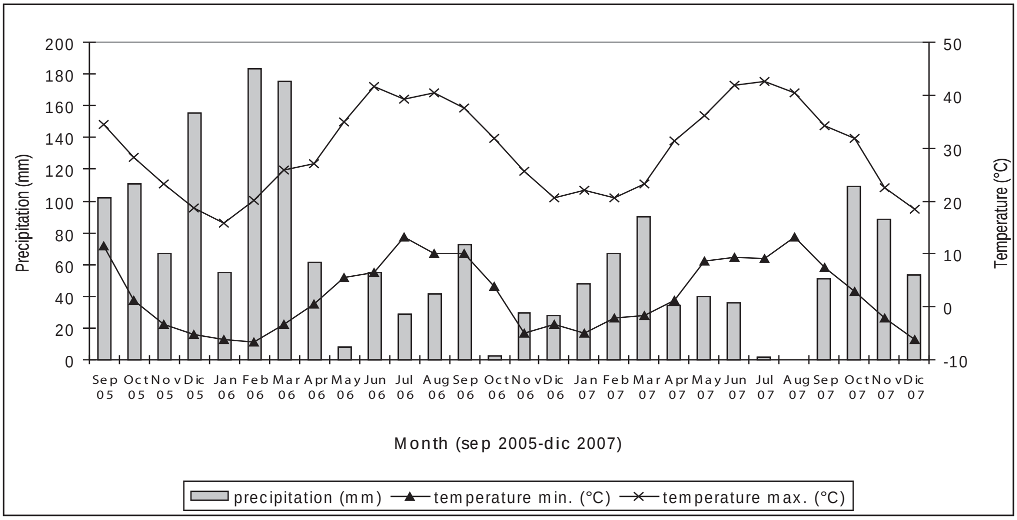

Figure 1. Climatic condition (precipitation and temperature).

The study was organized in a randomized complete block design with three replicates and each plot received the same treatment during the period of study. Plot size was 5 m by 2 m.

The experiment considered three cultivation techniques: (P1) minimum tillage to a depth of 20 cm using a disk harrow, (P2) minimum tillage to a depth of 30 cm using a disk harrow, (P3) conventional tillage by mouldboard ploughing to a depth of 40 cm followed by tillage to a depth of 20 cm using a cutter.

Tillage was carried out in January and a 100 units of ammonium nitrate were spread.

The stolons were manually replanted in rows 50 cm apart on 2/05/06 and a distance of 20 cm was left between each seedling. All the stolons were watered with a sprinkler immediately after replanting (about 400 m^3 of water/ha); the stolons were then watered a further four times, at 20 day intervals until the second harvest. In total, the plants were irrigated with 2000 m^3/ha/year of water.

Two manual weeding operations were carried out before each harvest. And before weeding floristic mapping was performed using the Bruan Blanquet method.

On 28/05/06, fertilization was performed using a mineral based leaf fertilizer containing NPK (40 40 20).

Two harvests were carried out per year: one before flowering (the third week of June) (D1) and one at the end of July (D2).

At each harvest some plants one meter long were harvested from each test group and the following biometric parameters were determined: stalk length, number of leaves, total fresh weight, fresh weight of the root, fresh weight of the stalk, fresh weight of the leaves, total dry weight and LAI. In order to calculate the dry weight, the product was kept in an oven at a temperature of 60°C.

All the data collected from the experiments were subjected to variance analysis using ANOVA statistical analysis.

III – Results and discussion

Tillage effected the biometric parameters significantly in both years (Table 2) but results were not significant for LAI.

The results shown in Table 2 indicate that all the biometric parameters examined were higher in P2, whereas only the root length was longer in P3 probably due to the fact that the soil was tilled to a lower depth of 40 cm which allowed the roots to grow longer.

In 2006, the highest precipitation levels were recorded in February and March and this rainfall was stored in the soil and was subsequently utilized by *Menta x Piperita* L. in the springtime during the taking of the root. The deeper tillage in P3 probably allowed the water to percolate deeper than in P1 and P2 and the seedlings were not able to utilise it. Then the biometric parameters examined in P3, apart from root length, were smaller than the parameters in P2.

It is possible that the minimum tillage depth of 20 cm (P1), compared to the deeper tillage depths (P2 and P3) permitted the growth of a greater number of weeds and so the biometric parameters of the seedlings in P1 were lower because they had to compete with more weeds (Figure 2), such as *Convolvulus arvensis* L. and *Chrysantemum segetum* L. in particular. In effect, the results of floristic mapping for 2006 indicate that the relative efficiency of weed containment (%) for *Convolvulus arvensis* L. was 50% in P1, 74% in P2 and 79% in P3 and in 2007 results showed an efficiency of 55%, 79% and 86% for P1, P2 and P3 respectively. The results of floristic mapping indicate that the relative efficiency of weed containment (%) for *Chrysantemum segetum* L. in 2006 was 67% in P1, 75% in P2 and 100% in P3 and in 2007 it was 78%, 77% and 96% for P1, P2 and P3 respectively.

In fact, all the biometric parameters in P1 were lower than or equal to those in P3, except for stalk length which was higher. The *Menta x Piperita* L. plants in P1 are probably higher because they had to compete with a greater number of weeds for the light.

Considering the parameters most strictly linked to the economic results, in particular total fresh weight, fresh weight of the leaves and total dry weight, higher values for 2006-2007 can always be found in P2 as shown in Figure 3. In effect, considering D1+D2 in 2006 the total fresh weight (g m^{-2}) in P1 is 442,3, in P2 it is 812 and in P3 it is 501,6 while in 2007 in P1 it is 347,2, in P2 it is 706,7 and in P3 it is 490,2. The fresh weight of the leaves (g m^{-2}) is 122,4 in P1, 348,8 in P2 and 160,8 in P3 in 2006 while in 2007 it is 116,8 in P1, 256,9 in P2 and 127,5 in P3. In 2006 the total dry weight (g m^{-2}) is 106,4 in P1, 170,8 in P2 and 112,24 in P3 and in 2007, 109,1 in P1, 179,3 in P2 and 145,4 in P3.

The results of this trial indicate that P3 has higher values than P1, but in the case of the fresh weight of leaves, a parameter of interest to the distilled essential oils industry, these differences are of minor importance.

In the case of the total dry weight, which is a parameter of interest to the herbalist industry, these differences also carry little importance.

Table 2. Influence of tillage depth on biometric parameters of *Menta x Piperita* L.

Tillage depth/ harvest/ year	Total fresh weight (g m^{-2})	Fresh weight of the root (g m^{-2})	Fresh weight of the leaves (g m^{-2})	Fresh weight of the stalk (g m^{-2})	Root length (cm plant)	Stalk length (cm plant)	Number of leaves (n m^{-2})	Total dry weight (g m^{-2})
P1xD1 06	160.3 E	72 E	51.2 F	32.72 E	15.3 D	17.3 D	179 E	33,6 DE
P2xD1 06	381.2 A	84.4 D	215.6 A	32.4 E	14.7 E	14.9 E	611 B	76.4 B
P3xD1 06	204.8 D	85.2 D	66.4 E	40.4 D	15.2 D	16.2 E	331 C	35.84 D
P1xD2 06	262 C	143.6 B	71.2 D	50 C	15.9 D	28.9 A	332 C	72,8 C
P2xD2 06	430.8 A	193.2 A	133.2 B	84.4 A	16.5 D	29.1 A	811 A	94.4 A
P3xD2 06	296.8 B	109.2 C	94.4 C	76 B	22.5 A	28.6 B	623 B	76.4 B
P1xD1 07	140.5 E	86.4 D	49.1 F	40.2 D	16.9 D	18.5 D	180 E	35,3 D
P2xD1 07	293.1 B	76.4 D	149.7 B	31.5 E	21.5 B	15.7 E	622 B	75.2 B
P3xD1 07	214.7 D	87.3 D	52.8 F	34.5 E	22.4 A	14.9 E	181 E	71.5 C
P1xD2 07	206.7 D	110.4 C	67.7 E	52.6 C	19.9 C	27.5 B	290 D	73.8 C
P2xD2 07	413.6 A	183.3 A	197.2 A	79.8 A	20.5 B	28.9 A	789 A	104.1 A
P3xD2 07	275.5 B	90.3 D	74.7 D	54.8 C	25.3 A	20.1 C	295 D	73.9 B

Values followed by the same letters in each column are not significantly different according to Tukey's ($p \leq 0.01$) test.

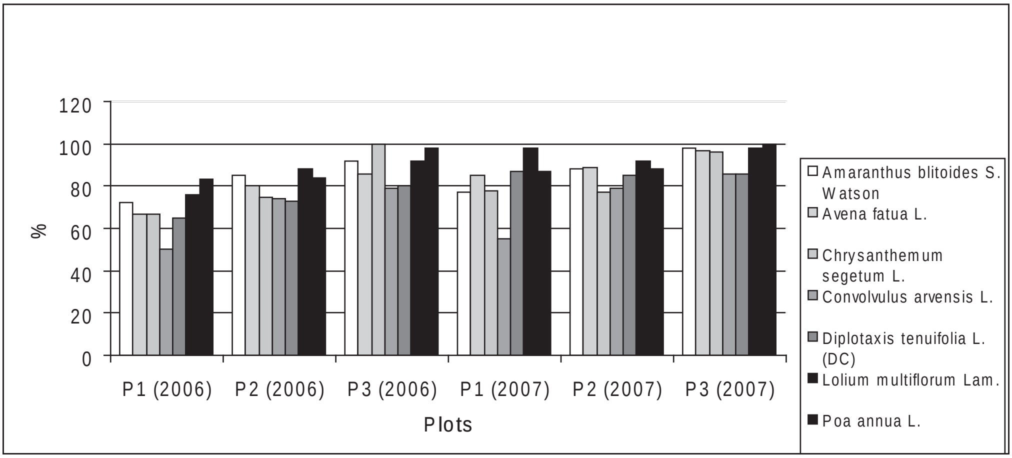

Figure 2. Relative efficiency of weed containment.

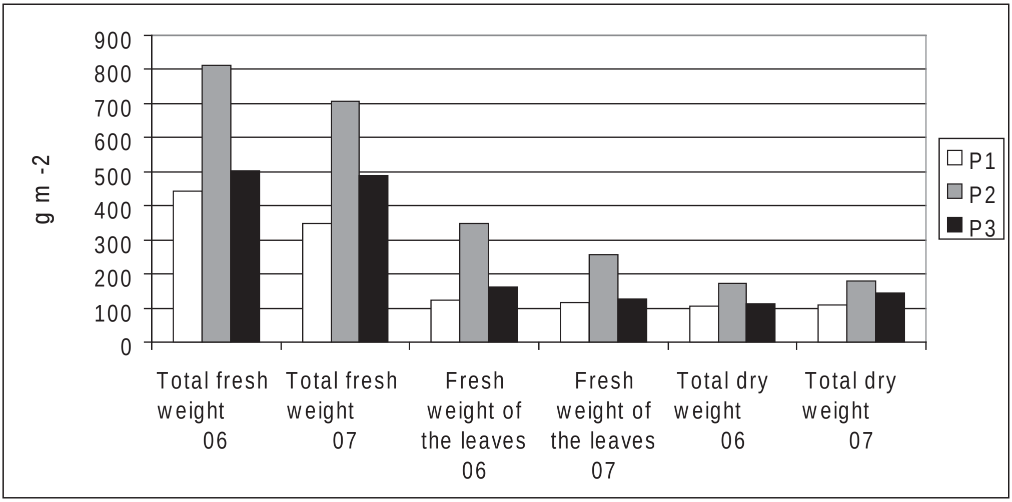

Figure 3. Total fresh weight, fresh weight of the leaves and total dry weight (06-07).

IV – Conclusions

In conclusion, the results of this trial indicate that the cultivation of *Mentha x piperita* L. (*Rubescens Camus* variety) in Mediterranean climatic conditions produces good results when minimum tillage to a depth of 30 cm using a disk harrow is adopted. Minimum tillage to 30 cm is probably more productive for *Menta x Piperita* L. because this technique makes it possible to simultaneously contain the growth of weeds and allow the soil to retain the water which is necessary for the plants.

Minimum tillage to a depth of 20 cm using a disk harrow is less productive than conventional tillage because it causes a greater number of weeds to grow.

Conventional tillage by mouldboard ploughing to a depth of 40 cm followed by tillage to a depth of 20 cm using a cutter is less productive than minimum tillage to a depth of 30 cm using a disk harrow, because the water percolates too deep and the seedlings are not able to utilise it.

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Peach leaf physiology and irrigation water and light availability

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Abstract. We studied the effect of available water and light into the canopy on leaf characteristics and physiology of two clingstone peach cvs. Irrigation water was reduced by 90% (deficit) since late June (3 weeks before harvest) and, the same day, 1.2 m wide Extenday reflective mulch strip was applied on the row. Incident and reflected ultraviolet (UV) and photosynthetically active radiation (PAR) were measured inside the canopy. Specific leaf weight (SLW) and chlorophyll content were measured every month from late May to late August on light exposed and shade leaves. Photosynthesis (Ps), transpiration (E) and other physiological parameters were measured or calculated in light exposed leaves periodically. The reflective mulch significantly increased reflected UV and PAR radiation in the canopy compared to control, while no similar trend was found for incident radiation. SLW and chlorophylls (a, b and total) were not affected by treatment in both cvs, while significant changes with time and leaf position were always observed. Deficit irrigation increased leaf temperature and decreased stomatal conductance, Ps and water use efficiency (WUE) compared to control. Combination of reflective mulch and water deficit was even more detrimental to leaf physiological functions as this combination treatment increased leaf temperature and decreased E, stomatal conductance, Ps, WUE and quantum yield compared to control and often to other treatments.

Keywords. Prunus persica – Photosynthetically active radiation – Photosynthesis – Transpiration – Chlorophyll – Specific leaf weight.

Physiologie de la feuille de pêcher et disponibilité en eau d'irrigation et en lumière

Résumé. *L'effet de la disponibilité en eau et en lumière dans le couvert sur les caractéristiques et la physiologie des feuilles de deux cultivars de pêchers pavies a été étudié. Trois semaines avant la récolte (fin juin), l'irrigation a été réduite de 90% (déficit) et un mulch Extenday réfléchissant de 1,2 m a été installé sur le rang le même jour. Les rayonnements UV et PAR incidents et réfléchis ont été mesurés à l'intérieur du couvert. Le poids foliaire spécifique (SLW) et la teneur en chlorophylle ont été mesurés tous les mois de fin mai à fin août sur des feuilles exposées à la lumière et à l'ombre. La photosynthèse (Ps), la transpiration (E) et d'autres paramètres physiologiques ont aussi été mesurés ou calculés périodiquement sur des feuilles exposées à la lumière. Le mulch réfléchissant a augmenté significativement les rayonnements UV et PAR réfléchis dans le couvert. Le SLW et la teneur en chlorophylle n'ont pas été modifiés par le traitement en déficit. La réduction de l'irrigation a entrainé une augmentation de la température des feuilles et une réduction de la conductance stomatique, de Ps et de l'efficience de l'eau (water use efficiency, WUE), par rapport au témoin. La combinaison de la réduction de l'irrigation et du mulch réfléchissant a eu des effets encore plus négatifs sur les fonctions physiologiques des feuilles.*

Mots-clés. *Prunus persica – Rayonnement photosynthétique actif – Photosynthèse – Transpiration – chlorophylle – Poids foliaire spécifique.*

I – Introduction

Irrigation consumes most of the available water quantities in the Mediterranean basin. Any possible improvement in water efficiency is necessary for the agricultural sustainability in the area (Laraus, 2004).

Peach tree has strong shoot growth thus requiring substantial amounts of irrigation water during the summer to sustain leaf productivity and yield. In peach trees, irrigation water is required mainly during the 3^{rd} fruit growth phase when fruit cells expand dramatically. Less water is required after fruit harvest, when, in the case of mid season ripening cultivars, water needs can be almost half of that of the summer period. On the contrary, most peach growers do not differentiate their irrigation strategies and continue to apply more than required water throughout the summer period. In addition, excees water during fruit growth can increase fruit size and yield, but it may significantly reduce peach quality. Thus, studies on water consumption by peach trees during the summer period and ways to monitor tree reaction to deficit irrigation are needed for the Mediterranean region.

Light availability inside the tree canopy is a major factor influencing leaf and fruit productivity and fruit quality. Pruning and training are practiced regularly in commercial orchards to optimise light availability and productivity. Fruit quality is even more influenced by light availability and fruit grown in the shaded parts of trees have poor taste and colour and require repeated harvests increasing crop costs and reducing the economic return in general (Lewallen and Marini, 2003).

Alternative ways to increase light availability inside the tree canopy include reflective mulch on the orchard floor, which could increase light availability inside the lower (i.e. the most shaded) parts of the canopy (Green *et al.*, 1995). The mulching could also influence weed growth, irrigation water evaporation from the soil surface and leaf and tree overall physiology. The effect of reflective mulch in combination with normal or deficit irrigation on peach leaf physiology has not been studied.

This study was an attempt to understand how reflective mulch on the tree row can influence light availability inside the canopy, fruit quality and leaf physiology under normal or deficit irrigation regimes.

II – Materials and methods

The peach (*Prunus persica* L.) orchard under study consisted of two clingstone cvs Loadel and Fortuna. During 2007, the trees were 8 years old, cup shaped and irrigation was performed by two dripper lines on each row with a 4 L/hr dripper every 50 cm. At least six trees - replicates were used per treatment.

Irrigation was performed twice a week for a total of 8 hrs/week until harvest and 6 hrs/week during the rest of summer until September (control treatment). Deficit irrigation trees received around 10% of the water applied above during the last 3 weeks before harvest (late June) and thereafter until September. In total, during the last three weeks until harvest control trees received weekly 500 L/tree and deficit trees 60 L/tree and during July, August and early September 400 L/tree and 50 L/tree, respectively.

Extenday® reflective mulch 1.2 m wide was applied on the tree row under the canopy in six control and six deficit trees three weeks before harvest and left in place until early September. Thus we studied 4 treatments: control, reflective mulch, deficit irrigation and combination of reflective mulch plus deficit irrigation.

Soil water content was monitored periodically with 60 cm soil profile capacity probes and tree response to irrigation and light manipulation treatments with thermal dissipation probes. These data are not presented in this article.

Light availability inside the canopy was measured with an ultraviolet sensor (included 250-400 nm, model UVM, Spectrum Techn., Plainfield, IL.) and a photosynthetically active radiation (PAR) 3-sensor compensating instrument (model LQS-QM, Spectrum Techn.). Incident light was measured 50 cm away from the trunk and 30-50 cm above the ground inside the canopy with the sensor facing up. Reflected light was measured at the same points but with the sensor facing down. Light was measured midday on the four horizons and their mean values are presented.

Leaf dry matter, specific leaf weight and chlorophyll content were measured or calculated periodically from the beginning of treatments and during the rest of summer in sun-exposed and in shade leaves. Leaf disks were removed with 9 mm diameter corer, their fresh weight and surface were measured, dried at 80°C and reweighed. The % leaf dry matter content and specific leaf weight were then calculated. Similar leaf disks were extracted in 95% ethanol and chlorophyll was measured spectrophotometrically based on the method of Wintermans and Mots (Wintermans and Mots, 1965).

Leaf physiological parameters were measured in two-day sets, immediately after an irrigation event and 1 day later, over the summer before and after harvest. Chlorophyll fluorescence was measured in sun-exposed and shade leaves (12 dark-adapted leaves per treatment) at noon time with a chlorophyll fluorometer (model OS-30p, Optisciences Inc., Tyngsboro, MA). A photosynthesis unit (model LCpro, ADC Bioscientific Ltd., Herts, England) was used to measure or calculate leaf temperature, PAR, leaf conductance, net photosynthetic and transpiration rates, water use efficiency and quantum yield (8 leaves per treatment) during the morning hours from 09:00 to 12:00, before high midday temperatures would significantly reduce leaf functioning.

Statistical analysis involved analysis of variance over treatment and time (and incident or reflected light in light measurements inside the canopy) for all parameters tested with SPSS programme (SPSS 14.0, Chicago, IL.). LSD or Duncan's mean separation is shown.

III – Results and discussion

Ultraviolet (UV) and photosynthetically active radiation (PAR) inside the peach tree canopy increased significantly above the reflective mulch (Table 1). Incident UV and PAR did not change significantly inside the canopy and were kept very low and close to compensation point for net photosynthesis. Reflected UV and PAR in the canopy above the reflective mulch were more than 10-fold and 4-fold, respectively, higher than above bare soil exceeding the 50% of incident light inside the canopy. Thus, UV radiation inside the canopy above the reflective mulch reached levels able to positively affect fruit quality in the lower most shaded part of the peach tree. Reflective mulches have previously been found to increase light availability inside the canopy (Green *et al.,* 1995).

Specific leaf weight (SLW) increased during the summer time from late May to early September in all treatments and both cvs studied. SLW data for cv Loadel are shown in Figure 1. SLW for cv Fortuna reached a plateau during August. Deficit irrigation applied since late June had no significant effect on SLW in both cvs. The presence of reflective mulch during July and August did not affect SLW. Only leaf position had a significant effect on SLW with sun leaves having overall about 20% higher SLW than shade leaves from early in the season until late summer (Marini and Sowers, 1990). As expected, sun leaves had higher SLW due to much higher net photosynthesis compared to shade leaves, which are marginally self sustained due to low PAR availability.

Leaf chlorophylls a and b followed the same trends as described herein for total chlorophyll. Leaf total chlorophyll (TCHL) decreased mainly in late summer in both cvs studied. TCHL data for cv Loadel are shown in Figure 2. Deficit irrigation and reflective mulch treatments did not significantly affect TCHL content in any of the two cvs studied. Shade leaves had higher TCHL than sun leaves, as an attempt to collect sufficient light for photosynthesis. The ratio chlorophyll a over chlorophyll b decreased with time over the summer, was not affected by deficit or reflective mulch treatments and was higher in sun leaves compared to shade leaves.

Various leaf physiological parameters were measured or calculated in two day sets before harvest and after harvest in July and later in August. The two day sets following each irrigation event were different for each cv as the time required for measurement of all parameters in certain number of leaves during the proper hours was the limiting factor. Nevertheless, leaf chlorophyll fluorescence measurements in sun exposed and shade leaves showed that deficit irrigation and reflective mulch treatments did not clearly affect chlorophyll fluorescence (data not shown). The

Fo and Fv/Fm leaf chlorophyll parameters showed clear changes between measurement days related to air temperatures prevailing. Also sun leaves always had higher Fo and lower Fv/Fm than shade leaves (data not shown). Chlorophyll fluorescence measurements showed that this factor is important to enlighten daily stress due to high temperatures, but could not depict (if any) stress due to deficit irrigation or reflective mulch and clearly distinguished sun exposed and shaded leaves.

Leaf functioning was also measured periodically in sun leaves. Sun exposed leaves from deficit irrigated trees had lower PAR compared to leaves from mulched trees (Tables 2 and 3). Leaf temperature of sun leaves increased in deficit irrigated trees and even more in mulched trees compared to control ones (Tables 2 and 3). The combination of lower PAR availability and higher leaf temperature in deficit irrigated trees suggests lower stomatal functioning compared to well irrigated (control) trees.

Actually, leaves from deficit irrigated peach trees had lower stomatal conductance than leaves from well irrigated ones in both cvs studied (Tables 2 and 3). Similarly, due to high PAR incidence and leaf temperature, leaves from reflective mulched trees had lower stomatal conductance than leaves from well irrigated ones. The combination of deficit irrigation and reflective mulch had the largest negative impact on stomatal conductance. This reduction in stomatal conductance resulted in a reduction in leaf transpiration rate due to both treatments, deficit irrigation or reflective mulch, and their combination compared to leaves from well irrigated trees in both cvs studied (Tables 2 and 3).

The reduction in stomatal conductance had further negative consequences on leaf net photosynthetic rate. Leaves from deficit irrigated peach trees had lower photosynthetic rate than leaves from well irrigated trees (Tables 2 and 3). This reduction in net photosynthetic rate was more pronounced when deficit irrigated trees were mulched as well, as leaf stomatal conductance was even lower. Well irrigated and mulched trees had lower (cv Fortuna) or similar (cv Loadel) leaf net photosynthetic rate compared to well irrigated (control) trees. Drought stress has previously been found to reduce stomatal functioning and net photosynthetic rate (Cornic and Massacci, 1996).

The reduction in net photosynthetic rate in leaves from deficit irrigated or mulched trees was larger than the reduction in transpiration rate. This resulted in significant reductions in leaf water use efficiency in deficit irrigated or reflective mulched trees compared to well irrigated ones (Tables 2 and 3).

Due to increased PAR availability and lowered net photosynthetic rate in reflective mulched trees, quantum yield was lowered compared to control especially when trees had the lowest net photosynthetic rate in the combination treatment with reflective mulch in deficit irrigated trees (Tables 2 and 3). Leaves from deficit irrigated trees had similar (cv Fortuna) or lower (cv Loadel) quantum yield compared to leaves from well irrigated trees as both available PAR and net photosynthetic rate decreased compared to well irrigated trees.

In conclusion, the application of reflective mulch did not affect specific leaf weight and leaf chlorophyll content although it increased the available light inside the canopy and partially in the outer parts of the canopy. This resulted in increased leaf temperature, which was detrimental to leaf functioning as stomatal conductance, transpiration and net photosynthetic rates, water use efficiency and quantum yield were reduced even more when mulching was applied in deficit irrigated trees to reduce water evaporation and weed growth.

Similarly, reduction of irrigation volume to 10% of well irrigated trees did not affect specific leaf weight and leaf chlorophyll content but it reduced stomatal conductance, increased leaf temperature and, as a result, reduced most leaf functions.

Table 1. Mean values of incident and reflected ultraviolet and photosynthetically active radiation measured inside the canopy of Fortuna and Loadel peach trees above bare soil (control) or reflective mulch on the tree row.

	cv. Fortuna		cv. Loadel	
	Control (µmol/m²/s)	**Reflective mulch (µmol/m²/s)**	**Control (µmol/m²/s)**	**Reflective mulch (µmol/m²/s)**
Incident UV	6.9 a	7.1 a	4.9 a	6.3 a
Reflected UV	0.4 b	3.7 a	0.4 b	4.2 a
Incident PAR	91 a	109 a	59 a	85 a
Reflected PAR	21 b	71 a	18 b	94 a

Mean values per cultivar and parameter measured are significantly different when followed by different letters based on Duncan's mean separation.

Table 2. Mean values of Fortuna peach leaf physiological parameters when trees were deficit irrigated, mulched with reflective cloth on the tree row or mulched and deficit irrigated.

Physiological parameter	Control	Deficit Irrig.	Deficit + Refl	Reflective
PAR (µmol mol^{-2} s^{-1})	1243 ab	1207 b	1266 ab	1306 a
Leaf Temp (°C)	33.0 b	33.6 a	33.8 a	33.8 a
Transpiration (mmol mol^{-2} s^{-1})	4.62 a	4.57 a	4.23 b	4.57 a
Stomatal Conductance (mmol mol^{-2} s^{-1})	0.301 a	0.265 b	0.222 c	0.255 b
Photosynthesis (mmol mol^{-2} s^{-1})	15.7 a	14.4 b	13.4 c	14.6 b
WUE (mmol mol^{-1})	3.49 a	3.24 b	3.24 b	3.20 b
QY (mol/100mol)	1.33 a	1.27 a	1.08 b	1.13 b

Mean values per parameter measured or calculated are significantly different when followed by different letters based on Duncan's mean separation.

Table 3. Mean values of Loadel peach leaf physiological parameters when trees were deficit irrigated, mulched with reflective cloth on the tree row or mulched and deficit irrigated.

Physiological parameter	Control	Deficit Irrig.	Deficit + Refl	Reflective
PAR (µmol m^{-2} s^{-1})	1314 ab	1281 b	1372 a	1372 a
Leaf Temp (°C)	33.2 c	33.8 b	34.2 a	34.0 ab
Transpiration (mmol m^{-2} s^{-1})	4.84 a	4.57 b	4.32 c	4.95 a
Stomatal Conductance (mmol m^{-2} s^{-1})	0.294 a	0.232 b	0.199 c	0.256 b
Photosynthesis (mmol m^{-2} s^{-1})	15.4 a	13.4 b	12.3 c	14.6 a
WUE (mmol mol^{-1})	3.27 a	3.00 b	2.92 b	2.97 b
QY (mol/100mol)	1.19 a	1.07 b	0.93 c	1.08 b

Mean values per parameter measured or calculated are significantly different when followed by different letters based on Duncan's mean separation.

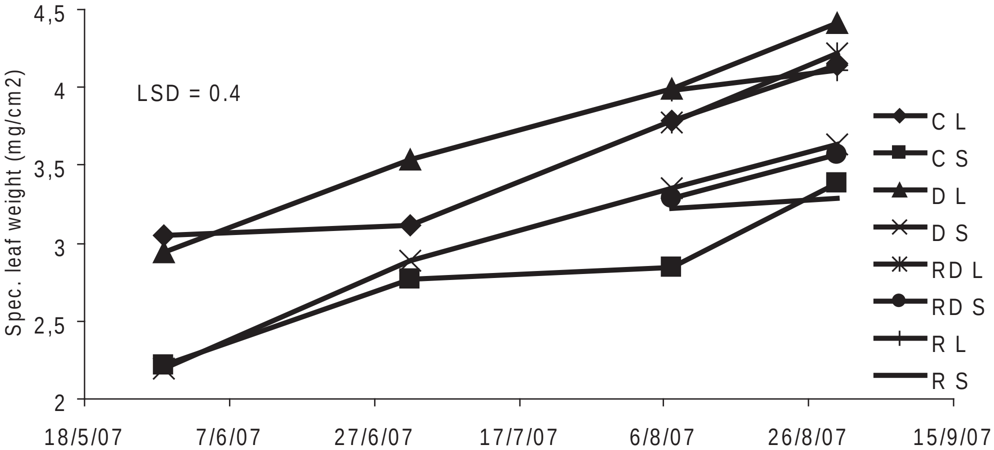

Figure 1. Specific leaf weight changes in sun exposed (L) or shaded (S) leaves during the summer 2007 in control (C), deficit irrigated (D) or reflective mulched (R) Loadel peach trees.

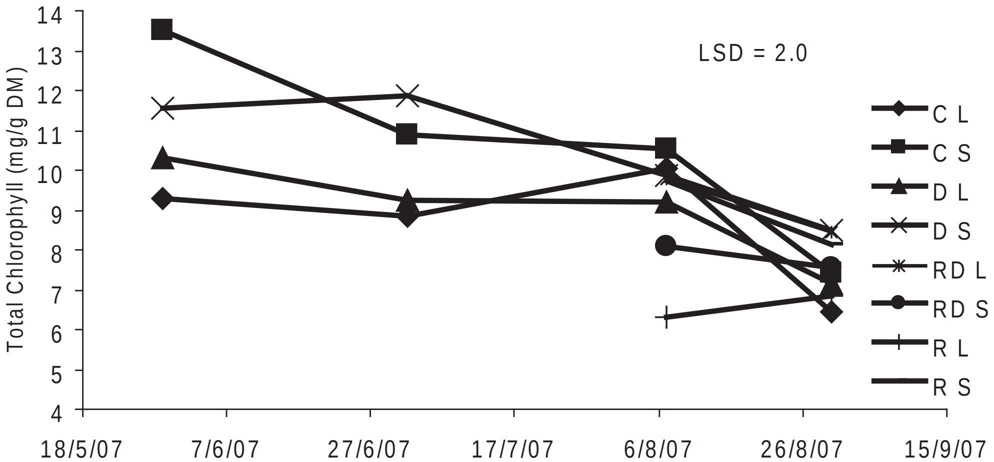

Figure 2. Total leaf chlorophyll content changes in sun exposed (L) or shaded (S) leaves during the summer 2007 in control (C), deficit irrigated (D) or reflective mulched (R) Loadel peach trees.

Acknowledgements

The authors would like to thank Prof. Constantinos Kittas for his kind review of the article and his help in French language translation. This work is part of IRRIQUAL, Sustainable orchard irrigation for improving fruit quality and safety, an EU-funded research program on FOOD, contract # 023120.

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Crop water status estimated by remote sensing information

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Abstract. Techniques to more accurately quantify crop water status are needed for determining crop water requirements and appropriate irrigation scheduling. Remote sensing techniques are a possible tool for estimating the crop water status. To verify this hypothesis, in 2007 a measurement campaign was carried out in Rutigliano (lat. 41°01' N, long. 17°01 E, alt. 147m a.s.l.), with the tomato as the test crop. This crop was subjected to three irrigation treatments. To monitor the water status, both 'remote sensing' (NDVI and radiative surface temperature) and 'manual' measurements (stomatal conductance and pre-dawn leaf water potential (PLWP)) were used. The NDVI index is a function of both crop growth (LAI and biomass) and the crop water status. The experimental data showed a linear relationship between PLWP and NDVI. From this relationship it seems possible to predict the crop water status starting from completely automatic measurements. Although additional research is needed, the remote sensing technique potentially offers an improvement of the irrigation scheduling.

Keywords. NDVI – Radiative temperature – Stomatal conductance – Pre-dawn leaf potential (PLWP).

Estimation de l'état hydrique des plantes par télédétection

Résumé. *Des techniques capables de quantifier d'une manière précise l'état hydrique des plantes cultivées sont nécessaires, afin de déterminer les besoins en eau des plantes ainsi que le programme à adapter pour le pilotage de l'irrigation. La télédétection est un instrument possible pour évaluer l'état hydrique des plantes. Pour vérifier cette hypothèse, une campagne de mesures a été menée en 2007 à Rutigliano (lat. 41°01' N, long. 17°01 E, alt. 147m), sur une culture de tomates. La parcelle cultivée a été soumise à trois traitements d'irrigation. Afin de suivre de près l'état hydrique de la plante, la télédétection (NDVI et température de surface radiative) ainsi que les mesures "manuelles" (conductance stomatique et potentiel hydrique foliaire de base PLWP) ont été utilisées. L'indice NDVI est une fonction de la croissance (LAI et biomasse) ainsi que de l'état hydrique des plantes. Les données expérimentales ont montré une relation linéaire entre PLWP et NDVI. De cette relation, il semble possible de prévoir l'état hydrique des cultures à partir de mesures complètement automatiques. Bien qu'une recherche supplémentaire soit nécessaire, la télédétection offre potentiellement une amélioration de la programmation de l'irrigation.*

Mots-clés. *NDVI – Température radiative – Conductance stomatique - Potentiel hydrique foliaire de base PLWP.*

I – Introduction

Irrigation is one of the most costly factor for the Mediterranean agriculture. Traditionally, irrigation scheduling has been based on weather station observations (Caliandro and Mastrorilli, 2001), which lack both the crop water status and the continuous spatial variation needed to realize a precision irrigation.

Since the 1970's, hundreds of studies have used satellite land observation data to monitor a variety of dynamic land surface processes (e.g., Anderson *et al*., 1976; Reed *et al*.,1994; Yang *et al*., 1998; Peters *et al*., 2002). Satellite remote sensing provides a synoptic view of the land and a spatial context for the correct management of irrigation at the district scale. Remote measurements of canopy temperature and the normalized difference vegetation index (NDVI) can be used for monitoring the crop water status and scheduling correctly the irrigation.

Radiative canopy temperature has been successfully used to time irrigation applications for well-watered crop growing conditions. The cumulative daily time that canopy temperature exceeds a crop specific temperature threshold is used to indicate the need for irrigation (Wanjura *et al*., 2003).

NDVI, which is the normalized reflectance difference between the near infrared (NIR) and visible red bands (Rouse *et al*., 1974; Tucker, 1979) is used extensively in ecosystem monitoring. The NDVI measures the changes in chlorophyll content (via absorption of visible red radiation) and in spongy mesophyll (via reflected NIR radiation) within the vegetation canopy. As a result, higher NDVI values usually represent greater vigour and photosynthetic activity (or greenness) of vegetation canopy (Tucker, 1979; Chen and Brutsaert, 1998). NDVI's role in water balance monitoring and assessment has been described several times during the last decade (Kogan, 1991; Kogan, 1995; Yang *et al*., 1998; McVicar and Bierwirth, 2001; Ji and Peters, 2003; Wan *et al*., 2004).

However, one limitation of remote sensing signals for scheduling the irrigation is the contemporary presence of both desiccated and wetted zone in the irrigated plots. This is typical of the irrigated row crops of the Mediterranean area.

The objective of this study is to estimate water status on the territorial level by obtaining these estimates for an entire district (Rinaldi *et al*., 2006a, and 2006b).

II – Materials and methods

To verify if remote sensing techniques are a possible tool for estimating crop water status, in 2007 a measurement campaign was carried out in Rutigliano (lat. 41°01' N, long. 17°01 E, alt. 147 m a.s.l.), at the CRA-SCA experimental farm, with the tomato as the reference crop. After the tomato crop attained the maximum LAI value (2.89) and the canopy covered the ground (>90%), it was subjected to three irrigation treatments (fig. 1): one was optimal, and the other two underwent "temporary" stress (early, at the setting of the fruit, and late, at its ripening). Irrigation was scheduled whenever PLWP reached -0.3 and -0.5 MPa, in full irrigated and stressed plots, respectively. However, the latter value of PLWP does not compromise the tomato growth.

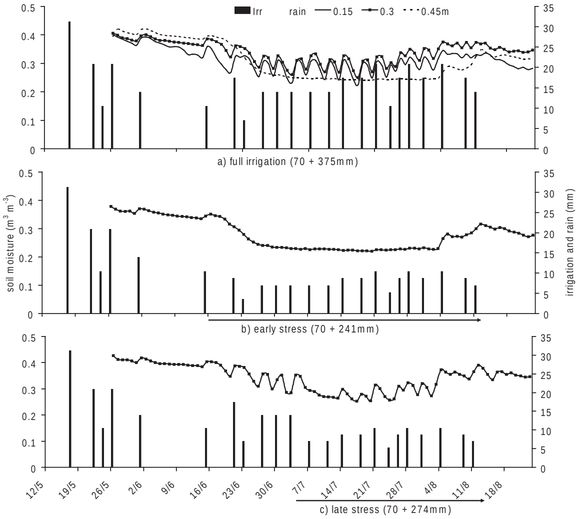

Figure 1. Soil moisture measured by the TDR technique at -0.15, -0.30 and -0.45m in a), and at -0.30m in b) and c). Amounts of irrigation (solid) and rain (dashed) are represented by vertical lines. Arrows in b) and c) indicate the temporary stress periods.

To monitor the water status, both ‘remote sensing’ (NDVI and radiative surface temperature) and ‘manual’ measurements (stomatal conductance and pre-dawn leaf water potential) were used. NDVI was monitored (each 10 minutes) through the sensor SKR 1800, as:

$$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$$

where ρ represents the ratio between reflected and incident radiations at two wave-length: Red (646 nm) and NIR (831 nm).

Surface canopy temperature was hourly measured through infra-red sensors (Everest Interscience Inc., USA, model 4000.4ZXL), placed at 1m above the vegetation surface.

Stomatal conductance was measured at noon (in not cloudy days) by a porometer (Delta T instruments, UK) and the pre-dawn leaf water potential (Ψ) was measured by the Scholander pressure chamber.

III – Results and discussions

The soil water status, above all for crops irrigated in rows, is difficult to define exactly. As shown in figure 2, the horizontal variability is quite high.

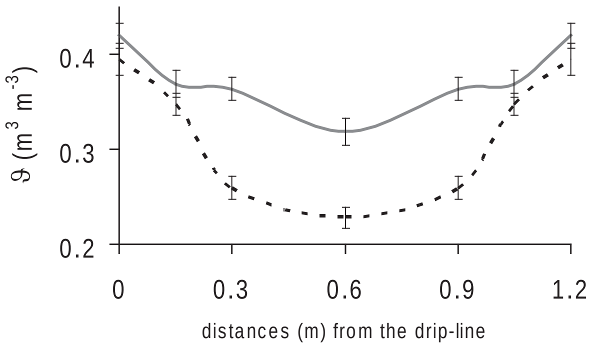

Figure 2. Volumetric moisture (at -0.3m depth) measured during the tomato season in the transect between two contiguous drip-lines under two water regimes: full irrigation (solid line) and stress (dashed line).

The indications acquired through remote sensing distinguish with precision neither the horizontal nor the vertical variations in humidity. Measurement of the crop water status (fig. 3), expressed through the maximum daily value of leaf water potential (Ψ) is affected by fewer errors because it is measured at “pre-dawn” (before sunrise), when the soil water status and the crop water status are in equilibrium. Measurements of PLWP have four advantages:

a) they are not influenced by the meteorological condition;

b) they integrate the variations in humidity that normally characterise the soil;

c) they are correlated to the water available in the soil (fig. 4);

d) they are correlated to the stomatal conductance (fig. 5).

For the purposes of irrigation management, the monitoring of PLWP allows for the scheduling of the irrigation and the prevention of stomatal closure. In other words, it allows to correctly follow the ‘regulated deficit irrigation’ (RDI), for saving irrigation water and maintaining crop productivity.

The main limitation in the use of the PLWP lies in the laboriousness of the method, such that it can not be extended to agricultural practice or to the estimation of water budgets through remote sensing. An alternative solution is to derive the crop water status by ‘automatic’ and, above all, ‘remote sensing’ measurements. Radiative temperature and NDVI have these characteristics.

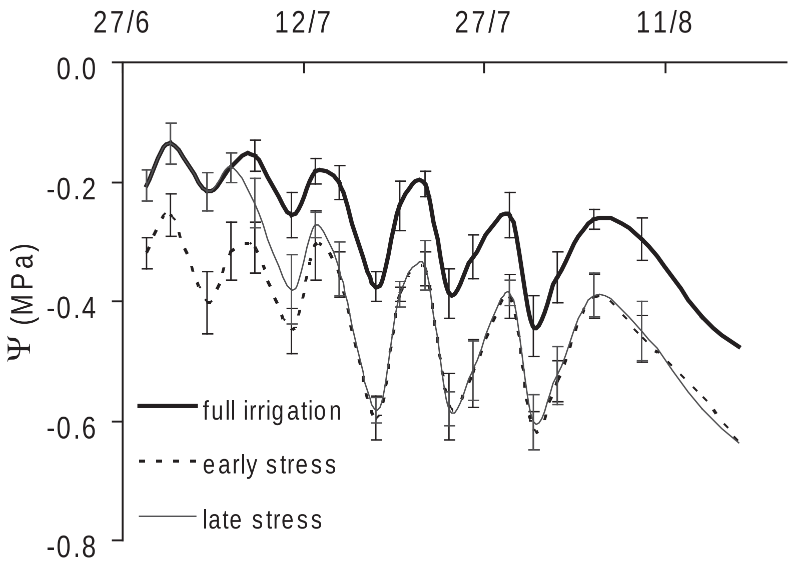

Figure 3. Daily variations in pre-dawn leaf water-potential (Ψ) during the tomato cycle grown under three water regimes.

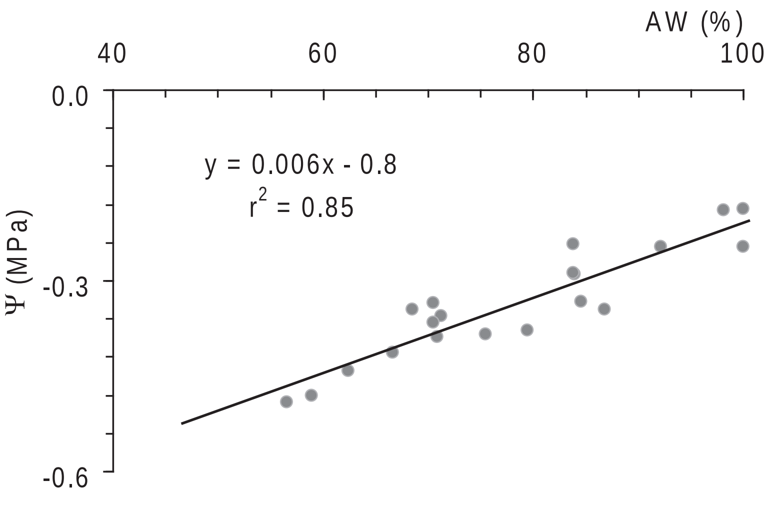

Figure 4. Relationship between pre-dawn leaf water-potential (Ψ) and soil available water (AW).

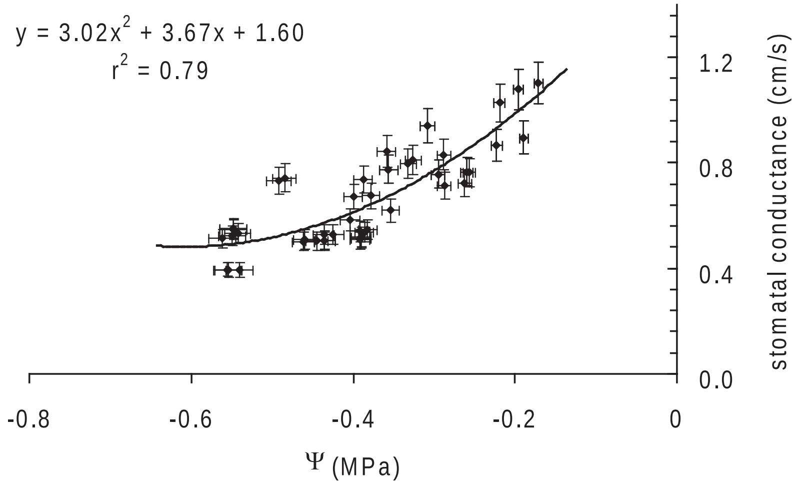

Figure 5. Relationship between stomatal conductance and pre-dawn leaf water-potential (Ψ).

The NDVI index varies during the crop cycle (fig. 6) following the crop growth (LAI and biomass). It should be underlined that the stress was applied after the maximum LAI value. Respect to the 'full irrigation' treatment, a reduction of the seasonal irrigation volume (-36% and -27% in early and late 'temporary stress' treatments, respectively) did not compromise the tomato growth.

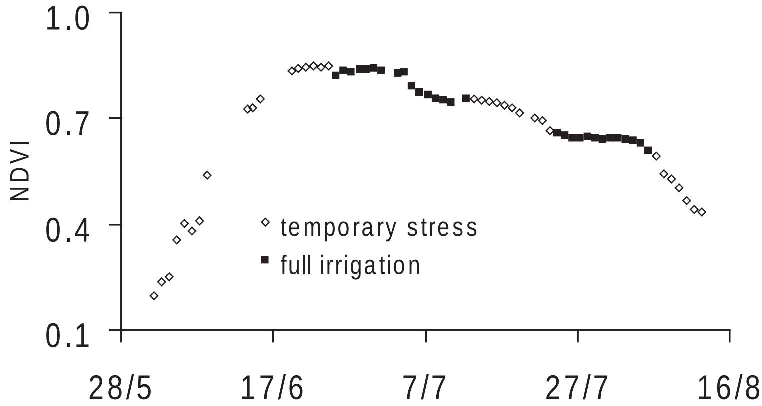

Figure 6. Variations of NDVI measurements during the tomato crop season. The different symbols stand for the two irrigation treatments. Each experimental point represents the average of the daily NDVI values measured in the time interval between 8 a.m. and 5 p.m..

Nevertheless between PLWP and NDVI a linear relationship results: $\Psi = 1.67 \cdot NDVI - 1.59$; $r^2 = 0.95$ (fig. 7). From this relationship it seems possible to predict the crop water status starting from completely automatic measurements and, above all, from those ones that can be acquired through remote sensing techniques.

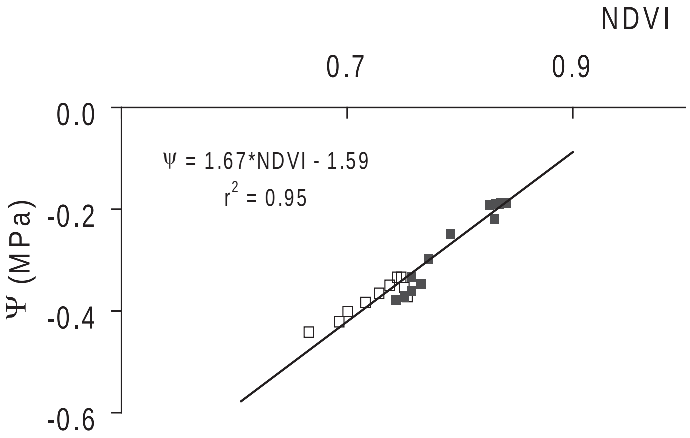

Figure 7. Pre-dawn leaf water-potential (Ψ) *vs* daily values of NDVI. Values derive from the full-irrigation (solid symbols) and the stressed (unfilled symbols) treatments.

Vice versa, the measurements of radiative temperature used to estimate the water status of the tomato proved to be unsatisfactory (fig. 8). The temperature of the vegetation, besides the soil water regime, is dependent on the meteorological conditions at the time of measurement.

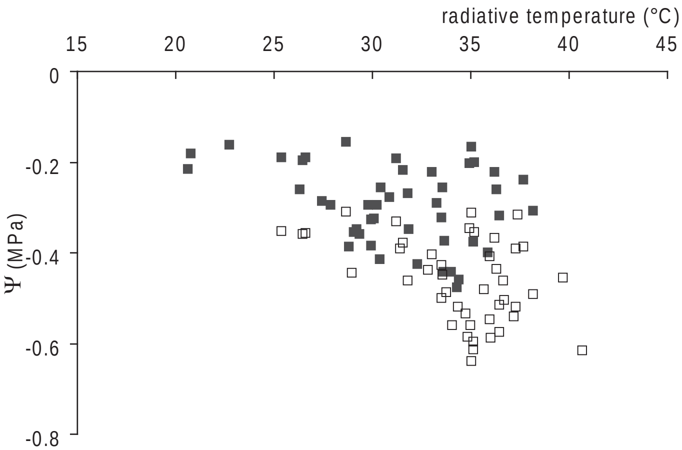

Figure 8. Pre-dawn leaf water-potential (Ψ) *vs* radiative temperature (maximum daily values). Unfilled symbols represent the measurements on the stressed tomato and solid symbols the measurements on the full-irrigated tomato.

IV – Conclusions

Continuous measurements of water status of crop let possible to schedule irrigation with the highest precision (Clarke, 1997). Mainly in the Mediterranean regions the precision is required to use efficiently the water resources at field and regional levels. The first results of this work in progress support the hypothesis of identifying the water status of vegetation (PLWP) upon the relationship based on NDVI data.

Aknowledgments

This study was realized within the activities of the AQUATER project, funded by the Italian Ministry of Food, Agriculture and Forestry Policies (under contract n. 209/7393/05).

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Effect of deficit irrigation on olive and olive oil quality during fruit storage

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Abstract. We evaluated the effects of deficit irrigation on olive fruit and olive oil quality. Mature 'Konservolea' olive trees were deficit irrigated during August (10% of control). Control trees received in total around 5600 m^3/ha. Total water savings in deficit irrigated trees were around 3000 m^3/ha. Quality parameters, as skin colour, flesh firmness, dry matter and total phenols, were evaluated on green olives harvested in late September, both at harvest and after 1 and 2 weeks of storage at 5ºC including. In early November, ripe olives were harvested and quality was evaluated on fruit and olive oil at harvest and after 11, 17 and 24 days at 5ºC. At harvest, ripe fruit size and shape, density, oil and water content, respiration rate, skin colour, firmness, and chlorophyll content were evaluated. The last five quality parameters were also evaluated during fruit storage, while acidity, peroxide value and spectrophotometric oxidation indexes were measured on olive oil. Deficit irrigation did not affect green olive fruit quality at harvest and after storage. Ripe fruit from deficit irrigated trees were slightly bigger and of more advanced maturity with lower oil content than control fruit. Olive oil extracted from fruit harvested from deficit irrigated trees was similar to olive oil obtained from control fruit at harvest, but, during fruit storage, the extracted olive oil quality deteriorated rapidly due to increased acidity and K270 index.

Keywords. *Olea europaea* – Phenols – Firmness – Colour – Acidity.

Effets de l'irrigation déficitaire sur la qualité de l'olive et de l'huile d'olive pendant le stockage des fruits

Résumé. *Nous avons évalué les effets de l'irrigation déficitaire sur la qualité de l'olive et de l'huile d'olive pendant le stockage des fruits. Des oliviers adultes de la variété 'Konservolea' subirent un traitement d'irrigation déficitaire durant le mois d'août (10% du traitement contrôle, dont les arbres reçurent 5600 m^3/ha). L'économie d'eau fut de 3000 m^3/ha. La qualité des fruits verts, récoltés fin Septembre, fut évaluée à la récolte et après 1 et 2 semaines à 5ºC. Début Novembre, les olives mûres furent récoltées et leur qualité évaluée (fruit et huile d'olive) à la récolte et après 11, 17 et 24 jours à 5ºC. Les cinq derniers critères furent aussi évalués durant le stockage des fruits, ainsi que l'acidité, le niveau de peroxydes et les indices spectrophotométriques d'oxydation de l'huile d'olive. L'irrigation déficitaire n'a pas affecté la qualité du fruit. Les fruits mûrs des arbres du traitement déficitaire furent légèrement plus gros et de maturité plus avancée, avec un contenu en huile inférieur a ceux du traitement contrôle. L'huile d'olive extraite des fruits du traitement déficitaire fut similaire a celle obtenue du traitement contrôle à la récolte, mais la qualité de l'huile extraite s'est détériorée rapidement pendant le stockage, due à l'augmentation de l'acidité et de l'indice K270.*

Mots-clés. *Olea europaea – Phénols – Fermeté – Couleur – Acidité.*

I – Introduction

Olive is an important crop in the Mediterranean region that has traditionally been cultivated with no irrigation and is known to attain acceptable production even under dry farming. Nevertheless, the last decade irrigated olive orchards proved to be more productive with increased shoot growth, flowering, fruit set and reduced biennial bearing and fruit drop (Inglese *et al.*, 1996; Proietti and Antognozzi, 1996). Water availability also improved the commercial value of table olives by increasing fruit size (Proietti and Antognozzi, 1996).

Despite the fact that water is beneficial to olive cultivation, we must keep in mind that water scarcity is a global problem that concerns everybody, especially in the Mediterranean region. Agriculture is still the greatest consumer of the water in the Mediterranean region, as more than 80% of available water resources are allocated to irrigation with relatively high losses exceeding 50% (Laraus, 2004). Most of olive growers apply water inefficiently, with lower or higher than required quantities. The efficient management of the limited water resources in the Mediterranean agriculture scientifically proven irrigation scheduling techniques and deficit irrigation. There are several cases of successful application of regulated deficit irrigation in the xerothermic regions like many Mediterranean areas (Fereres and Soriano, 2007). Studies have shown that there are advantages in reducing irrigation to olive trees at the time of slow fruit growth (pit hardening). Regulated deficit irrigation after pit hardening has been recommended replacing only the 66% of crop evapotranspiration at least in deep soils with good water retention (Tognetti *et al.*, 2006).

The optimisation of irrigation management practices requires more research to be done on olive tree response to water stress through regulated deficit irrigation and efficient irrigation management programmes. Thus, the aim of this work was to study the effect of deficit irrigation on the quality of olive fruit and olive oil from cv. Konservolea, a major Greek olive cultivar, at harvest and after fresh fruit storage.

II – Materials and methods

'Konservolea' olive trees from an olive farm located in Anchialos, Central Greece, were used. The soil is relatively heavy with many stones and around 5% slope facing south. Irrigation is done by low volume sprinklers with good water quality (conductivity <700 μS/cm). The trees are planted 5m x 5m and pruned yearly. The fruit is used for table olives (green or black) or for olive oil extraction. Six trees were the experimental units – replications per treatment: control**,** irrigated from the end of May to the end of July for a total of 5.76 m^3 of water per tree and from early August to mid September for a total of 8 m^3/tree and deficit, irrigated as the control until the end of July, and then irrigated just once in August receiving 0.32 m^3/tree. That is around 3000 m^3/ha water savings.

In this experiment we harvested by hand in two different periods:

First harvest occurred in late September for green table olives: fruit quality was evaluated immediately and after 1 and 2 weeks cold storage at 5°C plus 1 day shelf-life at the Lab. of Pomology, Univ. of Thessaly. Quality evaluation included skin color, flesh firmness, dry matter and total phenols. Skin color was measured using a colorimeter (Hunter Lab, MiniScan XE Plus, Reston, VA, USA), flesh firmness was measured, after careful removal of fruit skin on opposite sides of the fruit, with fruit firmness tester (Turoni Slr, Italy) equipped with a 4mm plunger without touching the pit. The % dry matter of olives was calculated after weighing the fresh mass of flesh pieces, drying them at 100°C until no further changes in mass and final dry mass measurement. For measuring total phenol content we used the Folin-Ciocalteau method expressed as gallic acid equivalents per 100 g fresh mass. Analysis of variance (ANOVA) was performed on raw data in order to detect statistical differences between treatments, and means separation was assessed with Tukey test.

Second harvest occurred in early November with ripe olives for olive oil extraction: four plastic boxes containing 25 kg olives each were harvested from each treatment. All boxes were left in a shaded well aerated place for two days until they were transported by car to the Postharvest Laboratory at the University of Foggia. Upon arrival, each treatment was divided in three replicates and the following attributes were determined on 35 fruit per replicate: fruit size (perimeter, major and minor axis, and projected area), and shape (roundness), bulk density, true density, seed ratio as percent of weight, moisture content and oil content (expressed as percentage on fresh and dry weight).

Then, the olives of each treatment were stored in 3 boxes (one for each replicate) in a humidified cold room at 5°C. Initially and after 11, 17 and 24 days, the following attributes were determined: colour, evaluated on 35 olives for each sample using a scale from 1 to 5, with 1= full green, 2 = partially black (less than 50%), 3= partially black (more than 50%) black, 4= not completely black, and 5 = completely black; firmness, as the load (in N) required to have a 3-mm deformation on the minor axis with a speed of 120 mm/minute, measured with an Instron Universal Testing machine, model 3340; and chlorophyll, with 20-ml pure methanol added to 5 g of frozen olive fruit samples and kept in the dark at room temperature for 24 hours, followed by measurements of absorbance at 666 and 653 nm and chlorophyll calculations as following (in mg/100g of fresh weight):

chlorophyll a= $(15.65*A_{666})-(7.34*A_{653})$ and chlorophyll b= $(27.05*A_{653})-(11.21*A_{666})$

In order to measure respiration rate, 1 kg of olives for each replicate, were stored in individual 9,42 L jars (three replicates for each treatment) for the entire duration of the experiment and all jars were connected to a continuous flow of humidified-air. Respiration rate (in ml CO_2/kg/h) was measured using a dynamic system; air samples of 0.5 ml were collected with a syringe from the inlet and the outlet tubings and differences in CO_2 concentration were detected with a gas chromatograph (Shimadzu, model 17A ATF, Japan) equipped with a TCD detector, and then referred to the sample weight and air flow.

At each evaluation time, from about 6 kg of olives from each lot, oil samples were mechanically extracted using a laboratory scale olive oil extraction plant constituted of a hammer crusher, a mixer, and a vertical open-centrifuge.

The following attributes were determined on oil samples according to the analytical methods described in Regulations EEC2568/91 and EEC1429/92 of the European Union Commission (EUC, 1991): titratable acidity (% of oleic acid), determined by titration of a solution of oil dissolved in ethanol/ether (1:1) with ethanolic potash; peroxide value (in meq of active oxygen per kilogram of oil) with a mixture of oil and chloroform/acetic acid left to react with potassium iodide solution in darkness, followed by titration of free iodine with sodium thiosulfate solution; K232 and K270 extinction coefficients were calculated from absorption at 232 and 270 nm, respectively, with a UV spectrophotometer using a 1% solution of oil in cyclohexane and 1 cm path length.

The statistical design was a CRD (Completely randomized design) and the data analyzed with a one-way ANOVA with irrigation regime as factor. Data on samples after harvest were treated alone and together with pooled data from all evaluation times. The first results give information about the state of the fruit and oil initially before storage, while the second allows evaluating the overall differences between treatments during storage.

III – Results and discussion

Skin color of green Konservolea olives, although found to be statistically dependent on storage duration, did not change profoundly in all color parameters evaluated (L*, a*, b*, C* and hue angle) as these fruit did not ripen to substantially lose green color and did not develop chilling injury (appearing as dull skin color developing with time to brown-black areas on the skin) (data not shown).

Fruit weight of green Konservolea olives was not negatively affected from deficit irrigation or time (data not shown). Deficit irrigation did not affect green fruit flesh firmness. The percentage of fruit dry matter of green Konservolea olives slightly decreased with storage duration and somewhat increased due to deficit irrigation compared to control (Figure 1). Total phenols in green Konservolea fruit were not affected from deficit irrigation but decreased with storage time (Table 1).

The effect of irrigation treatment on ripe olives at harvest was observed on fruit size, color and fruit flesh firmness, as deficit irrigated fruit were bigger (possibly due to variation in total fruit load per tree) than control fruit, despite to what was expected. Similarly, area, perimeter and major axis were significantly higher in deficit irrigated ripe fruit (Table 2). Color score of deficit irrigated ripe olives was significantly higher, indicating faster color changes from green to black and therefore a more advanced maturity stage, than control fruit. As a consequence, firmness was lower for deficit irrigated ripe olives than for control (well-irrigated) ones. This is in agreement with work on table olives irrigated or not, where non-irrigated olives ripened (softened and changed colour) faster than irrigated ones (Inglese *et al.*, 1996; Proietti and Antognozzi, 1996). No other differences in ripe olive fruit quality at harvest were observed (Table 2). Olives had a moisture content of about 53%, a true density of 0.88 and 0.97 g/ml for control and deficit irrigated fruit, respectively, and seed ratio at 20% by weight. Respiration rate ranged from 12 to 15 ml CO_2/kg/h, and total chlorophyll content was 1-2 mg/100 g of fresh weight at harvest (Table 2).

The irrigation regime didn't seem to affect quality parameters and respiration rate of ripe Konservolea olives during storage at 5°C except colour score, which was significantly higher in deficit irrigated olives (Table 3).

At harvest, ripe olives from control treatment had higher oil percent per fresh weight basis than deficit irrigated olives, i.e. 17 and 16%, respectively, but no significant difference was detected between the two treatments when oil content was expressed per dry weight basis (Table 4). Similarly irrigation increased oil content per fresh weight basis (and per dry weight basis) in Carolea olives compared to non-irrigated control (Inglese *et al.*, 1996). Regarding oil quality obtained from olives at harvest, the only significant difference between irrigation regimes was detected for K_{270} extinction coefficient, which was significantly higher for oil obtained from deficit irrigated olives, 0.2 versus 0.1, indicating a more advanced oxidation process, but oils from both treatments remaining within the range of extra virgin olive oil fixed at 0.22 (Table 4).

After storage, quality of oil extracted from deficit irrigated olives declined. Acidity increased to 1.2%, reaching above 1% even after 11 days of storage, thus over-passing the limit of extra-virgin olive oil fixed at 0.8% (Table 5), while oil obtained from well-irrigated olives did not show changes and remained stable during storage at around 0.5% (Table 5). Extinction coefficient at 270 was also significantly higher in oil obtained from deficit irrigated olives with average value over-passing the limit for extra-virgin oil, and indicating a more advanced oxidation process, while ΔK was about zero for both treatments.

IV – Conclusions

According to the experimental results green Konservolea olive fruit quality didn't change significantly with storage except of a slight reduction in total phenols.

The effect of irrigation treatment on ripe Konservolea olives at harvest was observed on fruit size, color and firmness, as fruit irrigated with deficit treatment were bigger, had higher color score and lower firmness than well irrigated olives. Thus, it seems that deficit irrigation advanced olive maturity at harvest. Deficit irrigation treatment also advanced skin color changes during fruit storage at 5°C, with no other differences detected concerning olive fruit quality.

Ripe olives from control treatment had higher oil content (on fresh weight basis) compared to olives from deficit treatment. Oil quality at harvest was similar between treatments except for K270 extinction coefficient, which was significantly higher for oil obtained from deficit irrigated olives, but both remaining within the range of extra virgin olive oil fixed in 0.22. Finally, oil quality after storage declined in deficit irrigated olives based on oil acidity and K270 extinction coefficient.

Table 1. Effect of deficit irrigation on total phenols of green Konservolea olives at harvest and after 1 and 2 weeks storage at 5°C.

Total Phenols (mg Gallic acid/100g FW)		
Time of storage	Control	Deficit
Harvest	106 ± 7,1	102± 5,1
1 week	110 ± 5,6	107± 3,5
2 week	79 ± 12	83± 11

Table 2. Effect of deficit irrigation on quality parameters of ripe Konservolea olives at harvest.

Parameter	Control	Deficit
Moisture content (%)	55.3 a	54.5 a
True density (g/ml)	0.88 a	0.97 a
Bulk density (g/ml)	0.5 a	0.5 a
Seed ratio (%w)	22.1 a	20.1 a
Area ($pixel^2$)	32073 b	32201 a
Perimeter (pixel)	682 b	720 a
Major axis (pixel)	229 b	242 a
Minor axis (pixel)	178 a	187a
Roundness	0.78 a	0.77a
Respiration Rate (ml CO_2/Kg/h)	15.6 a	12.6 a
Color score	3.6 b	4.4 a
Firmness (N)	17.9 a	12.4 b
Chl a (mg/100g)	0.4 a	0.6 a
Chl b (mg/100g)	0.9 a	1.6 a
Chl Total (mg/100g)	1.3 a	2.2 a

Within each row, values followed by different letters are significantly different for P<0.05

Table 3. Effect of deficit irrigation on quality parameters of ripe Konservolea olives during storage at 5°C, mean values for all storage evaluations are shown.

Parameter	Control	Deficit
Respiration Rate (ml CO_2/Kg/h)	12.5 a	11.1 a
Firmness (N)	13.1 a	11.3 a
Weight loss (%)	1.4 a	1.4 a
Color score	3.8 b	4.3 a
Chl a (mg/100g)	0.66 a	0.44 a
Chl b (mg/100g)	1.57 a	2.19 a
Chl Total (mg/100g)	2.23 a	3.17 a

Within each row, values followed by different letters are significantly different for P<0.05

Table 4. Effect of deficit irrigation on quality parameters of olive oil extracted from ripe Konservolea olives at harvest.

Parameter	Control	Deficit
Oil content (% FW)	17.1 a	15.7 b
Oil content (% DW)	40.0 a	37.3 a
Acidity (% oleic acid)	0.5 a	0.7 a
Peroxide value (meq O_2/ Kg)	7.6 a	7.5 a
K_{232}	1.2 a	2.4 a
K_{270}	0.1 b	0.2 a

Within each row, values followed by different letters are significantly different for P<0.05

Table 5. Effect of deficit irrigation on quality parameters of olive oil extracted from ripe Konservolea olives after storage at 5°C, mean values for all storage evaluations are shown.

Parameter	Control	Deficit
Acidity (% oleic acid)	0.5 b	1.2 a
Peroxide value (meq O_2/ Kg)	6.7 a	8.5 a
K_{232}	1.4 a	2.1 a
K_{270}	0.1 b	0.3 a

Within each row, values followed by different letters are significantly different for P<0.05

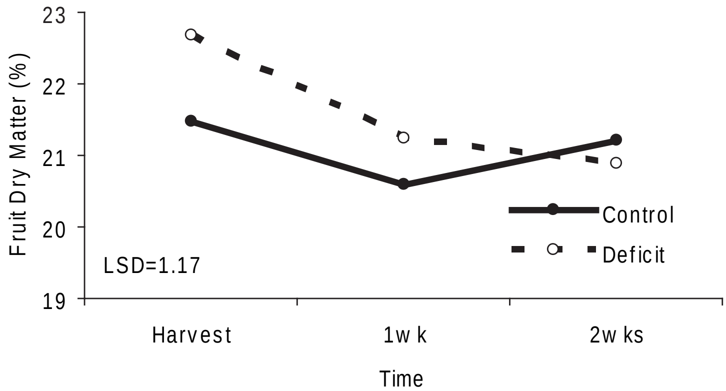

Figure 1. Effect of deficit irrigation on fruit dry matter (%) from Konservolea olives at harvest and after 1 and 2 weeks storage at 5°C.

Acknowledgements

The authors would like to thank Prof. Constantinos Kittas for his kind review of the article and his help in French language translation. This work is part of IRRIQUAL, Sustainable orchard irrigation for improving fruit quality and safety, an EU-funded research program on FOOD, contract # 023120.

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Unravelling the molecular cues of plant adaptation or survival to water deficit

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Abstract. When experiencing water deficit, glycophyte plants undergo physiological and biochemical changes aimed at limiting cellular damages and rescuing a new cellular homeostasis. Discriminate irreversible cell injury from adaptive rearrangements to water stress, is quite critical since only the latter plant response is compatible with active growth and development sustaining, ultimately, plant yield. An up-dated view of the molecular basis of cellular response to drought stress and of key functions activated able to protect cellular processes is summarized in the paper. It also reported a functional approach developed to identify genes with a crucial role in the adaptation to water deficit based on the systematic comparison of potato cell populations exposed abruptly or gradually to PEG-induced low water potential. Gradually adapted cells were characterized by distinctive metabolic adaptations (proline accumulation, changes in membrane lipid composition, de novo synthesis, etc) which enable them to grow actively at non-permissive water stress conditions. Differential gene expression in response to shock or gradually increasing water deficit was monitored by microarray technology, using the 1K TIGR potato cDNA array. More than 100 genes belonging to different functional categories were up-regulated in response to stress conditions. However, only a few induced genes were common to both cell populations, confirming that different gene networks mediate shock or long-term response to water deficit.

Keywords. Potato – Water stress/adaptation – Gene expression – Microarray.

Etude des signaux moléculaires d'adaptation ou de survie de la plante à la pénurie d'eau

Résumé*. La pénurie d'eau provoque chez les plantes glycophytes des modifications physiologiques et biochimiques qui visent à limiter les dommages cellulaires et à rétablir une nouvelle homéostasie.*

Distinguer entre les dommages cellulaires irréversibles et le nouvel arrangement adaptatif provoqué par le stress hydrique est très critique, puisque seule l'adaptation est compatible avec la croissance active et le développement qui soutiennent la production de la plante.

Une vision actualisée de la base moléculaire de la réponse des cellules à la pénurie d'eau et des fonctions-clés activées, est résumée dans cet article. En outre, on y décrit l'approche fonctionnelle développée pour identifier les gènes qui ont un rôle crucial dans l'adaptation à la pénurie d'eau. Cette approche est fondée sur une comparaison systématique des populations cellulaires de pommes de terre qui sont exposées, brusquement ou graduellement, à un potentiel hydrique bas, induit par le PEG. Les cellules graduellement adaptées ont été caractérisées par une adaptation métabolique typique qui leur donne la possibilité de croître activement en conditions non permissives.

Les technologies microarray (1K potato TIGR cDNA) ont détecté une expression génique différentiée, en réponse à l'adaptation brusque ou graduelle à la pénurie d'eau. Une centaine de gènes appartenant à différentes catégories fonctionnelles se sont surexprimés en cas de stress hydrique. Toutefois un petit nombre de gènes induits se sont révélés communs aux deux populations cellulaires, confirmant que les réponses choc et de long terme à la pénurie d'eau, sont arbitrées par différents réseaux de gènes.

Mots-clés. *Pomme de terre – Pénurie d'eau/adaptation – Expression génique – Microarray.*

I – Introduction

Fluctuating or permanent stress conditions affect the cultivation of most of the crops, causing yield instability and loss. This scenario is even more aggravated by the predicted forthcoming global changes in climate, the foreseen extremization of environmental conditions, the continuous increase of world population, the ever increasing deterioration of arable land and the scarcity of fresh water, all underscoring the importance of developing stress-resistant crops able to sustain growth and productivity in stressful environments. Drought is one of the major abiotic stresses affecting plant growth and reducing crop productivity being the 28% earth land represented by soils too dry for crop production (Bray, 2006). Agronomic amendments (irrigation, soil correction) might be still adopted to reduce the impact of drought stress on yield stability, but the additional costs for such modifications could be in many cases not economically advantageous. The increased occurrence of drought and his severity, imposes to select new tolerant varieties. Conventional breeding for drought resistance has been a basic approach for a long time and some successes have been achieved in crops such as maize (Hoisington *et al.*, 1996), wheat (Zhao *et al.*, 2000) and rice (Zhang *et al.*, 2006). However, a big gap remains between the current resistance levels and what is needed to guarantee yield stability for most of the major crops. Drought stress response and/or tolerance is a complex trait and is the result of the coordination of biochemical and physiological changes at the cellular and molecular level. Many of these changes involve a large number of genes, most of which are directly involved in the activation of adaptive mechanisms. The enormous body of information recently gathered on the molecular bases of plant response to stress signals and the identification of key genetic determinants in this process opened new opportunities for the development of tolerant plants based on marker assisted selection approaches as well as on innovative biotech approaches through targeted genetic manipulation of crop plants.

II – Molecular basis of plant response to osmotic stress

Plants have developed a wide variety of adaptive strategies to cope with environmental stresses; accordingly, plant cells have evolved signalling pathways to perceive and integrate different signals from their surroundings and to respond by modulating the expression of the appropriate genes (Knight and Knight, 2001). As complex trait, water stress tolerance is the result of the coordination of biochemical and physiological alterations at the cellular and molecular level, such as the increased level of ABA, the accumulation of various osmolytes and proteins coupled with an efficient antioxidant system. Many of these mechanisms have been characterized and have been found to exist in both tolerant and non-tolerant plants (Taji *et al.*, 2004). It is now clear that the difference between tolerant and non-tolerant crops at the molecular level involves a large number of genes. It has been estimated that the response to a stressful environment involves ca. 2000 genes, most of which are up-regulated upon stress (Bonhert *et al.*, 2001; Huang *et al.*, 2008). However, it is still unclear how many and which genes are directly involved in the activation of adaptive mechanisms. In fact, up-regulated genes do not necessarily have a role in adaptation, some might be induced because of stress-caused cell injury (Bray, 1997).

In the last decade different approaches have been adopted to dissect the complex molecular and biochemical mechanisms underlying plant stress response, to identify the genes involved and to establish their essential contribution to stress tolerance and protection. Several of the isolated genes, associated to the stress response and/or tolerance, have shown to be common to different environmental stresses, sharing a physiological osmotic component as determinant of the stress signal (water deficit, salt and freezing stress).

The characterization of a large number of stress-induced genes has significantly contributed to the understanding of the complex response to stress signals. Many of the genes, induced upon stress conditions, encode polypeptides, with putative protective roles in the stressed cells, such as in ion transport (uptake, extrusion and sequestration of ions), membrane stabilization and chaperone functions, and small organic molecules, called compatible solutes, osmolytes and osmoprotectants (proline, glicyne betaine, sugars) (Xiong and Zhu, 2002). Manipulation of the expression of this class of genes has long been the most common approach, first, to demonstrate their role and function in stress tolerance and, secondly, to produce stress-tolerant transgenic plants. Genes belonging to the different categories above described, cloned from plants or other organisms, have been over-expressed, under the control of strong constitutive promoters, in model and crop plants, with the final result to increase tolerance to a specific or more than one environmental constraints (Table. 1). Though an increase in the level of tolerance to the stress under study has been claimed in many cases, tolerance of the over-expressing transgenic plants has been evaluated only rarely in field trials under realistic stress conditions. Additionally, only in few cases the possible negative pleiotropic effects of the genetic manipulation on the plant phenotype have been thoroughly discussed (Umezawa *et al.*, 2006). Recently, research activities in the field evolved from the study of single genes directly involved in cellular stress tolerance (functional genes) to the identification and characterization of key regulatory genes involved in stress perception and transduction and able to rapidly and efficiently activate the complex gene network acting downstream the signalling cascade. In this context protein kinases and phosphatases emerged as key players in stress signalling processes in yeast and animals, and also in plants (Jonak *et al.*, 2002) triggering stress-induced transcription factors able to directly activate the downstream machinery of genes involved in stress-protection and relief. The identification of key transcription factors (TFs), as CBF/DREB, has opened the possibility to obtain transgenic plants with a coordinated induction of the entire network of genes involved in stress tolerance. Infact TF over-expressing transgenic plants revealed cold and dehydration tolerance by activation of the target genes with reduced negative pleiotropic effects when they were expressed under the control of inducible promoters (Kasuga *et al.*, 1999; Hsieh *et al.*, 2002). The complexity of the events occurring in response to stress have been recently approached by genomics tools; progress in the mass-scale profiling of the transcriptome, proteome and metabolome has allowed a more holistic approach in investigations of drought tolerance based on the measurement of the concerted expression of thousands of genes and their products. High-throughput mRNA profiling has been applied to investigate the changes in gene expression in response to dehydration (Ozturk *et al.*, 2002). Collectively, the transcriptome profiling experiments conducted on drought-stressed plants have confirmed the central role of transcription factors while unveiling the complex hierarchy of the regulatory network that differentially modulates the expression of dehydration signature genes in a tissue-specific manner (Shinozaki and Yamaguchi-Shinozaki, 2007).

Despite the approach used, many of the stress-induced genes, identified in glycophyte or xero- and halophytes, still have no assigned functions (Bouchez and Hofte, 1998; Grillo *et al.*, 2006). Different functional genomic strategies based on reverse and forward genetics approaches in model as well as in crop species, have rapidly developed in recent years and are now routinely used to define key functions (Bohnert *et al.*, 2006). Though the ”gain and loss” approach has highlighted the contribution of specific stress-induced genes in the physiological processes of stress tolerance, there is, however, no clear evidence that the agronomic performance of crop plants under stressful conditions can be improved by simply overexpressing one/few genes.

The advance in plant genomic research with new information on genome sequence and structure for an increasing number of crops and the establishment of powerful bioinformatic platforms for data management and analysis (Chaves *et al.*, 2003; Cattivelli *et al.*, 2007) were also crucial in providing new tools for plant breeders to approach the complexity of plant response to drought. The massive development of molecular marker technologies (RFLPs, RAPDs, SSPs, AFLPs) and the consequent generation of high density genetic maps for economical important crops, is leading nowdays to the identification of major Quantitative Trait Loci (QTLs) contributing to stress tolerance (Tuberosa and Salvi, 2006). The identification of genes underlying QTL by mapping the stress-induced genes (candidate gene approach), although is still a long way off, will ultimately provide the indication of the effective contribution of single/multiple candidate genes to stress tolerance and additionally will provide simple and efficient tools for effective molecular marker assisted (MAS) breeding for stress tolerance. It is becoming clear that the success of breeding for stable high yield will be only possible when a true integration of traditional breeding with plant physiology will be achieved using a multidisciplinary approaches based on plant genomics and advanced modelling.

Table 1. Transgenic plants tolerant to water stress obtained by over-expressing plant and microbial genes belonging to different functional categories (adapted from Grillo *et al.*, 2006).

Product	Gene	Origin	Host	Reference*
Osmolytes Metabolism				
Fructan	SacB	B. subtilis	Tobacco	Pilon-Smits et al., 1995
Trialose	Tps1	Saccaromyces	Tobacco	Romero et al., 1997
Poliamine	ADC	D. stramonium	Rice	Capell et al., 2004
Prolin	P5CS	Arabidopsis	Petunia	Yamada et al., 2005
Protective Proteins				
LEA	HVA1	Barley	Rice	Xu et al., 1996
Chaperone	Bip	Soya	Tobacco	Alvim et al., 2001
LEA	LLA23	Lilium	Arabidopsis	Yang et al., 2005
Detoxificant Enzymes				
Peroxidase	APX3	Arabidopsis	Tobacco	Yan et al., 2003
Superoxide dismutase	Mn-SOD	Tobacco	Alfalfa	McKersie et al., 1996
Transcriptional Factors				
DREB1/CBF	ZmDREB1A	Mais	Arabidopsis	Qin et al., 2004
DREB1/CBF	DREB1A/CBF3	Arabidopsis	Arabidopsis	Kasuga et al., 1999
AP2/ERF	SHN1/WIN1	Arabidopsis	Arabidopsis	Aharoni et al., 2004
bZip	ABF3	Arabidopsis	Rice	Oh et al., 2005
MYB	CpMYB10	C. plantagineum	Arabidopsis	Villalobos et al., 2004
Signal Trasduction				
MAPKKK chinase	NKP1	Tobacco	Mais	Shou et al., 2004
Famesyl transferase	ERA1	Arabidopsis	Oilseed	Wang et al., 2005
Others				
Ionic pump H^+	AVP1	Arabidopsis	Arabidopsis	Gaxiola et al., 2001
Malic enzyme	Chi-NADP-Me	Tobacco	Tobacco	Laporte et al., 2002
Expoxi-dioxigenase (ABA biosynthesis)	AtNCED3	Arabidopsis	Arabidopsis	Iuchi et al., 2001

* Reference are listed in Grillo et al., 2006

III – Cellular adaptation to water stress: a case study

As pointed out before, drought tolerance is a complex polygenic trait requiring the coordinated regulation of a large number of genes, as also recently confirmed by research studies based on global gene expression analysis in several plant species (Oono *et al.*, 2003; Rensink *et al.*, 2005; Bray, 2006). To discern stress-responsive genes that contribute to increase drought tolerance from those merely activated by a general stress response, our group has developed an *ad hoc* experimental system based on a potato (cv. Desiree) cell populations. Potato cells were exposed to a gradual increase in PEG-mediated low water potential (adapted cells) and to abrupt intense water stress (shocked cells) to study and compare systematically, at physiological and molecular level, the water stress response in these adapted cells and in non-adapted cells (Fig. 1) (Leone *et al.*, 1994a). Adaptation to water stress was found to be associated to several physiological and biochemical changes that include ability to sustain active cellular growth at conditions of water stress and salt conditions otherwise non permissive, accumulation of compatible osmoprotectants, such as proline (Leone *et al.*, 1994a), recovery of protein synthesis (Leone *et al.*, 1994b), changes in gene expression of stress responsive genes (Costa *et al.*, 2002; Ambrosone *et al.*, 2006), higher membrane stability due to changes in membrane lipid composition (Leone *et al.*, 1996).

A more complete description of the repertoire of genes involved in water stress adaptation, was obtained by comparing the global changes in gene expression in adapted potato cells with those induced by abrupt water stress in control cells by microarray analysis, using 1k and 10k cDNA slides from TIGR (The Institute for Genomics Research). In particular from the analysis of 1k, 64 up-regulated genes and 49 down-regulated genes during PEG adaptation, and 45 up-regulated and 22 down-regulated genes in response to PEG water stress were identified. Among the up-regulated genes, only two genes were found to be in shocked and adapted potato cells. Similarly, a limited number of common down-regulated genes, one was identified in the two cell populations. Altogether these data confirm that different gene networks are mediating the short- and long-term cellular response to water stress. Many of the identified genes highly expressed in the adapted potato cells belong to different functional classes, such as protein known to be involved in stress-response (e.g. heat shock proteins), involved in general cellular processes, e.g. protein synthesis, cellular transport, cell wall synthesis, and others. As already found as a results of transcriptome analyses in other crop species, about 20% of the stress responsive genes, identified in adapted potato cells, are highly expressed in stress conditions and matched with sequences in data banks with no assigned biological function. It is possible to speculate that genes up-regulated in shocked cells belong to early responsive genes providing initial protection and amplification of primary osmotic stress signals, while the genes whose expression is changed in adapted cells may be involved in tolerance to stress conditions. These results constitute the scientific and experimental background to further characterize identified genes with unknown functions and establish their role in drought tolerance. This will be approached through quantitative analysis of expression of selected genes in plant tissues in response to water stress and by a comprehensive functional analysis by both forward and reverse genetics approaches using also tools and materials available for the model plant *Arabidopsis thaliana*.

Acknowledgments

This work was partially funded by FIRB Project ‘Plant Stress’ of the Ministry of University and Research. Contribution n. 136 of The Institute of Plant Genetics, National Research Council (CNR-IGV).

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Estimating of water requirement and problems related to the application of a technique for rice irrigation based on intermittent submersion and soil matric potential scheduling

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Abstract. The paper deals with results of an experimental study carried out in north-western Po valley, aiming at the determination of the irrigation water requirement for a rice crop irrigated on level-basin, with a water saving technique (W.S.T.) using, instead of the traditional technique of continuous submersion, the intermittent submersion planned with the measure of soil matric potential in the root zone. In order to study the irrigation management problems related to the application of (W.S.T.), we have estimated by means of a mathematical model of the overland flow, the cut-off time equal to the final advance time for all the level-basins of a typical rice cultivated farm. The hydraulic parameters (infiltration and roughness) of the model were evaluated applying the continuity equation to the surface water profiles detected during the advance phase of three waterings. As shown by the results, in order to maintain the required matric potential values in the root zone, it is necessary to carry out a high number of waterings. Relief of the advancing surface water profiles made it possible to adequately determine the hydraulic parameter values useful for the application of the simulation model of the watering process. The applicatory interest of (W.S.T.) must be considered both in relation to the reduction of the seasonal irrigation water requirements and to the increase of the cost of labour, to the problems connected with the irrigation management at farm level, to the opportunity of the right-sizing of the fields and the irrigation network.

Keywords. Rice irrigation – Water saving technique – Intermittent submersion – Soil matric potential scheduling.

Estimation des besoins en eau et des problèmes liés à l'application d'une technique d'irrigation de la riziculture par la submersion intermittentte et le pilotage du potentiel matriciel

Résumé*. Cet article présente les résultats d'une recherche expérimentale conduite dans la Vallée du Pô au nord-ouest de l'Italie. L'étude vise à déterminer les besoins en eau d'une culture de riz, irriguée par une technique d'économie d'eau (W.S.T.) appliquant la submersion intermittente mesurant le potentiel matriciel de la zone racinaire, au lieu de la technique traditionnelle de submersion continue. Afin d'étudier les problèmes liés à la gestion de l'irrigation, on a calculé (avec un modèle mathématique) la durée d'arrosage correspondant au temps d'avancement final de la lame d'eau, pour tous les bassins d'une exploitation agricole typique cultivée au riz. Les paramètres hydrauliques (d'infiltration et de rugosité) ont été évalués, appliquant l'équation de continuité aux profils libres de l'eau avançant dans un bassin expérimental. Les résultats ont montré que, pour conserver dans la zone racinaire les valeurs prévues de potentiel matriciel, un nombre relativement élevé d'irrigations doit être effectué. La détermination de l'avancement des profils d'eau a permis l'évaluation des paramètres nécessaires à l'application du modèle de simulation. Afin de permettre une gestion rationnelle de l'irrigation même dans une exploitation agricole, l'intérêt applicatif de la technique doit être évalué par rapport à la réduction des besoins saisonniers en eau et à l'augmentation du coût de la main-d'œuvre et à la possibilité de redimensionner les exploitations à irriguer et le réseau de distribution.*

Mots-clés. *Irrigation – Riz – Économie d'eau – Irrigation intermittente – Pilotage du potentiel matriciel.*

I – Introduction

The research for methods to reduce water losses is an actual problem for rice irrigation in the territory delimited by Dora Baltea, Po and Ticino rivers in the north-western Po valley, where is located the greatest part of the Italian rice growing area (about 220.000 ha). The irrigation of rice in this area is traditionally operated with the continuous submersion method on level-basin throughout the entire irrigation season (from April to August); soil remain flooded to a depth of as much as 0.10 m until the final drying-out, apart from two or three periods of about five days to promote striking of the roots and to apply some nitrogen fertilizers and pesticides. The following seasonal values of irrigation water requirement can be considered in our study area for soils characterized by the probable presence of a plow soil layer (which is generally located 0.25 to 0.35 m below the field surface): 1000÷1600 mm for impermeable soils with a clayey texture; 1800÷2800 mm for normal permeable soils with a silt-loam to loam texture; 3000÷4000 mm for permeable soils with a sandy-loam texture; over 4500 mm for very permeable soils with a sandy texture where rice growing is only possible after suitable mechanical operation of clogging. Rice evapotranspiration in the growing period is estimated at 650÷750 mm (Allavena, 2001); it represents a relative small percentage of the total consumption, except in the case of clayey soils. Since the greatest part of the total consumption is constituted by the percolation and seepage losses (PS), it is obvious interest to develop irrigation techniques that enable their reduction.

The term “water-saving techniques” (W.S.T.) denominates irrigation techniques that aims at reducing (PS) losses by reducing the depth of ponded water, or keeping the root zone just saturated, or allowing the root zone to dry out to a certain extent after the submersion water vanished from the soil surface, before re-applying irrigation water (intermittent submersion). Rice irrigation with intermittent submersion is chosen because it reduces (PS) losses, while it allows for a better use of natural rains, cutting down irrigation water requirements. However, (W.S.T.) may cause the risk of yield reduction due to drought (with reference to the rice cultivation drought is defined as: situation where the water content in the root zone is below saturation) and temperature stress effects on the crop (Singh *et. al*., 2001; Bouman and Tuong, 2001; Belder *et al*., 2004; Mao *et al*., 2004). In the years 2000, 2001 and 2002, we have experienced a (W.S.T.) based on intermittent submersion and irrigation events planned with predetermined rules of watering given to the farmer (Allavena, 2004); now a (W.S.T.) based on intermittent submersion method and soil matric potential scheduling is studied. Methods to evaluate the hydraulic parameters for the use of mathematical models of the overland flow to simulate the watering process were then examined; for this study the soil water intake is described by the use of an empirical infiltration equation traditionally known as Kostiakov equation and hydraulic resistance of the irrigation run is expressed by the Manning’s roughness coefficient. These parameters are evaluated from the surface water profile measured in the field during the advance phase, through the application of the continuity equation. The system parameters determined in this way, are then used with an overland flow model to calculate the cut-off times taken equal to the final advance as a function of flow rates for all the level- basins of a typical rice cultivated farm in view of a rational irrigation management.

Following the above considerations, the study focuses on the following objectives: i) determination of the number of waterings strictly necessary to maintain a matric potential greater than -35 ÷ -45 kPa in the root zone during the entire irrigation season; ii) determination of the corresponding seasonal water requirement; iii) evaluation based on the surface water profiles of appropriate parameters for infiltration and roughness; iv) application of a parameterized model of the watering process to the planning of W.S.T. in a typical rice cultivated farm and discussion of the problems related to the irrigation management.

II – Material and methods

1. Field characteristics

Field experiments on rice (*Oryza sativa*) irrigation with a (W.S.T.) technique based on intermittent submersion and soil matric potential scheduling were performed during the years 2003, 2004 and 2005 in the rice cultivated areas of north-western Po valley. The experimental site, surrounded by flooded rice fields, is located near Bianzé (Lat. N 45° 17' 50''; Long. E 08° 07' 08''; Alt. 180 m a. s. l.) in the county of Vercelli at approximately 45 km north-east of Turin.

In order to characterize climatic conditions we have reported in Figure 1 the evolution of the reference evapotranspiration calculated with the Penman-Monteith equation (five days total) and daily values of rain measured with gauges scattered in the experimental field itself; total rain of the period 1 May ÷ 31 August was: 212.1 mm in 2004; 198.8 mm in 2005.

The experimental field is composed of two level basins, one irrigated with (W.S.T.) and the other with the traditional technique of continuous submersion; the basin irrigated with the intermittent submersion during the whole cropping season has a length of 152 m and a width of 36.7 m; the adjacent basin irrigated with the continuous submersion has a surface of 1.1 ha and similar edge conditions. The slope of the surface of the experimental basins was laser leveled to zero field slope (March 22th and 23th 2003); in subsequent years no laser levelling was carried out.

The textural soil properties are quite homogeneous in the profile and classified as a silt loam following the USDA soil classification system, with an average clay fraction of 9.3 %, an average silt fraction of 61.5 % and an average sand fraction of 29.2 %. On the contrary, the hydrologic horizon show a layer with a low permeability which is typical for areas cultivated for many subsequent years with the continuous submersion method. In fact, a shallow plow layer (from soil surface to 0.25 ÷ 0.30 m) overlays a plow sole with a thickness of about 0.1 m, and a sub layer extending to the water table (situated at a depth of about 0.8 ÷ 1.0 m from the soil surface during the period May to August); this is directly reflected by the dry bulk density values ρ_d: while ρ_d equals 1250 kg · m^{-3} in the top layer of the profile, the dense horizon shows a local dry bulk density of ρ_d = 1600 kg · m^{-3}.

The rice was sown: April 2nd in 2003 (cultivar "Carnaroli"); May 8th in 2004 and April 30th in 2005 (cultivar "Gladio"); the cultural practices were similar to those adopted by farmers of this region.

During the irrigation seasons of 2003, 2004 and 2005 soil matric potentials were measured manually every two or three days at 8 ÷ 9 a.m., in two locations of the experimental field with tensiometers having the porous cup at five different depths chosen between the soil surface and the water table; it allowed exploring soil-water dynamics as related to soil texture and structure, presence of a shallow plow sole, evapotranspiration of rice plants, watering and rains. Depths of the porous cups and corresponding evolution of the mean matric potential are reported in Figure 1 for the year 2005; in this paper for purpose of concision we mainly refer to the matric potential data determined in this year.

The watering was applied when the mean matric potential in the root zone was about -35 to -45 kPa; even though this threshold value may perhaps slightly reduce rice grain yield as compared to the optimal value of -10 or -20 kPa (Kukal *et al.,* 2005), it allows increasing time intervals between two consecutive watering and hence reducing labor costs.

2. Infiltration and hydraulic resistance evaluation for modelling shallow overland flow in a rice cultivated level-basin

The flow in a level-basin is an example of unsteady, non-uniform and gradually varied flow with free surface over a porous bed (Khanna and Malano, 2006). The full description of one-dimensional shallow water flow is based on the numerical solution of the continuity and the momentum Saint-Venant equations (Strelkoff, 1969). The models where all terms of the Saint-Venant equation are retained, are called "full hydrodynamic" or simply "hydrodynamic" models. Since in surface irrigation the overland flow velocities are small, a reasonable simplification consists in assuming the inertia terms in the momentum equation to be negligible ("zero-inertia models").

Based on the above quoted equations, various detailed simulation models have been developed to help in the evaluation of the level-basin irrigation, some of which have now come to a stage where they can be called "user-friendly" computer programs (e. g.: BASIN 2.0, Clemmens *et al.*, 1995; SIRMOD III, Walker, 2003; SURDEV, Jurriens *et al.*, 2001); among these, for calculations we have chosen the last (SURDEV). The use of design software is often hindered by the lack of appropriate field values for the parameters required as input, particularly: infiltration and hydraulic resistance.

Infiltration is difficult to determine or predict with reliability and accuracy, because in a surface irrigation unit it can vary temporally and spatially. Point infiltration measurements are normally made by infiltrometers (single or double rings; furrow, sprinkler, tension, infiltrometers), but it is laborious to account for the above said variations by these traditional point methods. To overcome these difficulties, irrigation engineering research has focused on the evaluation of infiltration over the whole irrigation unit by means of water advance data collected during an irrigation event (e. g.: Maheshwari and McMahon, 1992). Field data are often matched by empirical equations; the most widely adopted, particularly in "user-friendly" programs, is the power form infiltration equation (Kostiakov equation):

$$Z = u \cdot T^{v}$$

where, Z is the cumulative infiltrated depth (volume infiltrated per unit area of infiltrating surface); T is the infiltration opportunity time; (u) and (v) are empirical coefficients. Hydraulic resistance is also difficult to estimate reliably since its value varies with the condition of the soil surface, the type and density of vegetation, and the depth of flow relative to the height of vegetation. In the user-friendly programs the estimation of the hydraulic resistance is based on Manning's roughness coefficient:

$$n = (y^{5/3} \cdot S_f^{\ 1/2}) / q$$

where (y) is the surface water depth; S_f is the friction slope and (q) is the flow rate per unit width; nevertheless the suitability of the Manning equation to represent shallow flow in surface irrigation is questioned (Maheshwari and McMahon, 1992).

Surface water profiles determined in the experimental level-basin at advance times t_1 ; t_2 ; t_3 ; t_4 when the tip of the water front was at x_1 = L/4; x_2 = L /2; x_3 = 3L/4 and x_4 = L; (L = basin length), has been used to evaluate the Kostiakov infiltration equation and the Manning's roughness coefficient through the application of the continuity principle (Radhey and Pandya, 1972; Harun-Ur-Rashid, 1990; Hume, 1993; Strelkoff *et al*., 1999).

3. Evaluation of Kostiakov infiltration equation

Neglecting evapotranspiration, the volume balance principle, during the advance phase of water in a level-basin, can be expressed mathematically as:

$$V = q \cdot t = S + I$$

where V is the volume of inflow per unit width of level basin for a specified time (t); (q) is the constant rate of inflow of irrigation water per unit width; (t) is the elapsed time since the irrigation event began; (S) is the volume of water on the ground surface per unit width (surface storage) at time (t) and (I) is the volume of water infiltrated into the soil per unit width during the time (t). In the analysis it is assumed that the infiltration characteristics of soil are uniform over the length of the test level basin.

The application of the method requires the knowledge of the relationship describing the advance of the water front in the basin as a function of time since irrigation started (advance function); a power function relationship was used (Elliot and Walker, 1982):

$$x = a \cdot t^{b}$$

where (x) is the advance distance from the field lateral at the upper end of the basin at time (t); (t) is the advance time to (x); (a) and (b) are empirical constants determined fitting experimental pairs of data with the least squares regression method. Also required is the relationship between the total volume of infiltration when the water front is at (x) and the correspondent advance time (total volume of infiltration function); the total volume of water infiltrated per unit width at selected values of the advance time was computed from the volume balance equation; the surface storage (S) was evaluated using the surface water profiles obtained from the measures of the depths of flowing water in points located down the length of the basin. We used a power function relationship:

$$I = c \cdot t^{d}$$

where (I) is the total volume of water infiltrated per unit width of the test basin at time (t); (t) is the advance time; (c) and (d) are empirical constants determined fitting the computed pairs of data with the last squares regression method.

The volume balance method was applied as follows to calculate the coefficients of the Kostiakov infiltration equation based on advance times measured in the field at: $x = L/4$; $x = L/2$; $x = 3L/4$; $x = L$.

The final advance time t_L (advance time for $x = L$, where L = basin length) was divided into five equal time intervals (Δt). Using the advance function we calculated the advance distance x_i for the advance time: $t_i = i \cdot \Delta t$ with ($i = 1,2, \ldots, 5$), and the incremental advance: $\Delta x_i = x_i - x_{i-1}$ during each time interval. By the total volume of infiltration function we calculated the total volume of water infiltrated (I_i) at time t_i.

During $t_i = i \cdot \Delta t$ water advances to point $x = x_i$; assuming: that the average height of infiltration in Δx_i is Z^*_1 ; that the average height of infiltration in $\Delta x_{(i-1)}$ is Z^*_2 , and so on; the average height of infiltration Z^*_i at time t_i in Δx_1 will be:

$$Z^*_i = (I_i - Z^*_1 \cdot \Delta x_i - Z^*_2 \cdot \Delta x_{(i-1)} - \ldots\ldots - Z^*_{(i-1)} \cdot \Delta x_2) / \Delta x_1$$

Applying the above equation to all five time intervals we calculated the average height of infiltration (Z^*_i) in Δx_1 at corresponding times (t_i) from the start of irrigation. By fitting to above calculated pairs of data the power form of the average height of infiltration equation with least squares regression method, we calculate:

$$Z^* = m \cdot T^{n}$$

The coefficients (u) and (v) of the Kostiakov infiltration equation were obtained from the relationships:

$$Z^* = Z/T = (1/T) \int_0^T (u\, T^{v})\, dT = (u / v+1)\, T^{v}$$

where:

$$(u / v+1) = m \; ; \quad v = n$$

4. Evaluation of Mannig's roughness coefficient

Referring to a trapezoidal cells (e. g. the cells marked: n_A, n_B, n_C in Figure 2) the Manning's roughness coefficient (n) can be expressed as:

$$n = [2 / (q_e + q_u)] \cdot [(y_{m,s} + y_{m,i} + y_{v,s} + y_{v,i}) / 4]^{5/3} \cdot [(y_{m,s} + y_{m,i}) - (y_{v,s} + y_{v,i}) / 2\Delta x]^{1/2}$$

where q_e is the unit flow rate entering the cell; q_u is the unit flow rate flowing out from the cell; $y_{m,s}$; $y_{m,i}$; $y_{v,s}$; $y_{v,i}$ are the surface water depths at the vertices of the trapezoidal cell; Δx is the cell length.

The unit flow rate q_u is calculated as:

$$q_u = q_e - q_s - q_z$$

q_s being the unit flow rate corresponding to the volume of water in the cell between water surface profiles at t_{i+1} and t_i :

$$q_s = [(y_{m,s} - y_{m,i}) + (y_{v,s} - y_{v,i})] \cdot (\Delta x / 2) \cdot (1 / \Delta t)$$

where Δx = L/4 and $\Delta t = t_{i+1} - t_i$;

q_z is the unit flow rate corresponding to the volume of water infiltrated in Δx during Δt :

$$q_z = [(Z_{t+1} - Z_t) + (Z_{(t+1)^*} - Z_{t^*})] \cdot (\Delta x / 2) \cdot (1 / \Delta t)$$

where Z_{t+1} ; Z_t ; $Z_{(t+1)^*}$; Z_{t^*} are the cumulated infiltration depths calculated with the previous Kostiakov infiltration equation for the infiltration opportunity times at left and right vertices of the cell.

5. Determination of the surface water profiles for hydraulic parameters evaluation

Surface water profiles to evaluate hydraulic parameters as previously reported, were determined during the irrigation season of the year 2003. The measurement of flow to obtain the inflow hydrograph was done with a full-width rectangular weir; upstream was constructed a control structure with a spillway to maintain a constant water level in the supply channel. Advance times were measured when water front arrived at: ¼ L ; ½ L ; ¾ L ; and L starting from the beginning of the diversion of water from the field channel at the upper end of the basin.

Water-depth measurements was taken at stations along the basin using gauges consisting of a steel tube 200 mm in diameter and 0.2 m high, with holes of 10 mm near the base; in the inner surface a steel scale with the zero at the soil surface is fixed. The gauges were placed at: (0.5 m); (¼ L – 10 m); (¼ L) ; (1/2 L –10 m); (½ L) ; (3/4 L – 10 m); (¾ L) ; (L –10 m); (L) from the distribution channel; depth gauge readings were taken by men. The water-depth at ten meters before the points of advance time measurements was recorded because near the advancing front the shape of the surface profile is highly non linear. In the basin were realized two parallel lines of probes at a distance of 1/3 of the basin width from longitudinal bunds; when the advance front arrived at a measurement point, levels were measured in the upstream probes.

III – Results and discussion

1. Determination of the number of waterings and corresponding water requirements

In the irrigation season 2005, applying irrigation when the mean matric potential in the root zone was about -35 kPa, we have carried out six waterings in the level-basin irrigated by intermittent submersion (Figure 1).

The seasonal irrigation water requirement was 739 mm . Values of flow rate, cutoff time and height of watering for each irrigation event operated in this year are reported in Table 1. Likewise during the irrigation season 2004 we have carried out six waterings applying irrigation when the mean matric potential in the root zone was about - 45 kPa; the seasonal irrigation water requirement was 692 mm .

In the two years the time interval between two successive waterings without consistent rainfall and in the period of maximum ETrice, was about 10 days.

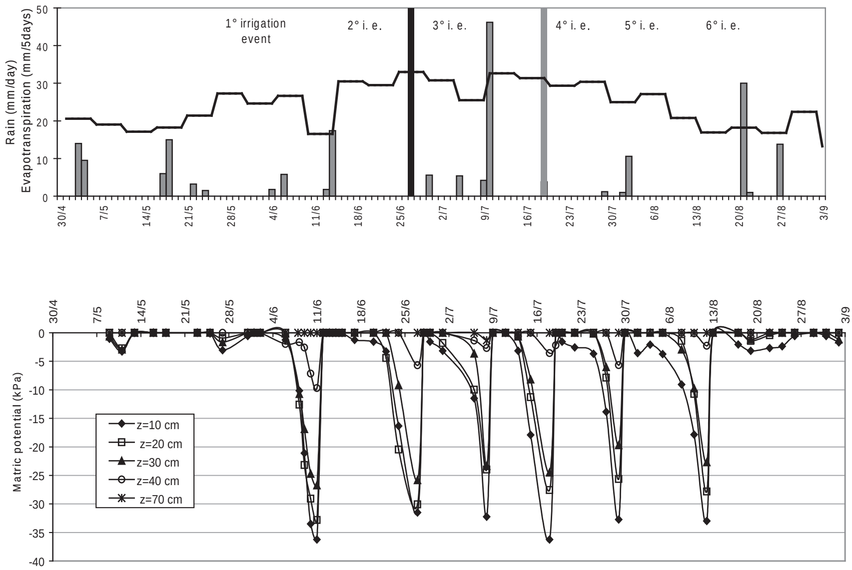

Figure 1. Depths fro m the soil surface of porous cup of the tensiometers (z) and corresponding values of the matric potential during the irrigation season 2005.

Table 1. Values of flow rate, cut-off time, height of watering (year 2005).

Date of the irrigation event	Average height of rice plants (m)	Irrigation flow rate ($m^3 \cdot s^{-1}$)	Experimental cutoff time (min)	Correspondent height of watering (mm)
11-06-05	0.10	0.094	118	119
27-06-05	0.25	0.091	122	119
08-07-05	0.50	0.096	110	114
19-07-05	0.60	0.094	115	116
30-07-05	0.60	0.092	130	129
13-08-05	0.75	0.093	142	142

For comparison, a water balance was applied to the basin irrigated with the continuous submersion method for successive periods of twenty days from the sowing date of the year 2005. The (PS) losses were directly determined in the field on the basis of the decrease of the surface ponded layer minus rice evapotraspiration and the volumes of submersion (operated after the three periods of about five days to promote striking of the roots and to apply some nitrogen fertilizers and pesticides) were calculated with the parameterized simulation model. The value of the seasonal irrigation water requirement for rice was calculated as 1800 mm; using the soil matric potential scheduling and the intermittent submersion a reduction at field scale of 60 % was realized. Rice yield at 14% moisture content was determined for the whole two basins, ranging to 7.3 Mg · ha^{-1} for the basin irrigated with the intermittent submersion, and to 7.9 Mg · ha^{-1} for the basin irrigated with continuous submersion.

2. Evaluation of the hydraulic parameters for the simulation of the watering process

In Figure 2 are reported, for example, the surface water profiles relatives to the watering of the day 25 – 06 – 2003, determined when the tip of the water was at a distance from the water inlet of x = 38 m; x =76 m; x = 114 m; x = 152 m; the correspondent advance times were: tad,38 = 30 min; tad,76 = 70 min; tad,114 = 125 min; tad,152 = 203 min .

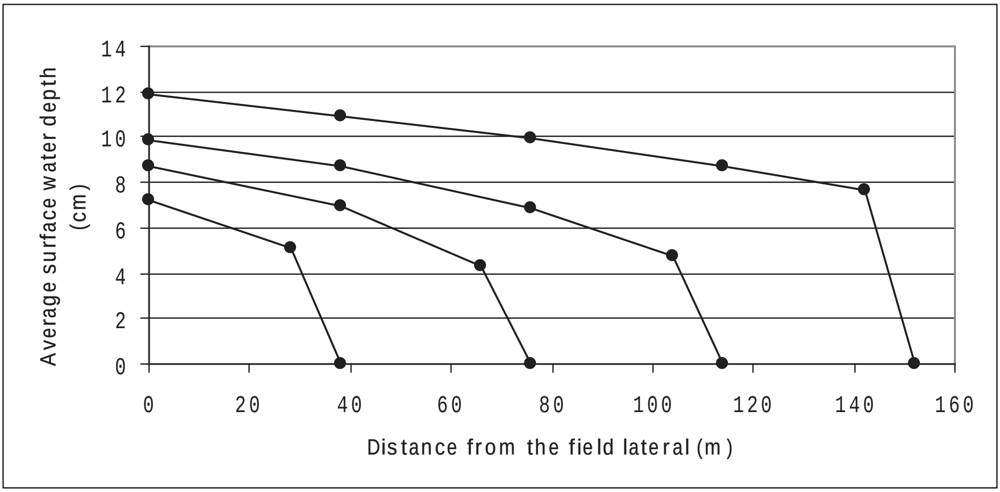

Figure 2. Water surface profiles determined in the experimental level-basin at different advance times for the irrigation event of the day 25-0 6-2003 (flow rate Q = 0.058 $m^3 \cdot s^{-1}$).

The examination of advance velocity during the watering did not highlight sudden variations, suggesting that the soil infiltration properties and the characteristic of the culture within the test basin were quite homogeneous as assumed for application of the volume balance method.

Applying the volume balance method to the three irrigation events monitored during the growing season of the year 2003 (for details refer to: Allavena, 2008) we obtained the averaged Kostiakov infiltration equation for the year 2003:

$$Z = 6.47\, T^{0.423}$$

In the above reported equations [F] is in [mm] and [T] in [min].

The computed infiltration equations generally involve cumulative infiltrated depths fairly elevated in the first twenty-thirty minutes, which follows a drastic reduction of the infiltration heights.

The Manning's roughness coefficient (n) estimate was done using the previously outlined method applied to the water surface profiles such as these shown in Figure 2.

The method was applied to each of the three cells of trapezium form marked n_A, n_B, n_C; these cells were chosen because the values of water depth at vertices has been measured directly in the field. The results of the calculations are presented in Table 4.

The mean value of Manning' s roughness coefficient is:

$$n = 0.19 \quad m^{-1/3} \cdot s$$

Recent determinations for crops such as rice, wheat, corn, cotton, irrigated on level-basin have given values of (n) around 0.1÷ 0.15 $m^{-1/3} \cdot s$ (Clemmens *et al.,* 1999; Fabiao *et al.,* 2003). The averaged Kostiakov infiltration equation and the mean value of the Manning's roughness coefficient calculated on the basis of the three watering monitored in the year 2003 were used to calculate the final advance time of the waterings effectuated in the year 2004 and 2005 with acceptable results, and then used for the computation of the final advance time of each level basin of a representative rice cultivated farm.

Table 2. Manning's roughness coefficients calculated on the basis of the water depth profiles determined in the field in the year 2003 (n_A, n_B, n_C = values calculated with reference to corresponding cells of Fig. 5).

Date of the irrigation event	Average height of the rice plants (m)	Irrigation flow rates ($m^3 \cdot s^{-1}$)	Manning's roughness coefficient ($m^{-1/3} \cdot s$)			Mean value ($m^{-1/3} \cdot s$)
			n_A	n_B	n_C	
24-05-03	0.15	0.049	0.177	0.176	0.250	0.201
07-06-03	0.30	0.083	0.160	0.181	0.202	0.181
25-06-03	0.60	0.058	0.198	0.202	0.200	0.200

3. Problems related to the application of W. S. T. at farm level

As concerning the problems related to the practical application at farm level of the (W.S.T.), we refer to the layout of a typical rice cultivated farm reported in Figure 3.

The farm, having a surface of about 50 ha, is irrigated with the traditional continuous submersion method. Water from the irrigation network reaches the head of a distribution channel running along the superior side of the unit and supplies it via an inlet; the surface of the farm is divided into diked rice fields with the bottom flat; the irrigation water flow from a level basin to another ("plot to plot" system) before arriving at the surface drainage canal. The irrigation stream is 100 ÷ 150 $l \cdot s^{-1}$ and canals are dimensioned for this flow. Today, level-basins are usually rectangular and may extend over several hectares; this is done in order to promote a regularly distribution of irrigation water, to allow the irrigation water has the same small height over the entire field, to promote farming techniques and mechanical operations, to reduce the amount of unproductive land represented by the dikes. The issues in question are reviewed below, together with some possible solutions.

First, the application of the intermittent submersion method in which the whole irrigation stream is delivered to a single level-basin does not permit the application of the "plot to plot" system; it is therefore necessary to change the irrigation distribution network to the basins by introducing new watering canals.

Secondly, the high number of waterings that need to be conducted during the irrigation season involves a substantial increase in the labor required for operating the irrigation of the farm. This may be reduced by: reducing the number of level-basins through the unification of the smaller ones and/or increasing the time interval between two successive irrigation events. To achieve the last goal: from the viewpoint of irrigation technique, it is possible to augment the height of submersion layer developed at the end of the watering and from an agronomic viewpoint the research must determine the minimum intervention threshold value of the matric potential in relation to sensitiveness of the rice culture, to the saturation deficit and to the specific agronomic techniques (manuring, weeding) adopted to obtain an acceptable production.

Thirdly, the calculation program SURDEV, with the introduction of the hydraulic parameters evaluated on the basis of the continuity equation and with reference to the case of cut off time equal to final advance time, was used to calculate for each basin of the farm, the cut-off time for the following values of the irrigation stream (Q) = 100; 150; 200; 300 $l \cdot s^{-1}$. Thereafter for each of the above values of the irrigation stream we calculated the total number of hours (O) necessary for irrigating all the basins of the farm, obtaining: for Q = 100 $l \cdot s^{-1}$, O = 155.2 h; for Q = 150 $l \cdot s^{-1}$, O = 104 h; for Q = 200 $l \cdot s^{-1}$, O = 80 h; for Q = 300 $l \cdot s^{-1}$, O = 56.8 h . The reported values must be increased of the total number of hours for the operations of waterings of the whole farm (e.g., 12 h); so, it was found that with the irrigation stream normally used (100 ÷ 150 $l \cdot s^{-1}$) it is not possible to irrigate the farm in the time interval of 10 ÷ 12 days previously identified: it is therefore necessary to use irrigation stream of 200 ÷ 300 $l \cdot s^{-1}$ and in consequence to resize the sections of the watering canals.

Fourthly it is appropriate to consider that so high irrigation streams directly runned in a single point of the level-basin can cause local erosion; it will be necessary to implement appropriate tournout structures to prevent erosion and possibly a head watering canal to allow a regular supply of the level-basins. In the case of more permeable soils the reduction of seasonal irrigation water requirement is more substantial (Allavena, 2004), but the problems associated with the transition to intermittent submersion are exacerbating.

Adopting (W.S.T.) on large scale in a territory where the widespread culture is rice irrigated with continuous submersion (e. g., the “Agro Vercellese” district) will have consequences for water use at larger spatial scale levels. Water lost from level-basins by percolation and seepage will enter the subsurface system through shallow water table and the surface system through drainage network; both the subsurface and surface systems can be exploited downstream by water reuse; less groundwater recharge may lead to a sensible drop in the groundwater table. This may reduce the possibilities of the re-employment of subsurface waters and can increase the percolation rates, offsetting the gains in water saving introduced at field level.

IV – Conclusions

From experimental data collected and from their elaboration, several conclusions and some suggestions for further studies can be drown:

i) to maintain in the root zone the required values of matric potential, a relatively elevated number of watering is necessary; for raising time interval between two successive irrigation events in order to reduce the amount of labor needed to carry out the waterings, from the viewpoint of (W.S.T.), it is possible to increase the height of the submersion layer (this height can be calculated using the parameterized model) and from an agronomic viewpoint the research must determine the minimum intervention threshold value of the matric potential in relation to sensitiveness of the rice culture to the saturation deficit and to the specific agronomic techniques (manuring, weeding) adopted to obtain an acceptable production;

ii) the evaluation of the advancing surface water profiles experimentally determined made it possible to adequately calculate, using the methods based on the continuity equation, the values of the hydraulic parameters required for the application of the user-friendly programs;

iii) the applicatory interest of (W.S.T.) at farm level must be valued in relation to: the reduction of the seasonal irrigation water requirements; the increase of the cost of labour; the problems connected with the irrigation management at farm level; the opportunity of the right-sizing of the fields and the irrigation network.

The values obtained in the experiments are crearly related to the case study examined; for their generalization it is necessary to extend the investigation to other hydropedological contexts.

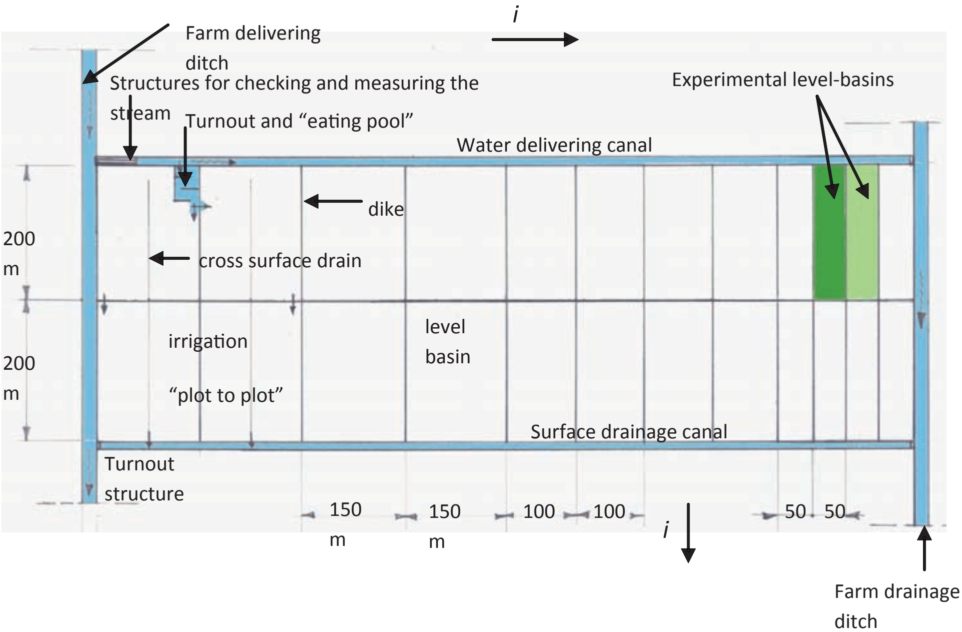

Figure 3. Schematic layout of a rice cultivated farm in north-western Po valley.

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Estimate of evapotranspiration using surface energy fluxes from Landsat TM

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Abstract. Daily evapotranspiration fluxes over the semi-arid Catania Plain area (Eastern Sicily, Italy) were evaluated using remotely sensed data from Landsat Thematic Mapper TM5 images. A one-source parameterization of the surface sensible heat flux exchange using satellite surface temperature has been used. The transfer of sensible and latent heat is described by aerodynamic resistance and surface resistance. Remote sensing-based assessments of crop water stress (CWSI) were made in order to identify local irrigation requirements. Evapotranspiration data and crop coefficient values obtained from the approach were compared with: (i) data from the semi-empirical approach "Kc reflectance-based", which integrates satellite data in the visible and NIR regions of the electromagnetic spectrum with ground-based measurements and (ii) surface energy flux measurements collected from a micrometeorological tower located in the experiment area.

Keywords. Evapotranspiration – Remote sensing – Surface energy balance – Water stress.

Estimation de l'évapotranspiration à partir des flux énergétiques superficiels du Landsat TM

Résumé. *Les flux journaliers de l'évapotranspiration dans la Plaine de Catania (Sicile de l'Est, Italie), à climat semi-aride, ont été évalués à l'aide des données de télédétection obtenues des images du Landsat Thematic Mapper TM5. La paramétrisation de l'échange des flux de chaleur sensible superficielle a été effectuée, utilisant la température superficielle mesurée par satellite. Le transfert de la chaleur sensible et latente est décrit par la résistance aérodynamique et superficielle. L'évaluation des données satellitaires de l'indice du stress hydrique de la culture « Crop Water Stress Index » (CWSI) a servi à identifier les besoins locaux en irrigation. Les données de l'évapotranspiration ont été confrontées avec : i) les données résultantes utilisant les coefficients culturaux calculés par l'approche semi-empirique basée sur la réflectance et ii) les mesures des flux de l'énergie de surface collectées sur une tour micrométéorologique située dans la zone d'expérimentation.*

Mots-clés. *Evapotranspiration – Télédétection – Bilan d'énergie de surface – Stress hydrique.*

I – Introduction

Generally, two main satellite-based approaches were applied over irrigated agricultural areas to estimate crop water needs in terms of evapotranspiration flux: (1) the reflectance-based crop coefficient method (D'Urso, 2001) and (2) the energy balance method (Bastiaansen *et al.*, 1998). In the reflectance-based crop coefficient method, spectral inputs in the red and near-infrared bands from ground-based radiometers, airborne sensors or satellite images are used to obtain vegetative indices related to the basal crop coefficient (Neale *et al.*, 1989). One of the main advantages of using crop coefficients is that they provide an underlying model for interpolation between satellite images over time. In the energy balance method, remotely sensed data in the thermal infrared spectrum are used to model different components of the energy balance equation, such as net radiation, soil heat flux, sensible heat flux and latent heat flux. The method is more complex to apply, requiring calibrated satellite imagery and the use of an atmospherically corrected thermal infrared band, which for most satellite instruments translates into lower spatial resolution. Modeling evapotranspiration on a large scale with heterogeneous surface conditions requires a great deal of simplification, while preserving the key surface elements which control energy balance. For example, in the absence of vegetation, the surface characteristics can be described by surface albedo, emissivity, roughness length, and soil moisture content. When vegetation is present, the surface parameterization becomes more complex because vegetation transpiration is affected by the morphological and physiological characteristics of vegetation. When surface temperature is measured by a satellite (or an aircraft), the complex surface status can be lumped together, the remotely-sensed surface temperature representing a spatially integrated thermal status of the surface (Zhang *et al.*, 1995). Based on these considerations, actual evapotranspiration from a heterogeneous surface can be conceptualized as a one-layer process from an average surface transferring sensible and latent heat. In the paper, a one-layer resistance model was applied to estimate evapotranspiration fluxes over a semi-arid agricultural area in Eastern Sicily (Italy). Remotely sensed data of spatially integrated surface characteristics were combined with ground-based agro-meteorological measurements. Satellite data was provided by the Landsat Thematic Mapper TM5 sensor during June-September 2007. The objectives of the study were (i) to compare satellite-based energy balance surface fluxes with micrometeorological data from a flux tower that could be used to scale ET over orange orchards; (ii) to apply a reflectance-based approach to derive relationships between Landsat-based vegetation indices and crop coefficients (K_c) and (iii) to recognize plant water stress by satellite-based estimates of the crop water stress index (CWSI).

II – Modeling approach

1. The surface energy balance approach

The complex relationships between surface temperature, vegetation features and energy flux have been analyzed by several authors (Monteith, 1991; Zhang *et al.*, 1995) and numerous studies have proposed the use of one-dimensional (1-D) models to describe radiation conduction and turbulent transport mechanisms which influence energy balance and surface temperature (Friedl, 2002) (Figure 1). Generally, all such models are based on energy conservation principles which dictate that net radiation R_N is balanced by the soil heat flux G, sensible heat flux (H) and latent heat flux (LE) at the surface

$$R_N = G + H + LE \quad (1)$$

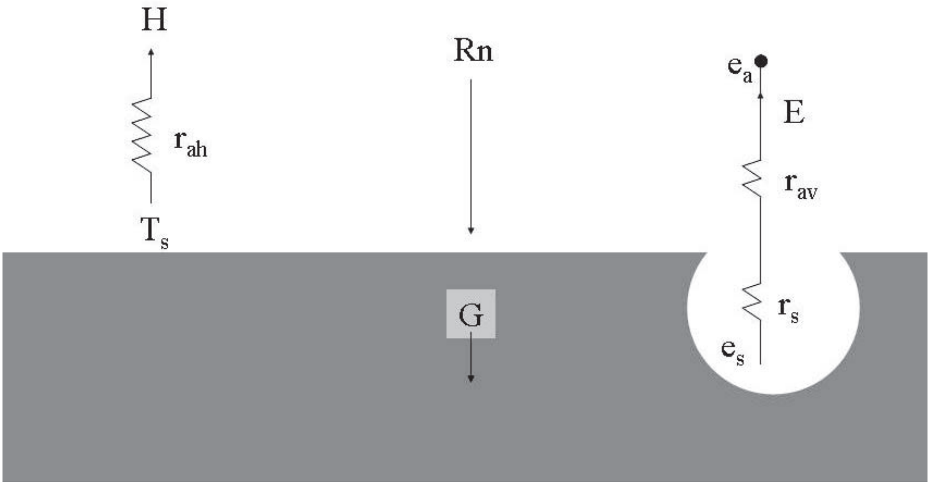

Figure 1. Schematic diagram of one-source thermal-based model for energy balance terms.

Generally, it is assumed that R_N may be easily computed, and G is parameterized in a straightforward fashion (as a simple proportion of R_N). The two remaining terms, H and LE, are turbulent flux quantities and are the most difficult to estimate. In the study, net radiation was estimated as:

$$R_N = R_S(1-r) + \varepsilon_a \sigma T_a^4 - \varepsilon_S \sigma T_S^4 \tag{2}$$

where R_s is the incoming short wave radiation (Wm^{-2}), σ is the Stefan-Boltzman constant, ε is emissivity and T is the temperature (K) with the subscripts 'a' and 's' for air and surface respectively; the surface albedo (r) is computed as in Menenti (1984). Soil heat flux was calculated by assuming that the ratio G/R_N is related to the fractional vegetation cover (Boegh *et al.*, 2002)

$$(G/R_N) = f_v (G/R_N)_{veg} + (1-f_v)\cdot(G/R_N)_{soil} \tag{3}$$

with $(G/R_N)_{veg}$=0.05, $(G/RN)_{soil}$=0.315, and f_v estimated from LAI. The terms of Eq. (1) are modelled using a 1-D flux-gradient expression based on a convection analogue to Ohm's law

$$H = \rho C_p \frac{T_S - T_a}{r_{ah}} \tag{4}$$

where ρ is air density (Kg m^{-3}), C_p is the specific heat of air at a constant pressure (J kg^{-1} K^{-1}) and r_{ah} is the aerodynamic resistance for sensible heat (s m^{-1}). Eq. 4 is a one-layer bulk transfer equation based on the assumption that the radiometric temperature measured by a thermal infrared radiometer is identical to the aerodynamic temperature. In fact, in the case of full canopy cover, there is near-equivalence between these two temperatures and it is found that estimates of evapotraspiration using radiometric temperatures are in good agreement with observed values (Zhang *et al.*, 1995). In the study surface temperature T_s was derived from band 6 TIR of Landsat TM5 using the model developed by Sobrino *et al.* (2004)

$$T_S = \frac{T_B}{1+\left(\lambda \cdot T_B / r\right)\ln(\varepsilon)} \tag{5}$$

where λ is the wavelength of emitted radiance, r=h·c·σ equaling 1.438 10^{-2} mK, where h is Planck's constant, c the velocity of light and σ the Boltzman constant; emissivity ε was estimated through (Sobrino *et al.*, 2001)

$$\varepsilon = f_V \varepsilon_V + (1-f_V)\cdot \varepsilon_S \tag{6}$$

where ε_v and ε_s denote emissivity of vegetation (0.985) and soil (0.960). The fractional vegetation cover fv is related to leaf area index (LAI), $f_V = 1 - e^{-0.5\cdot LAI}$ (Norman *et al.*, 1995). By applying the inverse of Plank's radiation equation, spectral radiance in the thermal band was converted to brightness temperature T_B

$$T_B = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda + 1}\right)} \tag{7}$$

where K_1 and K_2 are calibration constants defined for Landsat 5 TM sensor (Chander and Markham, 2003): L_λ is the pixel value as radiance (W m^{-2} sr^{-1} μm^{-1}). The inverse of Planck's law, used to derive T_s, can be interpreted as a correction of the atmospheric and emissivity effects on the data measured by the sensor (Sobrino *et al.*, 2004). Latent heat transfer is expressed as

$$LE = \frac{\rho C_p}{\gamma} \frac{e_s(T_s) - e_a}{r_{av} + r_s} \quad (8)$$

where γ is the psychometric constant, $e_s(T_s)$ is the saturated vapour pressure at the surface temperature (kPa), e_a is the vapour pressure at the reference height (kPa), r_{av} is the physiological resistance (s m^{-1}) to moisture transport at the surface. The surface resistance r_s (s m^{-1}) to vapour transfer exerts strong control on the partitioning of available energy (R_N-G) between H and LE. The aerodynamic resistance r_{ah} of eq. 4 was calculated on the basis of the Monin-Obukhov surface layer similarity theory (Brutsaert, 1982)

$$r_{ah} = \frac{\left[\ln\left(\frac{z-d}{z_{oh}}\right) - \Psi_{sh}\right] \times \left[\ln\left(\frac{z-d}{z_{om}}\right) - \Psi_{sm}\right]}{k^2 \cdot u} \quad (9)$$

where z_{oh} e z_{om} are roughness lengths for sensible heat and for momentum (m), respectively; $z_{om}=0.13 \cdot h_c$ (with h_c the mean height of the crop in meters); $z_{oh}=0.1 \cdot z_{om}$ (Chodhury *et al.*, 1987); $d=0.66 \cdot h_c$ is the zero-plane displacement height (m); Ψ_{sh} e Ψ_{sm} are the stability correction functions for momentum and sensible heat; k is von Karman's constant; u (m s^{-1}) is the wind speed at level z (10 meters). The stability correction functions were determined with the Businger-Dyer formulations (Sugita and Brutsaert, 1990) for unstable conditions (Businger, 1988). Surface resistance was determined by substituting eqs. (4) and (8) into eq. (1), without making a distinction between soil evaporation and plant transpiration

$$r_s = \frac{(e_s(T_s) - e_a)}{\gamma\left[(R_N - G)/\rho C_p - (T_s - T_a)/r_{ah}\right]} r_{av} \quad (10)$$

in which the physiological resistance r_{av} was considered equal to r_{ah} (Zhang *et al.*, 1995). The extrapolation of LE into daily estimates, which most interests agricultural water management, was based on evaporative fraction (EF) (Bastiaanssen, 1995)

$$EF = \frac{LE}{R_n - G} \quad (11)$$

Daily evapotranspiration ET_{24} (mm d^{-1}) values were then calculated by the following equation

$$ET_{24} = EF \frac{R_{N,24}}{L} \quad (12)$$

where L (MJ m^{-2} mm^{-1}) is the latent heat of vaporization and $R_{N,24}$ is the daily net radiation measured by a micrometeorological flux tower.

2. The crop water stress index

The CWSI was computed as (Idso *et al.*, 1981)

$$CWSI = \frac{(T_s - T_a) - (T_s - T_a)_{lower}}{(T_s - T_a)_{upper} - (T_s - T_a)_{lower}} \quad (13)$$

where $(T_s\text{-}T_a)$ is the measurement, $(T_s\text{-}T_a)_{lower}$ is the theoretical minimum value for $(T_s\text{-}T_a)$ and $(T_s\text{-}T_a)_{upper}$ is the theoretical maximum value for $(T_s\text{-}T_a)$. Jackson *et al.* (1988), using a steady state energy balance of a crop canopy, developed a theoretical CSWI where

$$T_s - T_a = \frac{r_{ah}(R_n - G)}{\rho C_p} \times \frac{\gamma(1 + r_s/r_{ah})}{\Delta + \gamma(1 + r_s/r_{ah})} - \frac{VPD}{\Delta + \gamma(1 + r_s/r_{ah})} \quad (14)$$

in which VPD is the vapor pressure deficit (kPa); the other variables of Eq. 14 are satellite-based estimates and were introduced in the previous paragraph. The maximum theoretical value for (T_s-T_a) was evaluated assuming r_s approaches infinity and the minimum theoretical value for (T_s-T_a) was defined by setting r_s equal to zero in Eq. 14.

3. The K_c reflectance-based approach

The reflectance-based crop coefficient method (D'Urso, 2001) consists of the direct application of a theoretical ET equation to define K_c (Doorenbos and Pruitt, 1977; Allen *et al.*, 1998)

$$K_c = \frac{ET_c}{ET_0} \quad (15)$$

While reference evapotranspiration (ET_0) accounts for variations in weather and offers a measure of the 'evaporative' demand of the atmosphere, crop coefficients (K_c) account for the difference between reference (ET_0) and potential (ET_c) crop evapotranspiration. Crop coefficient values (K_c) were expressed as follows (Stanghellini *et al.*, 1990):

$$K_c = \sum_{i=0}^{4} C_i LAI^i \quad \text{with} \quad C_i = a_i + b_i r \qquad i = 0,.1,2,.3,.4 \quad (16)$$

where the coefficients a and b of the polynomial equation were determined as functions of climatic data (net radiation R_N, air temperature T, air humidity RH, and wind speed u) measured by the automatic stations located in the study-area, and canopy properties (LAI, albedo r) determined using remote sensed data.

III – Application of the proposed approaches

1. Experimental site and micrometeorological energy fluxes

The Catania Plain area is the largest agricultural district in Sicily (Italy), with an area of about 50,000 ha. It is characterized by citrus orchards for more than 90% of the irrigated area (about 18,000 ha). The climate is semi-arid and the annual potential ET exceeds by about 30% the mean annual rainfall (about 500 mm) (Consoli *et al.*, 2006). During June-September 2007, surface energy fluxes, meteorological data and radiometric temperatures were measured by a micrometeorological flux tower located in a experimental orchard with a fetch of more than 200 m in all directions. Net radiation R_N was measured using a net radiometer mounted above the orchard canopy. Soil heat flux density G was measured using soil heat flux plates and soil averaging temperature sensors. High frequency temperature data was collected at 4 Hz using two 76.2 µm diameter fine-wire thermocouples mounted at 0.5 meters above the canopy top. When plotted against time the temperature traces show ramp-like characteristics, which are used to estimate heat fluxes using a conservation of energy equation (Gao *et al.* 1989; Paw U *et al.* 1995). The temperature data was analyzed to determine the mean ramp amplitude (a) and the inverse ramp frequency (d+s) using a structure function (Van Atta, 1977) and time lags of 0.25 and 0.50 seconds for each of the two thermocouples. Sensible heat flux was calculated, using the Surface Renewal technique, as

$$H = \alpha \rho C_p \left(\frac{a}{d+s} \right) z \quad (17)$$

Factor α is a correction term for unequal heating below the sensors. In combination, half-hourly data on H, R_N and G were used to calculate latent heat flux density (LE) as the residual of the energy balance equation. Soil moisture was monitored continuously using the Time Domain Reflectrometry (TDR) technique in different fields within the experimental area, at soil depths of 15, 30 and 60 cm. Leaf area index (LAI) values were measured with a Licor LAI-2000 digital analyzer at regular intervals during the satellite acquisitions.

2. Processing satellite-based data

The satellite data consisted of Landsat Thematic Mapper TM5 images acquired on June 14th, July 22nd, August 17th and September 8th 2007. The images were geometrically rectified to a UTM projection system (Jensen, 1986). The reflectance values in the VIS/NIR region were calculated from the images, or at the top of atmosphere or by applying a correction for the atmospheric effects. Thermal band 6 needs no calibration, since the derived surface temperature data accords well with the surface temperature data from the infrared thermometers mounted at a height of 4 m above ground and pointing 45° towards the surface. Landsat TM pixels encompassing the tower site were used to establish relationships between flux tower ET and the satellite data for energy flux and vegetation indices.

IV – Results and discussion

1. Comparing the model estimates of energy flux with micrometeorological measurements

Sensible heat flux (H) from the micrometeorological tower was between zero and 3.4 MJ m^{-2} d^{-1} with an average of 2.5 MJ m^{-2} d^{-1}. Latent heat flux (LE) average was 11.6 MJ $m^{-2}d^{-1}$, varying between 4.2 and 16.2 MJ $m^{-2}d^{-1}$. Net radiation (R_N) values were between a maximum of 18.9 and a minimum of 2.7 MJ m^{-2} d^{-1}, with an average of 13.3 MJ $m^{-2}d^{-1}$. On a daily basis the G term was generally close to zero. Micrometeorological tower fluxes during the satellite overpass (10:00 a.m. local time) were plotted in Figure 2. In general, agreement between the modeled and observed fluxes was good. The observed mean energy fluxes were respectively 521.5, 42.5, 31.7 and 447.3 W m^{-2} for R_N, G, H and LE flux densities. The energy fluxes obtained by processing TM bands during the satellite acquisition dates had a relatively narrow spatial distribution (maximum time variation of about 24%) at the tower site, with average values of 570, 40.4, 45.6 and 408.3 W m^{-2} respectively for R_N, G, H and LE flux densities.

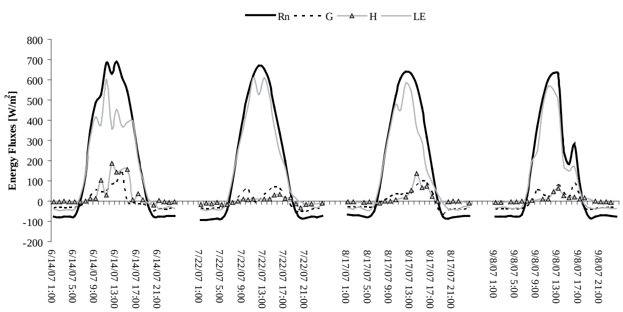

Figure 2. Hourly energy flux at the micrometeorological station.

The spatial variability of surface energy fluxes from Landsat scenes of about 850 mixed pixels was depicted in Figure 3. The study revealed that the amount of energy available for physical and biological processes over the crop (R_N) varied from a maximum of 638 to a minimum of 361 W m^{-2}. The main variation of LE occurred due to variations of R_s, T_s, LAI and soil moisture. The LE variation was from 127to 564 W m^{-2}. The G range was 28.8-48.5 W m^{-2}, with a maximum spatial variation of 10%. H flux from the surface to the atmosphere varied from 74.7 to 17.5 W m^{-2}, with a mean of 45.6 W m^{-2} and spatial variation of 24%. Daily satellite ET_{24} (mm d^{-1}) values strongly (R^2=0.8) correlated with NDVI and LAI. ET correlated more weakly (R^2=0.37) with R_N across the period, showing that the plants were not radiation-limited most of the time. Hence, ET was mainly determined by the amount of green vegetation or functioning vegetation in the agricultural field which is typical for semi-arid landscapes (Nagler *et al.*, 2007). The calculated ET_{24} values compare fairly well to the tower flux estimates of ET using Surface Renewal technique.

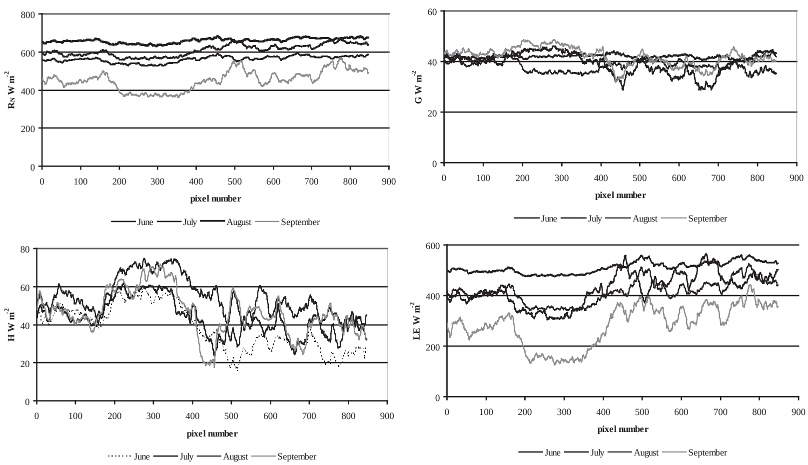

Figure 3. Spatial distribution of remote sensed energy fluxes.

Mean ET_{24} values across June-September 2007 were 4.98 and 5.08 mm d^{-1}, respectively, from the satellite energy balance approach and from tower flux measurements with a temporal variability of about 15%. In Figure 4, the satellite-based crop coefficients (K_c) were compared with tower flux K_c and the results of the reflectance-based approach. K_c during June-September 2007 were in the ranges 0.75-0.92, 0.76-0.89 and 0.5-1.14 from respectively, satellite energy balance, reflectance-based approach and tower flux data. Maximum variability occurred with K_c tower flux data whereas the satellite-based K_c estimates were more uniform. On average (about 0.8), K_c were slightly higher than those reported in the widely used FAO publications for orchards with about 70% ground cover. Linear correlations express the increase in K_c from the reflectance-based approach with NDVI (Rouse, 1974). The linear trend presents a determination coefficients (R^2) higher than 0.90, with minimal scatter around the regression lines. Figure 5 depicts the surface resistance (r_s) as functions of the fractional vegetation cover (fv). In the Figure, r_s tends to change logarithmically with vegetation density variation. Dense vegetation (fv=0.88; r_s 145-160 s m^{-1}) has been found for stressed canopies in semi-arid areas (Soegaard, 1999). High surface resistances reflect dry soil surfaces and, generally, correspond to low soil moisture content at the irrigated site. This was confirmed by soil water content at selected control sites reaching minimums of 27% when the T_s-T_a difference was maximum. As expected, both T_s-T_a and r_s are lower when LAI (and fv) is high. Generally, a rather small range of r_{ah} values represents each fv.

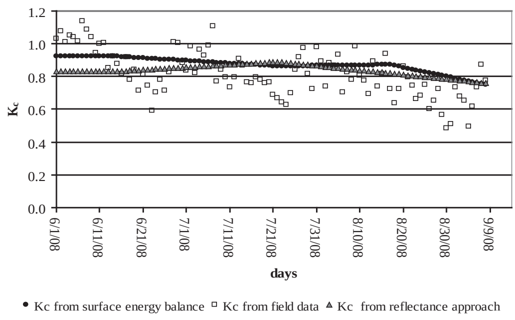

Figure 4. K_c from field data compared with K_c from the satellite approach.

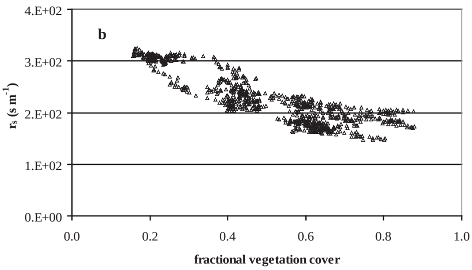

Figure 5. Satellite-based surface resistance (rs) as a function of fv.

In order to examine satellite observations for plant water stress, the theoretical upper and lower limits for T_s-T_a are plotted against fv, together with the T_s-T_a observations in Fig. 6a. The T_s-T_a range is fairly small for a given fv which represents homogeneous surface conditions. Generally, observed T_s-T_a exceeded the theoretical lower limit, symbolizing the increase of surface control on LE probably caused by a reduction in the soil water availability and increased plant water stress (Fig. 6b). The study revealed a mean CWSI from satellite data of 0.6 with a low variation (9%) for each value of fv. Energy flux data from the micrometeorological tower determined a mean CWSI of 0.67 during satellite acquisitions. Previous studies on CWSI for many crops in different parts of the world highlighted that $CWSI_s$ higher than 0.6 indicate soil moisture depletion requiring irrigation.

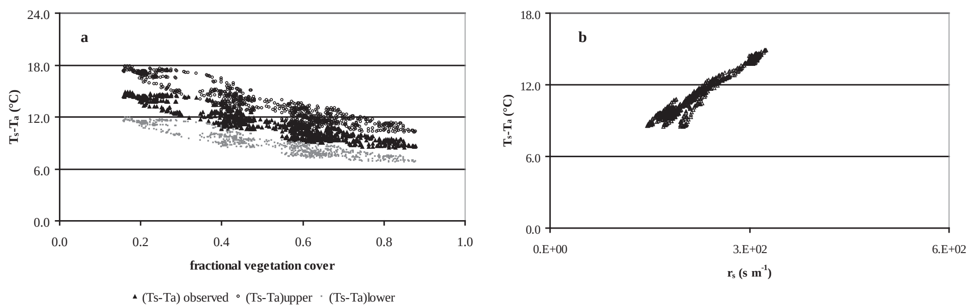

Figure 6. (a) (T_s-T_a) as a function of f_v; (b) (T_s and T_a) as a function of r_s (b).

V – Conclusion

In this study, a one-layer resistance model was used for the spatial estimation of evapotranspiration rates, vegetation indices and features using Landsat TM and local agro-meteorological data. The model formulates the transfer of sensible and latent heat fluxes between the surface and atmosphere using the concept of aerodynamic resistance and surface resistance. Maps of atmospheric resistance, surface resistance, surface energy flux, evapotranspiration rates and CWSI were produced. The satellite-based estimates of ET rates compare well with the micrometeorological tower-based ET flux. However, the method should be tested thoroughly using an extended spatially distributed dataset. Reflectance-based crop coefficient values K_c had about the same range of variation of data on K_c derived by the one-layer energy balance method, with a mean of 0.8, slightly higher than the widely used FAO 56 data. The satellite-based estimate of surface resistance r_s tended to be lowest for dense vegetation (fv≈0.88) and highest for bare soil or canopies with intermediate vegetation cover. The surface resistance approaches 145-160 s m^{-1} for dense vegetation highlighting water stressed canopy conditions. A tendency to quite steady atmospheric resistance is partially due to the effect of fully vegetated pixels and the low spatial resolution of surface temperature T_s. The results of the satellite surface energy balance were further used to compute the upper and lower theoretical limits of T_s-T_a for each image's pixels. In particular, the dependency of T_s-T_a lower and upper limits on the fractional vegetation cover and surface resistance was demonstrated. Derived and measured $CWSI_s$ were in good accordance and had a mean of about 0.6 which indicates a certain soil moisture depletion. Finally, estimating ET within wide spatial scales by one-layer models and integrating ground-based meteorological data with satellite observations is a useful tool for quantifying and controlling water consumption especially in areas of limited water supply.

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Field examination of the hydrological behaviour of a typical vertisol in a cropped area

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Abstract. The site was selected in a cropped area on a typical vertisol, fairly uniform in depth, down to about 2.5 m. It was difficult to install anchored rods and piezometers at different depths (0.2-0.3-0.4-0.5-1-1.5-2 m and 2.5 m for piezometers).

Soil moisture was monitored for a certain time by drilling the ground and soil samples were dried in an oven.

Cases studied were: (A) a period of dry months with severe drought (10.4 mm in 132 days);(B) a second period with exceptionally uniform precipitation (about 3.5 mm/day during 2 months). These seasonal conditions permitted the following observations: for (A) the swelling of the soil in the lower extreme cannot be strictly compared to Philip's (1969) concept of a free expansion of the water ponding on soil due to the overburdening of different conditions; for (B) the expected tendency to begin a stationary water flux depends strongly on the water regime in the previous period. In a dry period, the water accumulates in the deepest piezometers, being fed by water from the upper source at a progressively increasing rate of water rise. The regime of stable water flux is therefore delayed. The hydraulic conductivity changes in different soil layers according to the water content.

Keywords. Piezometers – Swelling soil – Vertisol – Water table.

Observations de terrain du comportement hydrologique d'un vertisol dans un champ cultivé

Résumé. *Les sols gonflables sont caracterisés par des phénomènes de distribution des efforts entre la phase solide et liquide. L'ouvrage aborde plus particulièrement les difficultés de l'implantation verticale des tiges de métal et des piézomètres à différentes profondeurs (0,2-0,3-0,4-0,5-1-1,5-2 m pour les tiges de métal et 2,5 m pour les piézomètres) dans un vertisol. L'humidité a été quantifiée pendant deux ans en perforant le terrain et, la mesure directe de la teneur en eau des échantillons a été faite par séchage.*

On a examiné deux situations météorologiques différentes. (A) une saison caracterisée par une période sèche (10,4 mm de pluie en 132 jours) et (B) une saison humide avec une pluviosité exceptionnellement uniforme (3,5 mm de pluie par jour pendant deux mois). Ces conditions climatiques ont permis les observations suivantes : dans la phase sèche (A) le gonflement des argiles est nettement différent par rapport au schéma de libre expansion proposé par Philip (1969), à cause de la présence d'une nappe phréatique d'environ 2.5 m de profondeur ; dans la phase humide (B) le flux des eaux n'est pas stationnaire et dépend avant tout du régime hydraulique au début de la période des pluies. Dans ce contexte, en période sèche l'eau s'accumule dans les piézomètres les plus profonds, alimentés par l'eau dérivant de la source supérieure à un taux croissant de rémontée. Ce phénomène se produit lentement initialement, et s'accélère avec de l'infiltration de l'eau. La conductivité hydraulique change dans les différentes couches du sol en fonction de leur humidité.

Mots-clés. *Piézomètres – Sol gonflable – Vertisol – Nappe phréatique.*

I – Introduction

The contribution of the soil swelling process to the distribution of the total mechanical stress between solid and liquid phase according to a load factor is considered under field conditions. The field observation of a swelling soil rich in clay (vertisol) is not common due to certain organizational issues such as finding an agricultural area with this kind of pedology (Talsma, 1974) or the possibility to install equipment required by the research and then verify if there is an underground water accumulation. Under these conditions researchers have found difficulties in monitoring the water balance in the profile, which would be useful to better understand and rationalize the cropping system in the area.

For these reasons, notwithstanding some organizational drawbacks, it was decided to install some instruments to start a first examination of the hydrology of these swelling soil systems in a cropped area.

II – Material and methods

The experimental area considered is situated on the Emilia-Romagna plain. The soil is a vertisol classified as "Ustic endoaquerts fine mixed mesic", series Risaia del Duca (Benciolini, 1996), Eutric Vertisols according to the FAO classification. The initial profile of the considered soil surface is given in Fig.1. The soil is very deep, apparently fairly uniform, and rich in slickenside formation at least in the upper part of the profile. It was considered to have had deep underground water ("suolo di valle") in the past. The usual tillage depth is about 0.35 m. The rainfall regime was recorded by a weather station 100 m far from the experimental site. During the rainy season (winter) the surface soil becomes sticky and access to the experimental area is difficult; in the dry season (summer) visible cracks remained on the soil surface for a depth of 0.2-0.4 m.

Figure 1. Distance from the left side of the field.

The succession of crops grown in the area were wheat, maize, barley, and sugarbeet, never irrigated during the experimental period (Fig. 2). The main characteristics of the tilled soil (0.35 m) are: 72.8 % clay (< 0.002 mm) and 26.8 % silt (0.02-0.002 mm); moisture θ_g at wilting point, 1500 kPa, 27.8 % and at field capacity, 33 kPa, 38.6 %; clay minerals are smectite 31 %, illite 54 %, kaolinite 9 % and chlorite 6 %; lime 18 %, pH (1:5) 8.2.

The plot was 41 m long x 1.5 m wide and accommodated two randomized replications of anchored rods and piezometers (Fig. 3 a,b,c) along the top line of a field transversally shaped as a near elliptical surface (mean transversal height difference 0.4 m between borders of lateral drainage ditches).

The bores for the installation of the rods and piezometers were drilled on October 17 of 2001 by the firm GEOTEA of Bologna. At the same time the cores of the deepest bores (approximately 2.5 m from soil surface) of both replications (a, b) were taken for sections roughly corresponding to 0.50 m. The soil parameters given by the firm suggest that the bottom of the considered soil profile should be quite near to a lower water table (somewhat deeper than 2.5 m) and that the soil properties change adequately. Immediately after cutting, the sections from the cores were put in impermeable cases and then taken to the DiSTA laboratory. Each section was divided into two parts and on each of them textural analysis (pipette method) and gravimetric soil moisture determinations were performed.

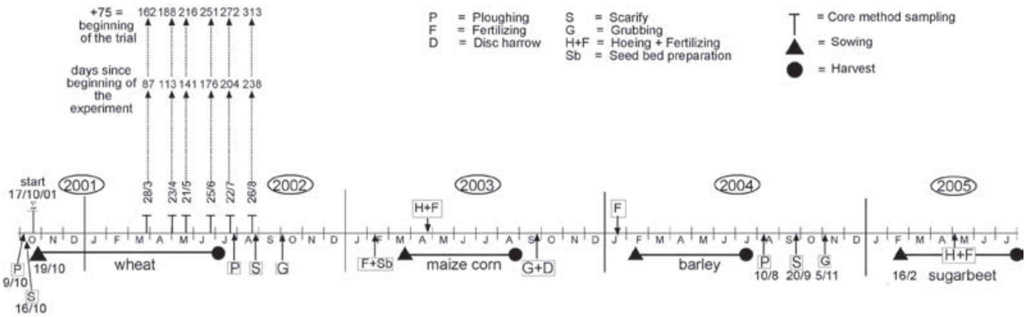


Figure 2. Distribution of crops and cultural operations during the experimental period.

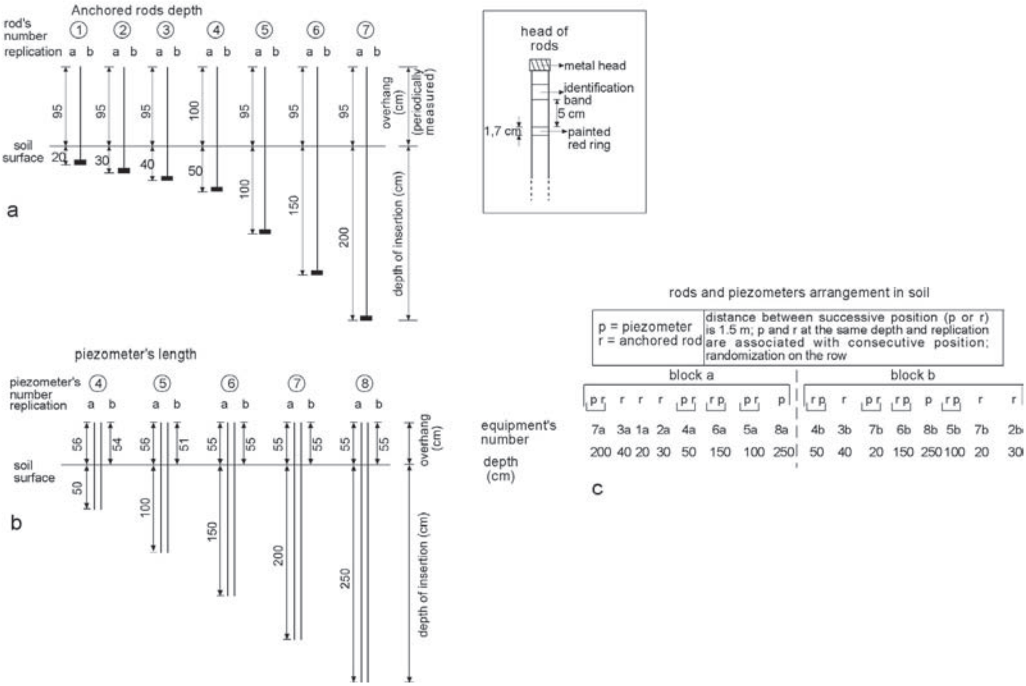


Figure 3. Depths of the rods (a), piezometers (b) and their randomization (c).

A representation of the clay fraction (less than 0.002 mm) variation along the profile of both replications, as well as their mean, is shown in Fig. 4. The analogous variation of moisture content as θ_g (as $m^3\ m^{-3}$ of dry soil) is shown in Fig. 5. Examination of fig. 4 shows that the mean clay content (%) remains fairly uniform along the soil profile and shows relative minimum (52.5-57.5%) at a depth of 1.53 m and maximum (70.0% - 71.5%) near the soil surface at about 0.13 m depth. The role of both moisture and clay content on the dry bulk density can be only analysed taking the approximated dry bulk density as a dependent variable and θ_g and clay as independent variables for a multiple regression. The data from both replications show a high correlation (R^2= 0.99) with the dominant effect of the moisture θ_g (Fig. 6) and a lower effect of the clay content in this range.

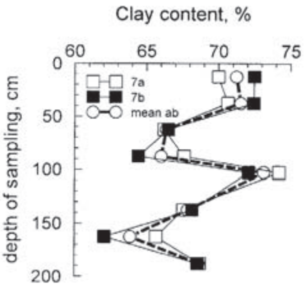


Figure 4. Clay content function of depth.

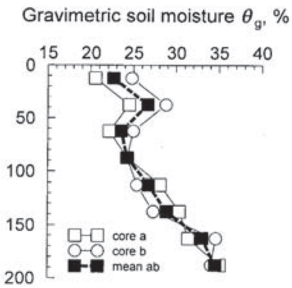


Figure 5. Water content in the soil profile.

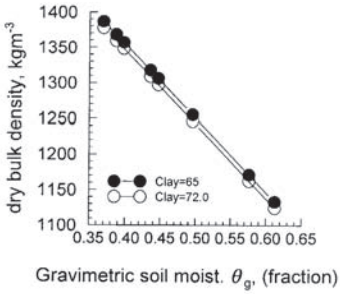


Figure 6. Gravimetric moisture function of depth.

Under the conditions of this experiment a deeper underground water table was suspected for which the anchoring system suited to a rigid soil (as Talsma and Van der Lelij, 1976) was inadequate; it was therefore decided to fix the a metal disc (0.08 m diameter and 0.02 m thick) to the lower end of the rods. The distances of the rods from the soil surface were: 0.2-0.3-0.4-0.5-1.0-1.5-2.0 m.

The piezometers consisted of plastic tubes (0.08 m diam.) extending out of the soil surface 0.5 m, with the lower end of the piezometers at the following depths: 0.5-1.0-1.5-2.0-2.5 m.

1. Moisture monitoring

For the evaluation of the moisture along the soil profile and its change throughout the trial, fifteen profiles were investigated during the wheat and maize growing season from 27/11/2001 to 6/11/2003. Each profile was perforated at a lateral distance not less than 1.5 m from the alignment of the rods and piezometers (2 or 4 replications monthly) using an auger (5.5 cm diam.) and taking samples at selected depth intervals. The soil water content of the samples was determined gravimetrically in an oven at 105 C°.

A first precaution was that in order not to disturb the successive observations all auger holes were perforated under the nearby wheat or maize plants. Otherwise the moisture determinations could have been vitiated due to the uptake of water from the crop plants to meet the evapotranspiration and any rainfall in the upper layer.

The second, more general risk was that a compression effect by the auger could squeeze out part of the soil water content from the soil sample. It was considered that assuming no residual air content when the soil saturation was reached, the water content (θ_g, fraction) of a sample could only be valid if there was in the soil before sampling:

$$\theta_g \le \rho_l \left(\rho_b^{-1} - \rho_s^{-1}\right) \quad (1)$$

where ρ_l, ρ_s are respectively the mass per unit volume (kg m^{-3}) for water and solids and ρ_b is the dry bulk density. This limit is wide in the present case, where the maximum θ_g found in the lower soil levels is about 0.59 and the corresponding ρ_b is 1149 or less for a wetter soil.

The analysis of variance of the data from both replications was performed according to the classical design of randomized blocks.

III – Results

2. Moisture variation

Fig. 7 shows the tendency of the moisture to increase when moving downwards. From the evaluation at intermediate times there was for all depths a constant deviation from a linear regression line. Given the apparent correspondence at certain times and depths it seems that there must be some reasons to explain the higher moisture at about 1.80 m compared to the values at local 2.00 m. This rather surprising behaviour is not confirmed by the clay and moisture variation as in Fig. 4 and Fig. 5. As described in Fig. 7 (b and c), these anomalies appeared mainly when the determinations of moisture were extended to 5 different depths.

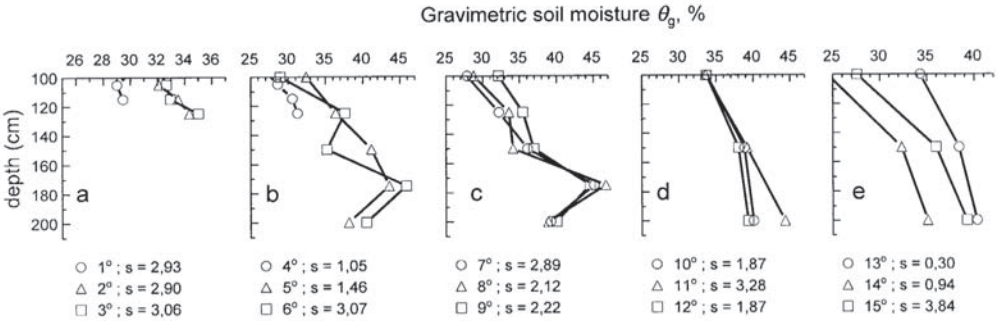


Figure 7. Gravimetric soil moisture at different depth and time.

2. Displacements of rods

Fig. 8a demonstrates that the alignment of the rods is still usually evident and seems to suggest that the process did not appreciably change along the transept. If we analyse in detail the change in time (Fig. 8b) of the top soil (about 1 m), it is evident that the curvature is upward; on the contrary the curvature is not so for the lower layers at about 2 m.

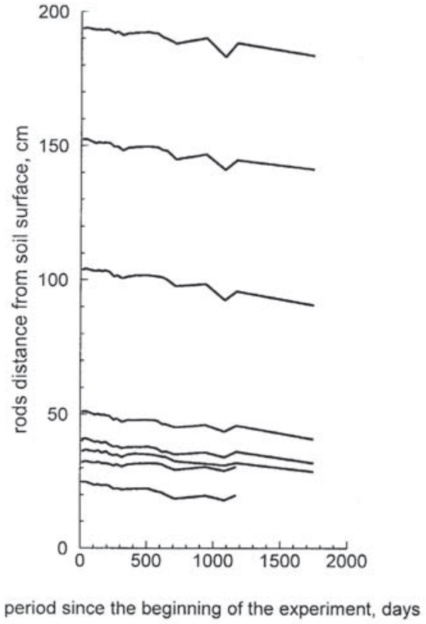


Figure 8a. Variation of the rods height.

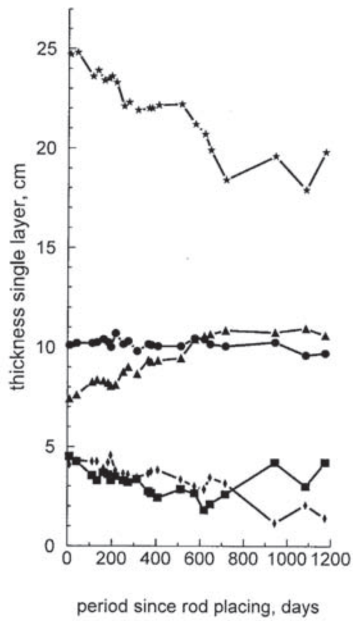


Figure 8b. Differences between layers in the first period.

3. Piezometers examination

The data recorded for each piezometer, after averaging between two replications, are synthesized in Fig. 9. A discontinuous perched water table is evident inside the upper 0-0.50 m layer. It includes 4 episodes with high water levels in the piezometer readings. Their water table only exceptionally reaches the surface soil (possible ponding) in the 2^{nd} and 4^{th} episode. In the 2^{nd} episode a connection with the lower aquifer occurred. The piezometers measure the "submersion potential" at the point reached by the lower opening of the tube; this potential includes

$$\varphi = P + z \tag{2}$$

where Φ is the submersion potential (in m), *P* is the hydraulic pressure (in m) at that point, and ***z*** is the gravitational component (in m). It is interesting to note that an upper piezometer often starts before the lower piezometers and reaches its basis, which demonstrates that the water is flowing from above. The graphs of the lower piezometers are often more skewed. In most cases the level of water in the lower piezometers does not reach the level of the water in the upper piezometers (there is a difference of submersion potential) showing a potential gradient promoting the descent of the water. The excursion of the submersion potential is mostly greater, the deeper the piezometers are inserted. These considerations prompted us to evaluate the speed of water rise in the piezometers (differences of values at consecutive registration (d*h*) divided by the difference in time of registration (d*t*); this means the derivative d*h*/d*t*). Fig. 10 shows that this speed increases appreciably with the piezometer depth. In the deepest piezometers the graph is continuous and shows a periodicity similar to that of the rainfall. The greater speed in the fluctuation of the lower piezometers suggest a higher hydraulic conductivity in these layers. This could be explained by higher θ_v content (less probable for some reduced porosity). The first explanation seems more acceptable and implies that the moisture θ_g increases downwards along the profile (Fig. 5).

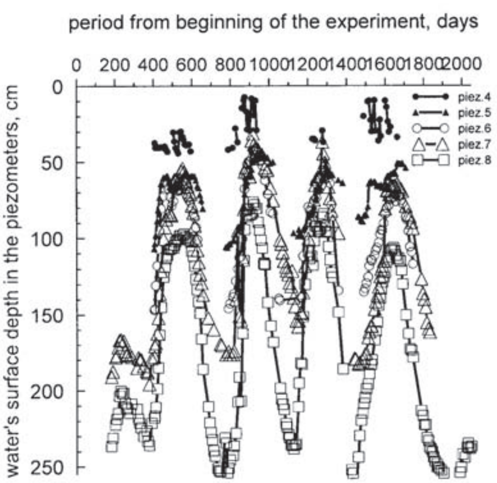


Figure 9. Superimposed water level in the piezometers at different depth.

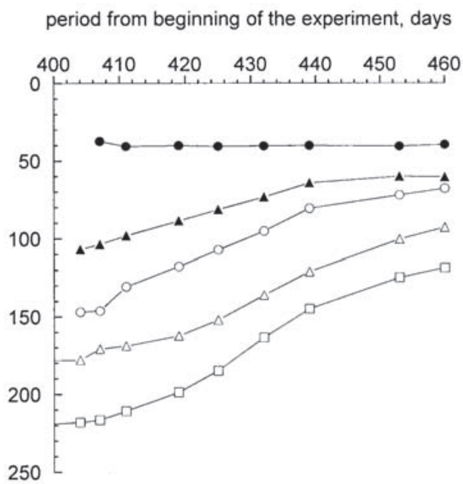


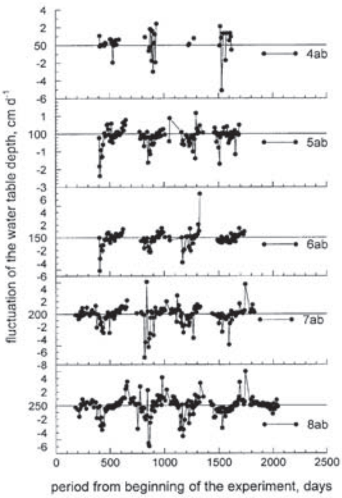
Figure 10. Variation of water levels in the piezometers (phase B).

IV – Discussion

It is notable that the variability of the pressure in the piezometers is minimum in the more superficial piezometers and greater for the deeper layers at 2.5 m (Fig. 11).

The empirical observations clearly show how complex are the processes involved in the practical conditions mostly dominated by the meteorological fluctuations (Fig. 12). Among the experimental times two occasional meteorological periods were found to promote interesting discussion. Period A, in which an initial prolonged time of severe drought occurred from the beginning of the observations (17 October 2001; 10.4 mm in 132 days) and period B characterized by a daily rainfall of 3.5 mm.

In the first rainless period the soil system apparently moved gradually towards a near static water condition. In effect it is well known (Childs 1969) that for given constant potential evaporation in the air (I_p), the effective loss of evaporation from a water table (W.T.) under the surface of a uniform soil decreases with increasing depth of the W.T., though more with coarser soils. This means that during the conditions for model A the water in the soil profile should tend gradually to approach a static equilibrium, though not rigorously so, as recognised by Talsma *et al.* (1974). These latter authors define "apparently stable conditions", such as those taken at single traits of this static model (Fig. 12). When analysing the first period A, a simplification of the model is useful assuming the texture and the fine structure to be vertically uniform. This hypothesis is assumed valid down to depth 0.35 m previously analysed (Cavazza *et al.*, 2006). At the lower boundary of the model a fixed W.T. level is to a depth of 2.5 m (the end of the deepest piezometers). This can represent a W.T. connected to a wide area. Assuming that Fig. 12 represents the state of equilibrium expected, starting from the lower boundary one expects to find a swollen soil and a somewhat reduced solid constant. If the W.T. increases the soil water content should increase due to the possible entering of water from interconnected W.T. but there is a reduction owing to the manifestation of the overburden component of water in this soil that reduces upwards. When waterlogging exists, there are conditions of continuity up to the water-air surface boundary so that the soil material can freely expand up to its swelling capacity (including colloidal suspension; Fig. 12); in the present model, on the contrary, the soil swelling is limited by the local Ω component.



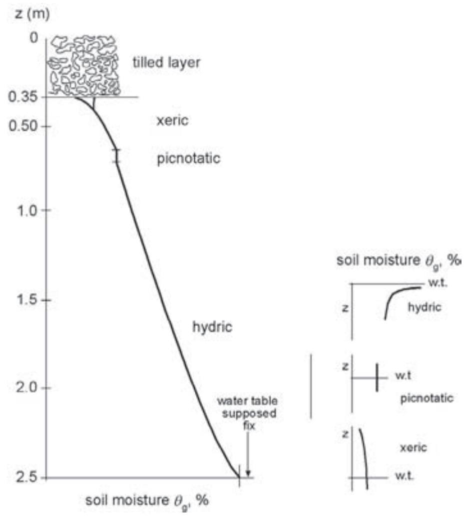


Figure 11. Fluctuation of water in piezometers. **Figure 12. Diagram of the water potential in a soil with water table.**

The equilibrium conditions for the total water potential Φ in the case of model A were therefore:

$$\Phi = z + \psi + \Omega \tag{3}$$

where z is the gravitational potential (≥ 0) measured from the W.T.; ψ is the matric potential (< 0) corrected by the height (i.e. as given by common techniques); Ω is the overburden potential (indicated by Talsma, 1974, as apparent steady flow):

$$\Omega = \alpha \int_{z}^{0} g \rho_{bw} \mathrm{d}z, \tag{4}$$

where α is the fraction of the mechanical load (the integral part of the equation) being α = 0 for dry soil and 1 for saturated soil; under the integral g is the gravity constant (9.81 m s^{-2}) and ρ_{bw} is the wet bulk density which is a function of the distance along the path from z to the 0 m depth.

According to equation 3, z increases with increasing distance from the W.T. and consequently Ω > 0 reduces; Ψ < 0 also decreases so that θ_g (kg kg^{-1}) also decreases (see Fig. 12). This reduction of Ψ corresponding to an increase of z from the W.T. changes the water profile which according to Philip (1969) shifts from the hydric to the picnotatic and then to a xeric profile (see insert in Fig. 12). These profile changes are expected to occur in the higher part of the model. When the xeric profile is reached the solid particles at a certain moisture can be subject to a *stretching* (as evidenced by Chertkof, 2005) so that with further decrease of θ_g under the tillage layer cracks can form in the soil with much more complex physics. The whole water and solid content are slightly different from that of Smiles(2000), notwithstanding Talsma's (1974) caution.

In the second period B it happened that daily rainfall was fairly constant (mean 3.5 mm/day) and this suggested the possibility of a gradual increase of the water flux capacity of the soil. This implies a shift of the soil entry through the surface towards a final stationary water flux. These manifestations are expected to vary greatly with the water feeding intensity at the soil surface. An extremely low water accumulation and W.T. rise at the end of the surface feeding makes the column profile not saturated. A maximum flux through the soil column is expected on the contrary when all pores are completely saturated along the profile and the real stationary condition can be realized only through a fairly short water path before dispersion.

When the W.T. rises or the piezometers indicate that a certain level of water air boundary is formed the total water potential Φ (known as "subsidence potential") is more simpler expressed as:

$$\Phi = z + P \qquad (5)$$

where *P* is now the hydraulic pressure and ***z*** the W.T. of the level reached by the piezometers. Under this surface there is not the matric potential (water-air interaction), nor an overburden water potential. This simplifies the examination of equilibrium between different piezometers.

V – Conclusive considerations

As a whole it is evident that the hydrology of this soil classified as typical vertisol can be better understood as a soil comprised of two hydrological sources: meteorological fluctuations and that artificially created by underground water sources. This strictly depends on the meteorological variability and the cropping use of the soil and the basic underground water table which might have very variable conditions. The upper soil layer including the tilled layer and part of the lower layers is more or less affected by the development of the root rhizosphere (about 1 m) and often has somewhat stronger competition so that the water from above is more widely retained, creating an almost suspended water layer. Along most of the lower layers down to the basic water table, the water is held in a quasi-equilibrium to the basic water level. This water moves less freely according to the meteorological regime and follows the superimposed water change.

Irrigation should take these facts into account (which are not often simple to examine). The possibility to observe two particular situations have shown that there were hydrological laws responsible for most of the apparent irregularities between these lower water tables.

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Analysis of the reservoirs operation in on-demand irrigation systems

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Abstract. Operation of a daily compensation reservoir in on-demand irrigation systems depends mainly on the geometric characteristics (depth and reservoir surface area), the downstream demand and the upstream supply. This paper presents a stochastic methodology based on real coded genetic algorithms aiming at generating the optimal supply hydrograph able to satisfy the network demand and taking into account the volume of the storage reservoir. An executable computer program was developed on C++ language. The model was applied and tested on one reservoir of the *Sinistra Ofanto* irrigation scheme (Italy) facing the risk of emptying during peak periods. Results demonstrated that it is possible to find solutions overcoming this risk where two theoretical alternatives were proposed based on the results of the simulations.

Keywords. Reservoir's operation – On-demand irrigation system – Genetic algorithm.

Analyse du fonctionnement d'un réservoir dans les systèmes d'irrigation à la demande

Résumé. *Le fonctionnement d'un réservoir de régulation journalière dans les systèmes d'irrigation à la demande dépend principalement de ses caractéristiques géométriques (profondeur et surface d'occupation), de l'offre et de la demande en eau. Ce papier présente une méthode stochastique basée sur le principe des algorithmes génétiques pour la détermination de l'hydrographe d'alimentation du réservoir afin de satisfaire la demande en eau du réseau. Pour atteindre cet objectif, un fichier exécutable a été développé sur C++. Le modèle a été appliqué et testé sur un réservoir du périmètre irrigué de la Sinistra Ofanto (Italie) qui présente un risque de vidange durant les périodes de pointe. Deux alternatives, qui ont prouvé leur efficacité, on été proposées pour résoudre le problème.*

Mots-clés. *Fonctionnement du réservoir – Système d'irrigation à la demande – Algorithme génétique.*

I – Introduction

The optimal balance between inflow and outflow at a given compensation reservoir in on demand irrigation system is a crucial issue for ensuring good system's operation.

Severe climatic conditions, high crop water requirements (changes in crop pattern and/or growth stage) and farmers' behavior are inter-correlated components and may induce risk of emptying the reservoir especially during peak periods. When such a condition is verified, air entering into the pressurized network may cause unsteady flow and consequently damages the pipes. To prevent such a problem, managers are often induced to modify the on-demand delivery schedule into arranged demand by rotating part of the network alternatively for few days. Such a modification causes all the farmers to irrigate simultaneously when their sector receives water. As a result, this practice does not necessarily provide for water saving but, in certain conditions, it can even increase farmers' withdrawals (Lamaddalena *et al.,* 1995). It is thus important to make diagnostic analysis for the reservoir's operation and review the water balance between inflow and outflow at the reservoir level.

The developed methodology is based on a stochastic approach using the genetic algorithms. In fact, the Genetic Algorithm approach is successfully used for the identification of the optimal solution in many hydraulic problems especially in the design of water distribution systems (Shin and Park, 2000; Tolson *et al.,* 2004; Nouiri *et al.,* 2005; Reca and Martinez, 2006; Elferchichi, 2007). For basic understanding and full description of the genetic algorithms approach, it is possible to refer to Goldberg (1989), Dréo *et al.,* (2003).

To reach the above-said objective, a weighting objective function, including violations of the admissible reservoir water levels (maximum, minimum and target reservoir water level) was proposed and an executable computer program was developed.

The approach was applied to the reservoir (R.1) of the district number 4 in the *Sinistra Ofanto* irrigation scheme (Italy).

II – Modeling approach

This work aims to verify if the supply system {maximum inflow discharge and reservoir storage capacity} is able to satisfy the downstream demand of a given reservoir (R). The hydraulic variables of the model are reported in Figure 1.

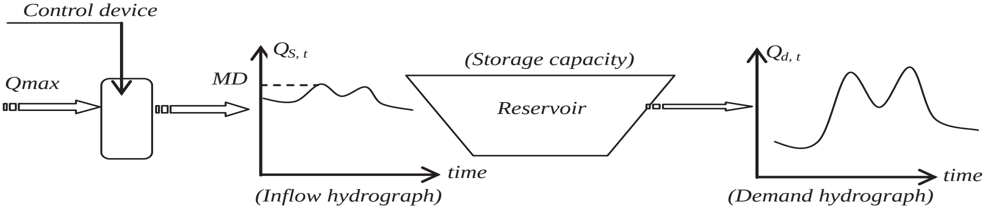

Figure 1. The hydraulic variables of the model.

Where: Q_{max} is the maximum discharge allocated to the reservoir (from design and/or current data) and MD is a fraction of Q_{max}, which represents the maximum value of the inflow hydrograph that guarantees the reservoir's regulation. MD is always less than or equal to Q_{max}.

1. Mathematical formulations

A. The objective function

The adequate inflow hydrograph is achieved by minimizing the violation of a fixed minimum level (H_{min}), a fixed maximum level (H_{max}), and a fixed target level (HT) into the reservoir.

Minimizing such a violation corresponds to maximizing the relative functions as written below:

$$F_1 = \frac{1}{1 + MV(H_{max})}$$

$$F_2 = \frac{1}{1 + MV(H_{min})}$$

$$F_3 = \frac{1}{1 + V(HT)}$$

Where $MV(H_{max})$ is the maximum violation of a fixed H_{max}; $MV(H_{min})$ is the maximum violation of a fixed H_{min}, and V(HT) is the maximum violation of a fixed HT. Violations of the admissible water levels in the reservoir are:

$$V(H_{max}) = h(t) - H_{max} \qquad \text{if} \qquad h(t) \geq H_{max}$$

$$V(H_{min}) = H_{min} - h(t) \qquad \text{if} \qquad h(t) \leq H_{min}$$

$$V(HT) = | HT - h(t) | \qquad \text{for} \qquad t = T$$

Where $V(H_{max})$ is the violation of the maximum water level; $V(H_{min})$ is the violation of the minimum water level and V(HT) is the violation of the target water level.

The following objective function "F" was used for solving the problem:

$$\text{Maximize } F = W_1F_1 + W_2F_2 + W_3F_3$$

W_1, W_2 and W_3 being the weighting coefficients, whose sum is equal to 1.

Based on the maximization of this objective function, the output result is a supply hydrograph characterized by a maximum simulated discharge (MD).

B. Boundary conditions

The reservoir water balance is modeled as follow:

$$h(t+\Delta t) = h(t) + \frac{[Q_s(t+\Delta t) - Q_d(t+\Delta t)]*\Delta t}{S}$$

where Δt is the time step; h (t) is the water level at time ; h $(t+\Delta t)$ water level at time $t+\Delta t$; Q_s $(t+\Delta t)$ is the inflow discharge at time $(t+\Delta t)$; Q_d $(t+\Delta t)$ is the demand discharge at time $(t+\Delta t)$and S is the average reservoir surface area, assumed as

$$S = \frac{storage \quad capacity}{reservoir \quad depth}$$

Boundary conditions for such an optimization problem are:

$$h(t=0) = Ho$$
$$h(t=T) = HT$$
$$H_{\min} \leq h(t) \leq H_{\max}$$

Where H_o is the initial water level; HT is the water level after a certain period of operation T, called target water level; H_{max} is the maximum reservoir water level; H_{min} is the minimum reservoir water level

The main objective is to keep the reservoir water level between the maximum and the minimum value.

2. The Genetic Algorithm approach

The Genetic Algorithm, whose name recalls the strong operational similarity with the biological behavior of living beings (Marseguerra and Zio, 2000), was formally introduced in the United States in 1975 by John Holland at the University of Michigan. It is a stochastic optimization search method that belongs to the soft computing technologies. Genetic algorithm is a particular class of evolutionary algorithms, categorized as global search heuristics. It can be applied to many complex problems that are difficult to solve using traditional techniques such as linear and non-linear programming or methods based on gradient calculations (Goldberg, 1989; Hrstka and Kucerova, 2004; Savic and Walters, 1997).

Given the extensive literature existing on the theory of the Genetic Algorithm, only few basic concepts are reported in this paper.

The possible solution of the problem is defined as a chromosome. This is subdivided into genes. A genetic algorithm starts with an initial population of random generated chromosomes with respect to the problem constraints. Then, new populations are generated and evaluated through iterative, random and probabilistic mechanisms ruled by the four fundamental operators of parent selection, crossover, replacement and mutation (Marseguerra and Zio, 2000). The iterative procedure is shown in Figure 2.

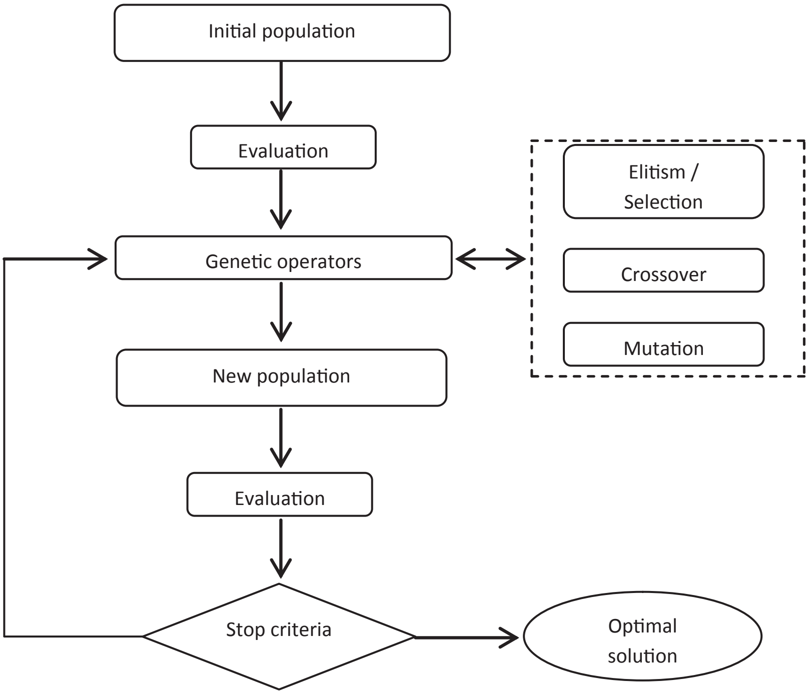

Figure 2. Principle of the Genetic Algorithms.

By using the genetic algorithm approach, the objective function is translated into a positive fitness function that measures the suitability of a chromosome and its performance to satisfy the objective of the problem to be optimized.

In this work, a real coded genetic algorithm was used. The structure of the solution for the investigated hydraulic problem is a sequence of real values of inflow discharges. Therefore, the solution represents the hourly supply hydrograph that should guarantee the optimal reservoir operation. Each value of the inflow discharge is called gene. Thus:

Chromosome: Qs (1), Qs (2),…, Qs (i),…, Qs (T/Δt): Inflow discharges

Gene: Qs (i)

Each gene is a set of equal flows during the interval Δt. For example, by considering a simulation for one day with a time step of 6 hours, the solution (supply hydrograph) over 24 hours is:

$$\{Qs(1), Qs(1), Qs(1), Qs(1), Qs(1), Qs(1), Qs(2), Qs(2), Qs(2), Qs(2), Qs(2), Qs(2), Qs(3), Qs(3), Qs(3), Qs(3), Qs(3), Qs(3), Qs(4), Qs(4), Qs(4), Qs(4), Qs(4), Qs(4)\}$$

The initial population of chromosomes (supply hydrographs) was randomly generated under the constraints of non negative values and the maximum simulated inflow discharge (MD). Each chromosome is evaluated on the basis of the value of the fitness function.

III – The case study

The reservoir (R.1) of the Sinistra Ofanto irrigation scheme (Italy) was studied. It has the following characteristics: H_{min} = 0.5 m; H_{max} = 4 m; H_o = 4 m; HF = 4 m; V = 28000 m3. The maximum allocated discharge Q_{max} (from the design) is equal to 790 ls-1.

The reservoir faces the risk of being often empty during peak periods. Consequently, managers are often induced to modify the on-demand delivery schedule into arranged demand by rotating part of the network alternatively for few days. Such a modification causes all the farmers to irrigate simultaneously when their sector receives water. As a result, this practice does not necessarily provide for water saving but, in certain conditions, it can even increase farmers' withdrawals (Lamaddalena *et al.*, 1995).

The objective was to identify an adequate inflow hydrograph that satisfies the farmers' demand and avoids emptying the reservoirs, without changing the on-demand delivery schedule. The model was tested with the 10-day peak period data collected during the year 1999, which can be considered as a typical one.

IV – Results and discussion

1. Actual situation of the reservoir R.1

Results of the above described case study are presented in figures 3 and 4. Figure 3 shows that there is no flexibility in the supply hydrograph. In fact, the reservoir is using its maximum allocated discharge (Q_{max}) starting from the second day. Nevertheless, the reservoir presents violations of the minimum admissible water level (MV(H_{min}) = 0.182 m) by the end of the sixth day, as shown in figure 4.

As a result, the supply system is not able to ensure a good operation of the distribution network starting from Tc and, consequently, managers are induced to modify the on-demand delivery schedule into arranged demand.

Two alternatives are discussed hereafter as proposals to solve the problem without modifying the on-demand delivery schedule.

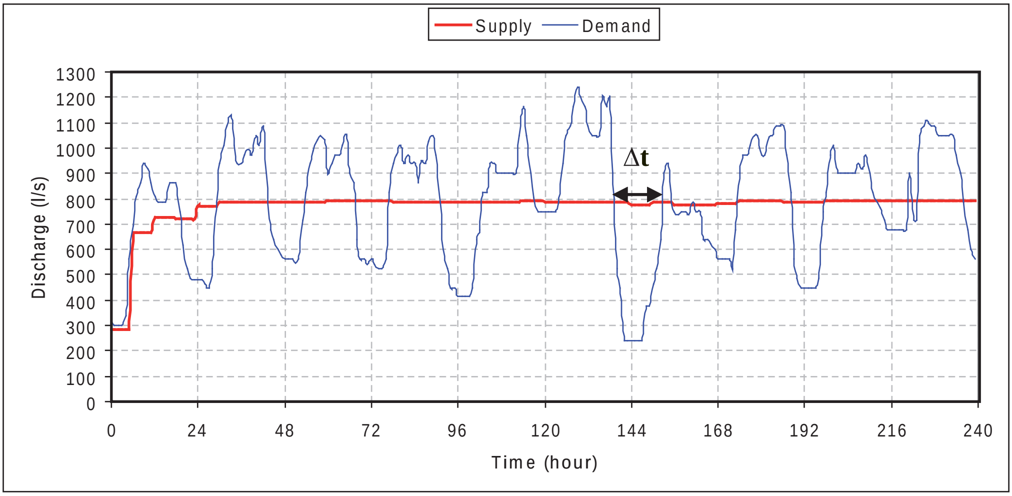

Figure 3. Supply hydrograph with respect to the recorded demand hydrograph for the 10-day peak period (the real case).

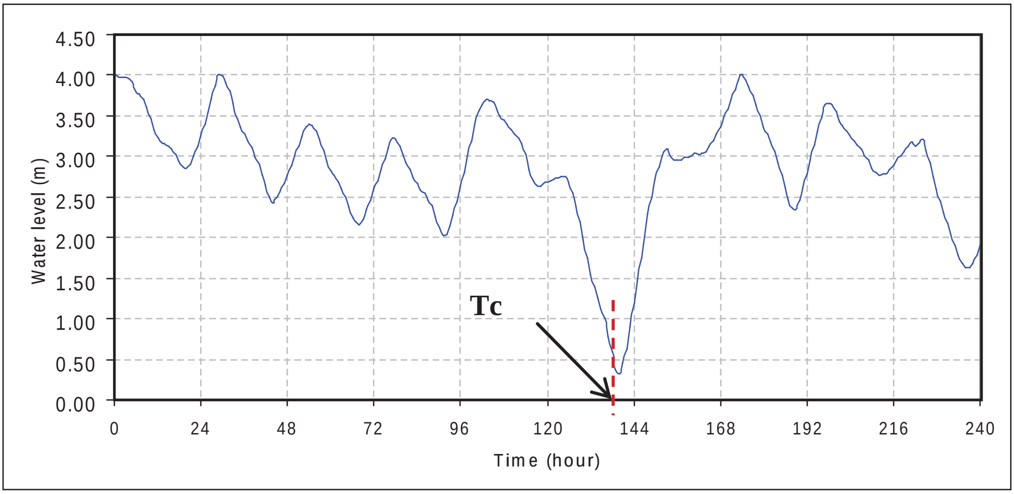

Figure 4. Reservoir water level with respect to the recorded demand hydrograph during the 10-day peak period (the real case).

2. First alternative: changing the maximum inflow discharge

The period where the risk of emptying of the reservoir occurs is represented by Δt = 15 hours in figure 3. Therefore, ΔQ calculated by the following equation should be added to the maximum allocated discharge (Q_{max}) in order to avoid emptying of the reservoir:

$\Delta Q\ (ls^{-1}) = MV(H_{min})^{*}\ S * 1000 / (\Delta t * 3600)$

Then: $\Delta Q = (0.182 * 7000 * 1000) / (15 * 3600) = 23.6\ ls^{-1} \approx 24\ ls^{-1}$

Therefore, the maximum allocated discharge should be 814 ls^{-1} instead of 790 ls^{-1}.

The simulation with the new maximum allocated discharge is presented in figures 5 and 6.

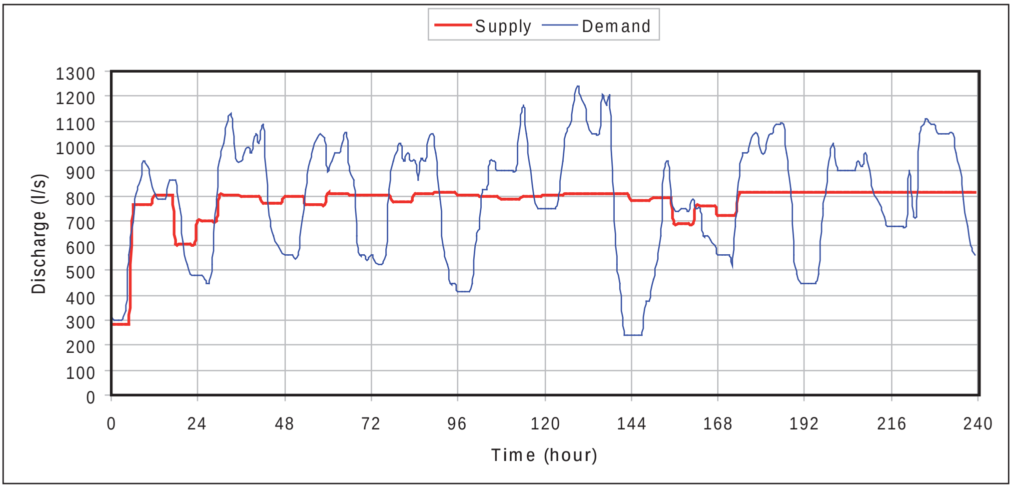

Figure 5. Supply hydrograph with respect to the recorded demand hydrograph for the 10-day peak period (first alternative).

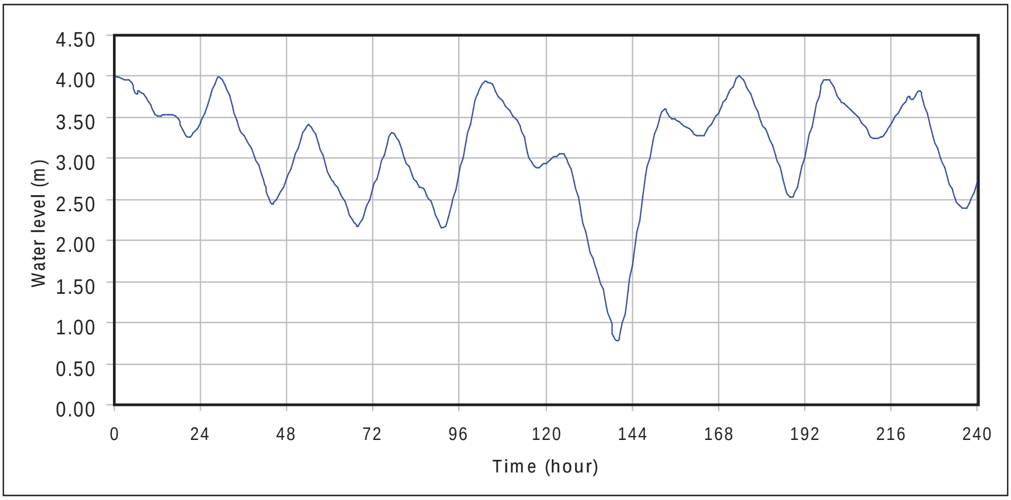

Figure 6. Reservoir water level with respect to the recorded demand hydrograph during the 10-day peak period (first alternative).

From figure 5, it can be observed more flexibility given to the supply hydrograph. No violations of the minimum and maximum admissible water levels are observed (Fig.6).

3. Second alternative: changing the storage capacity of the reservoir by increasing the maximum admissible reservoir water level

In this alternative the maximum admissible reservoir water level is H'_{max} = 4.182 m instead of H_{max} = 4 m.

Therefore, the new characteristics of the reservoir are:

- a storage capacity (SC) = 29274 m^3
- an initial water level (H_o) = 4.182 m
- a maximum admissible water level (H_{max}) = 4.182 m
- a target water level HT = 4.182 m

The simulation with these new input data shows that the flexibility of the supply hydrograph (Fig. 7) is similar to the one of figure 3. The risk of emptying of the reservoir is not observed (Fig.8).

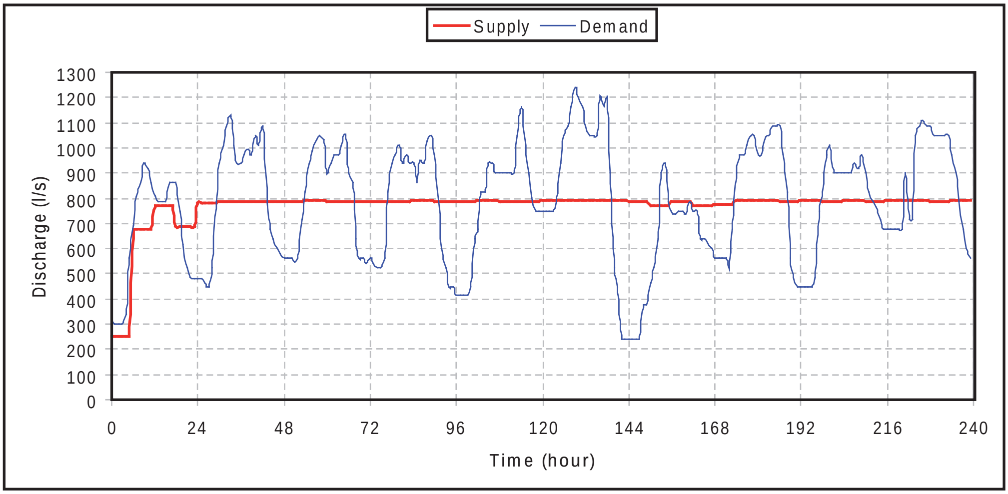

Figure 7. Supply hydrograph with respect to the recorded demand hydrograph for the 10-day peak period (second alternative).

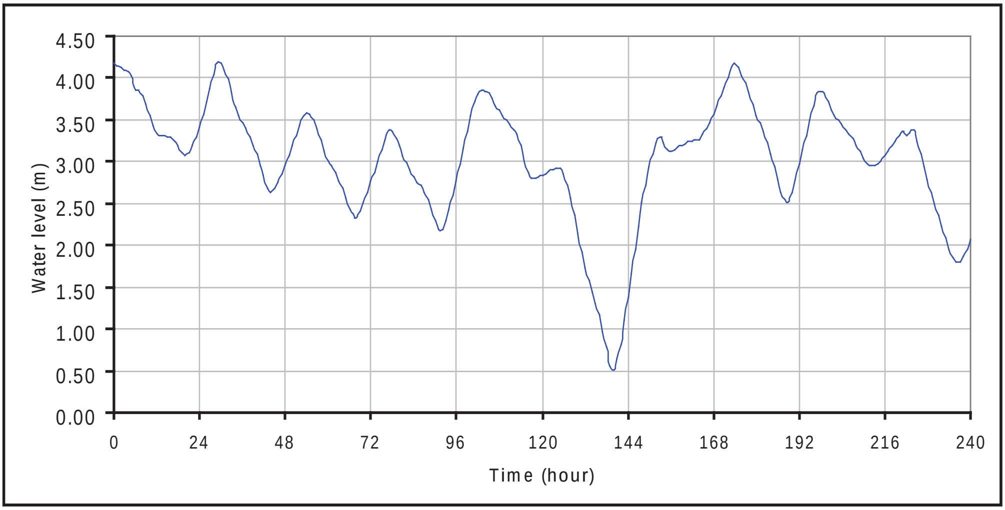

Figure 8. Reservoir water level with respect to the recorded demand hydrograph during the 10-day peak period (third alternative).

The solutions presented by the two alternatives are based on the actual recorded demand hydrograph and the maximum allocated discharge.

The results show that with some minor improvement of the upstream, the on-demand delivery schedule may be maintained without risk of emptying of the reservoir even during the peak period.

V – Conclusion

In on-demand irrigation systems, when the supply {Maximum allocated discharge, reservoir storage capacity} doesn't match the demand, emptying of the upstream reservoir is verified. Therefore it is recommended to verify and ensure the water balance between the supply system and the water demand and propose adequate solutions to reach this objective.

In this paper, the analysis of the reservoir water balance was performed using a stochastic approach based on the genetic algorithms where the output is the optimal supply hydrograph.

The case of the reservoir R.1 in the Sinistra Ofanto irrigation scheme (Italy) was studied. The result given by the model is in line with the field observations. In fact, it was demonstrated that the reservoir faces the risk of emptying during the peak period despite the use of the maximum allocated supply discharge during the whole period.

To overcome this problem, two theoretical alternatives were proposed based on the result of the simulations. No-emptying was verified by the model for the above said alternatives.

The economic feasibility of the technical proposals are not discussed in this paper and deserve an in-deep separate analysis.

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The evapotranspiration of crop protected by windbreak

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Abstract. As a result of the reduction of water resources, it is necessary to adopt agronomic strategies to mitigate crop evapotranspiration (ET) in the Mediterranean environment. The mechanisms with which windbreaks modify the microclimatic components and the evapotranspiration have been studied through laboratory testing (wind-tunnel), observations in the field (in Australia and in USA) and crop models. The extrapolation of the results of these studies does not allow for the quantification of their effective benefit in crop water consumption. This study proposes modifications to the Penman-Monteith formula to allow for calculation of the water requirements of wheat and bean in the presence of windbreaks. The experiments were carried out in Rutigliano, (Southern Italy). The microclimatic data were recorded in an experimental field protected by a windbreak of *Cupressus arizonica* L., positioned in a perpendicular direction to the prevailing winds (N). The analysis of the microclimate highlighted that wind speed was mitigated up to 60% when the winds arrive from the Northern sector up to a distance less than 18 times the height of the windbreak (18 H); moreover the temperature rose up to 3.5°C for a distance less than 5H during the hottest seasons and only with the prevailing winds. These results were used to correct the reference evapotranspiration formula (ET_0) and the crop coefficients (Kc). With these corrections, the action of windbreaks on ET and water consumption were simulated. The simulations highlighted that, during 2000, the reduction of ET near the windbreak was 115mm for wheat and 95mm for bean. Different heights of the windbreak were simulated on a 1ha bean plot to quantify the contribution to effective water savings. The simulation highlighted that 8m high barriers offered the maximum water savings, estimated by 36% greater than consumption for an unprotected plot.

Keywords. Agrometeorology – Dry-farming systems – Evapotranspiration – Natural windbreak – Water use efficiency.

L'évapotranspiration des cultures protégées par des brise-vent

Résumé. *Vue la scarsité des ressources en eau, il est nécéssaire d'adopter des stratégies agronomiques qui minimisent l'évapotranspiration des plantes (ET) dans la région méditérranéenne. Les mécanismes par lesquels les brise-vent modifient les composantes microclimatiques ainsi que l'évapotranspiration ont été étudiés au moyen de tests en laboratoire (soufflerie), d'observations sur le terrain et de modèles de culture. L'extrapolation des résultats issus de ces études ne permet pas de quantifier leur bénéfice effectif sur la consommation d'eau par les plantes. Cette étude suggère de modifier la formule de Penman-Monteith (FAO, 56) pour permettre le calcul des besoins en eau du blé et des haricots en présence de brise-vent. Ces expériences ont été réalisées dans une région du sud de l'Italie (Rutigliano). Les données microclimatiques ont été enregistrées sur un terrain experimental protégé par un brise-vent de Cupressus arizonica L. placé en position perpendiculaire par rapport aux vents dominants (N).*

L'analyse du microclimat met en évidence que la vitesse du vent s'est réduite jusqu'à 60% pour les vents du nord, jusqu'à une distance inférieure à 18 fois la hauteur du brise-vent (18H) ; de plus la température augmente jusqu'à 3.5°C pour une distance inférieure à 5H pendant les saisons les plus chaudes et seulement en présence des vents dominants. Ces résultats ont été utilisés pour corriger la formule d'évapotranspiration de référence (ETref) et les coefficients culturaux (Kc). Grâce à ces corrections, l'action des brise-vent sur ET et la consommation d'eau ont été simulées. Les simulations ont mis en évidence qu'en 2000 la réduction de ET près du brise-vent était de 115mm pour le blé et de 95mm pour les haricots. Au contraire, pendant la saison 1996 il n'y a pas eu de variations de ET à n'importe quelle distance du brise-vent. Différentes hauteurs de brise-vent ont été simulées sur un champ d'haricots de 1ha pour quantifier sa contribution sur l'économie effective d'eau. La simulation a mis en évidence que des barrières de 8m de hauteur assurent l'économie d'eau maximale, estimée à 36% par rapport à la consommation d'un champ non protégé.

Mots-clés. *Agrométéorologie - Systèmes de cultivation à sec - Evapotranspiration - Brise vent naturel - Efficience d'utilisation de l'eau.*

I – Introduction

In the Mediterranean environment, the limited availability of water implies the need to search for agronomical solutions that can mitigate the consequences of water deficits and increase the efficiency of the irrigation supply.

One of the various solutions proposed in dry farming, the windbreak, reduces crop evapotranspiration by modifying the aerodynamic and thermal components of the energy balance (Burke, 1998).

However, experimental results have been widely varying (Kort, 1988; Nuberg, 1998).

The information gathered from experiments carried out in the Mediterranean region are fragmentary and limited to a few tests carried out in Italy (Casa *et al.*, 1994) and Tunisia (Ben Salah *et al.*, 1989; Benzarti, 1989).

More numerous and organic specific studies have been carried out in Australia (Cleugh *et al.*, 2002). However, the Australian trials can not easily be transferred to the European Mediterranean environment, since Australia contains widely contrasting climatic conditions.

It is, therefore, necessary to carry out a more up-to-date study of the influence of windbreaks on the cropping systems of the Mediterranean region, as regards micrometeorology, evapotranspiration and crop productivity.

The present work takes into account the effects of the windbreak on the microclimate (aerodynamic and thermal components) and proposes the changes in the Penman-Monteith equation (Allen *et al.*, 1998) to calculate the water requirements of the crops (FAO water balance model).

The experiment was carried out in a typical Mediterranean environment on wheat and bean crop. The forecasts for climatic changes, provided by global circulation models, indicate an increased water deficit for the Mediterranean region (greater climatic demand and lower supply of rain), making easy to hypothesise an increase in water stress for crops in the future. Given this situation, the aim of the study is to answer the question whether windbreaks, by reducing the evapotranspiration demand on the scale of the parcel, can contribute to reduce the water stress risk for crops cultivated in the Mediterranean area.

II – Materials and methods

The trials were carried out at the experimental farm of the Research Unit for Crop Systems in Dry Environments (CRA – SCA), in Rutigliano (lat: 40°59', long: 17° 59', alt: 147m a.s.l.), in Southern Italy. The location is characterized by a Maritime-Mediterranean climate, with a notable aerodynamic component (speed wind > 2.8 ms^{-1}) and dominant winds coming from North. The average rainfall is approximately 600mm with precipitation concentrated mostly during the autumn, while quite scarce during spring and summer. This rainfall is insufficient to meet the evapotranspiration demand of the atmosphere (annual water deficit: 560mm).

The microclimate parameters have been recorded on the wheat and bean cultivated in an experimental field (100 x 200 m) in which is present, in perpendicular position to the dominant winds, a windbreak of *Cupressus arizonica* L., (height 3 m, long 150 m, age 20 years).

During the year 2005, microclimatic surveys were carried out on a central strip of the parcel, perpendicular to the cypress barrier. Measurements were made in various positions, at progressive distances from the windbreak and within the balanced boundary layer (Wieringa, 1993). At the position farthest from the windbreak the direction of the wind was measured while the other inputs (solar radiation, net radiation, wind direction, precipitation) were measured at a single position (3H), as they are not influenced by the action of the windbreak (Marshall, 1967). All the data were automatically registered each hour by the Campbell CR10X data-logger.

It is known that the protected area is linearly reduced when the diagonal flow exceeds 45° (Cleugh e Hughes, 2002). Moreover, the protected area is reduced by 75% when the wind is parallel to the windbreak (Burke, 1998) and it continues even when the direction of the wind is opposite to the barrier (Burke, 1998; Caborn, 1957; Cleugh and Hughes, 2002; Marshall, 1967; Sturrok, 1972). Granted that from previous experience and given the low frequency of winds coming from North-East, East and South-East (Figure 1), the micrometeorological data were selected on the basis of the sector the wind came from:

- *North: North, North-East, North-West;*
- *Lateral: West and East;*
- *South: South, South-East, South-West*

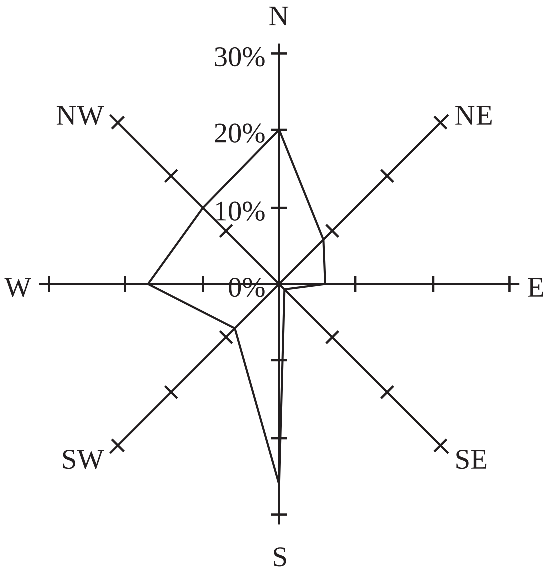

Figure 1. Distribution of the wind direction during the experimental trial.

The coefficients of correction were gotten by the analysis of the climatic data and they were used in FAO water balance model.

III – Results and discussions

The analysis of the microclimate highlighted that the efficacy of the windbreak altered in function of the wind direction. On days with wind coming from the Northern sector, the protection offered by the windbreak determined a reduction in wind speed for a distance of up to 18 times the height of the windbreak (18H). In particular, the slowest speeds were registered in proximity to the barrier (< 5H); vice versa, the values increased by 60% in the unprotected area (>18H). When the winds came from the sector E-W and South a maximum reduction was respectively verified by 20% and by 22% for a distance of 10 H (Figure 2).

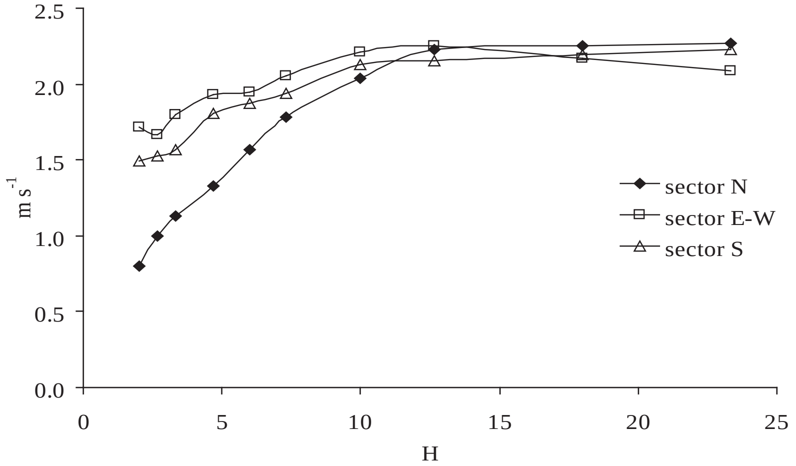

Figure 2. Wind speed (ms-1) as a function of the distance from the windbreak (H) during the cycle of the wheat and bean crop.

During the dominant winds and for both the crops, the temperature remained constant for the entire area in which the micrometeorological measuring sensors were installed, but it increased by about 1° C in the area between the windbreak barrier and 5•H. Instead, if the hours with temperatures above usual (> 29° C) are taken into consideration, the increase in temperature was 3.5°C in the same area (Figure 3).

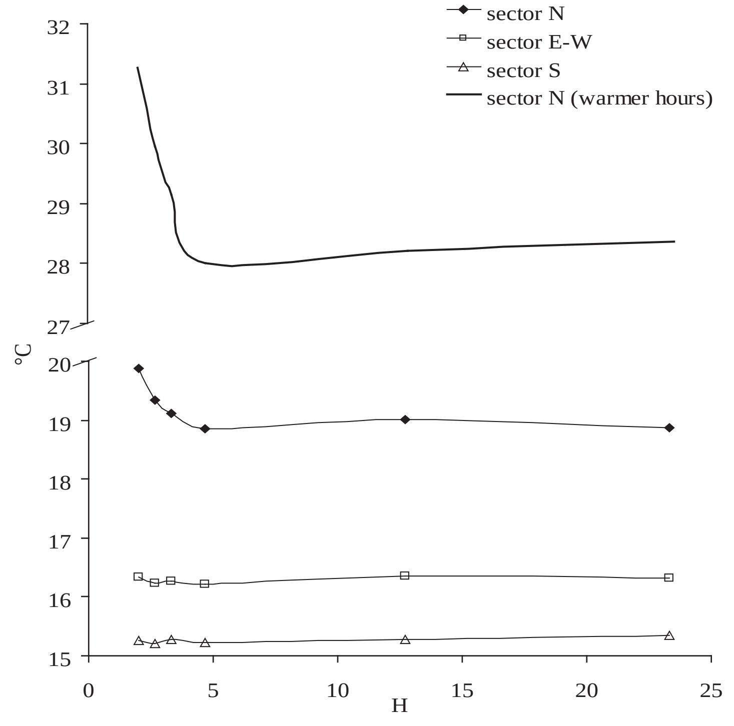

Figure 3. Air temperature (°C) as a function of the distance from the windbreak (H) in the cycle of the wheat and bean crop.

The air humidity (RH) did not vary with the distance from the windbreak (Figure 4).

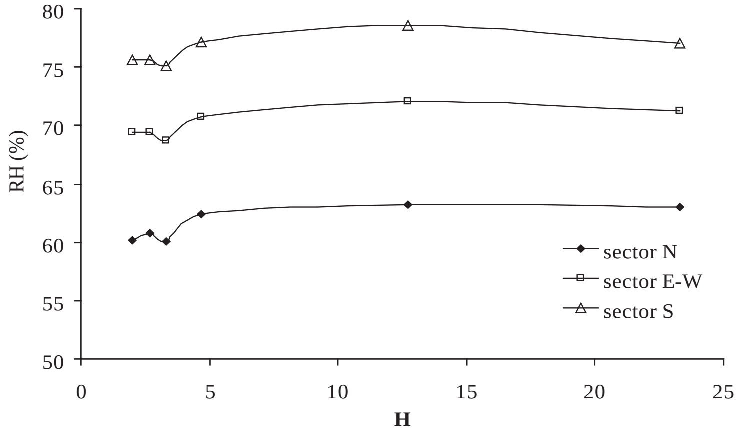

Figure 4. Relative humidity (%) as a function of the distance (H) from the windbreak.

All these experimental results were used to correct the reference evapotranspiration formula (ET_0) and the crop coefficients (Kc-dual) by the coefficients of correction of the wind speed (vd) and temperature (td):

a) correction of the reference evapotranspiration (FAO Penman-Monteith equation)

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot \frac{900}{T+273} \cdot u_2 \cdot v_d \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 u_2 \cdot v_d)} \quad (1)$$

where vapour pressure deficit (e_s-e_a) derives from the pressure of saturated vapor to the temperature of the air (e*(T)) corrected by the coefficient of reduction of the temperature (t_d):

$$e*(T) = 0.6108 \cdot 2.7183^{\frac{17.27 \cdot T \cdot t_d}{T \cdot t_d + 237.3}} \quad (2)$$

b) correction of the Kc-dual:

$$Kc_{\max} = 1.2 + \left[0.04 \cdot (u_2 \cdot v_d - 2) - 0.004 \cdot (RH_{\min} - 45)\right] \cdot \left(\frac{h}{3}\right)^{0,3} \quad (3)$$

where u_2 is the wind speed at 2 m above round surface and h is the mean plant height during mid-season stage (m).

By these corrections, the action of windbreaks on ET and water consumption were simulated by the FAO water balance model.

The simulations highlighted that, from 1984 to 2006, windbreaks caused an average reduction in ET of 50mm for bean and 60mm for wheat. The effect of the windbreak depends on meteorological conditions. In particular, in 2000 the reduction of ET near the windbreak was 115mm for wheat and 95mm for bean. On the contrary, in 1996 there were no variations in ET at any distance from the windbreak (figure 5).

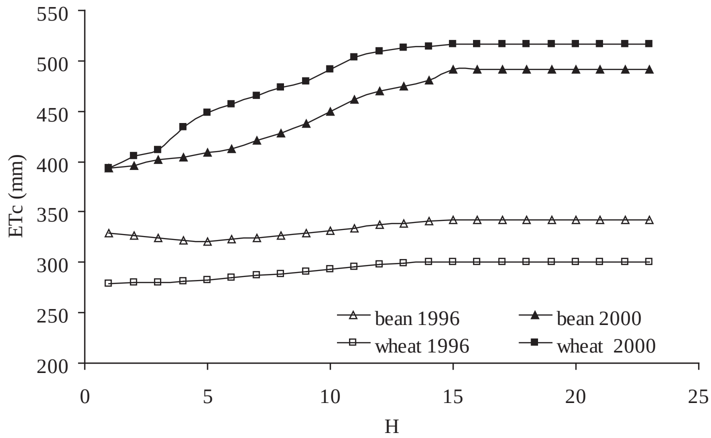

Figure 5. ETc (mm) as a function of the distance (H) from the windbreak.

Different heights of the windbreak were simulated on a 1ha plot (100m x 100m) to quantify the contribution to effective water savings for the bean. The simulation highlighted that 8m high barriers offered the maximum water savings, estimated by 36% greater than consumption for an unprotected plot (Figure 6).

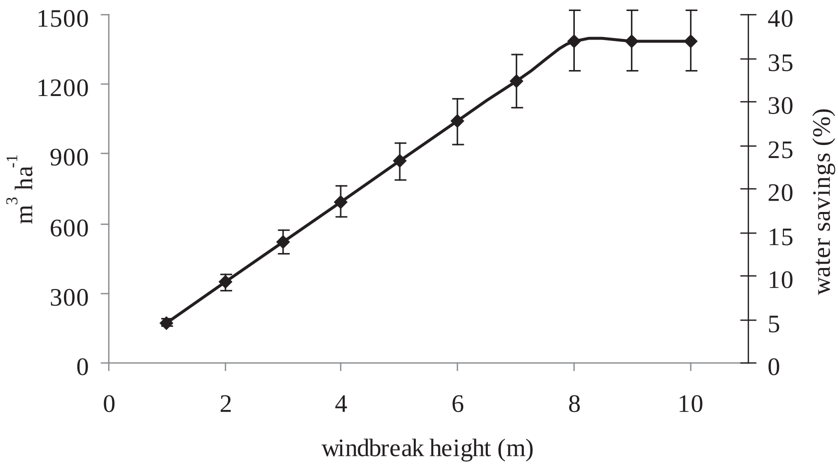

Figure 6. Water saving of the bean as a function of heigth of windbreak in an area of 1 ha.

IV – Conclusions

The experimental results highlighted the windbreak's potential for containing evapotranspiration and improving the efficient use of water in a typical Mediterranean environment. The study is also a useful update of knowledge about the agronomical role of these protective structures, greatly undervalued in Mediterranean agronomy.

It is useful to specify that the introduction of windbreaks must be preceded by a careful analysis of the aerodynamic characteristics of the environment, with the objective of evaluating how to position the windbreak with regards to the strongest winds. In all situations, it is necessary to opt for a windbreak with adequate vertical growth, so as to increase the extension of the area with maximum protection.

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WUE estimation by using direct and indirect modelling of water losses of sugar beet cropped in a semi-arid environment

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Abstract. Many expressions of water use efficiency (*WUE*) have been proposed in literature, but the most diffuse one is based on the ratio between crop yield and cumulative actual evapotranspiration (ET_a). A big error can be made if the water consuming is badly evaluated. The best way to give the ET_a is to measure it, but often it is estimated. At plot scale, there are two different methods for estimating ET_a: the direct and the indirect method, both based on the Penman-Monteith model. In order to evaluate the errors made on *WUE* due to the ET_a modelling, in this work we evaluate the water use efficiencies in the growth period when *LAI* is greater or equal to 2. Three methods of ET_a estimation is used (direct, single K_c, dual K_c) for a sugar beet crop cultivated in Capitanata Plain (southern Italy) during two experimental field campaigns. The actual evapotranspiration has been measured directly by eddy covariance or by aerodynamic method. All the measurements have been done at hourly scale, but the estimation are presented at daily and seasonal scales. The results show that for *WUE* indicators, the direct method of ET_a calculation gave better performances with respect to the indirect ones, with worst results for the single crop coefficient approach.

Keywords. Actual evapotranspiration – Penman-Monteith – Crop coefficient.

Estimation de l'efficience d'utilisation de l'eau (WUE) par modélisation directe et indirecte des pertes d'eau de la betterave sucrière cultivée en région semi aride.

***Résumé**. Plusieurs expressions de l'efficience d'utilisation de l'eau (WUE) sont disponibles dans la littérature scientifique, mais la plus diffuse est celle basée sur le rapport entre la production d'une culture et l'evapotranspiration réelle cumulée (ET_a). Une grossse erreur peut être commise si la consommation en eau d'une culture n'est pas bien déterminée. La façon la plus correcte pour déterminer la WUE est de la mesurer, mais en tout cas elle peut être estimée. A l'échelle de la parcelle deux méthodes peuvent être considérées: l'une directe et l'autre indirecte ; toutes les deux sont basées sur le modèle de Penman-Monteith. Pour évaluer l'erreur sur la WUE provoquée par la modélisation de l'ET_a, nous calculons dans cet article l'efficience d'utilisation de l'eau dans la période de croissance d'une culture, quand l'indice foliaire (LAI) est égal ou plus grand de 2. Trois méthodes d'estimation de l'ET_a sont analysées (directe, single K_c et dual K_c) pour une culture de betterave à sucre, cultivée en Capitanata (Italie du sud), pendant deux campagnes expérimentales. L'evapotranspiration réelle a été mesurée par deux techniques: eddy covariance et technique aérodynamique. Les mesures ont été faites à l'échelle horaire, tandis que les estimations sont présentées à l'échelle journalière et saisonnière. Les résultats montrent que quand l'ET_a est calculée par la méthode directe, les indicateurs de WUE donnent des valeurs beaucoup plus fiables de celles obtenues en utilisant les méthodes indirectes, surtout pour l'approche du K_c single.*

***Mots-clés.** Evapotranspiration réelle – Penman-Monteith – Coefficient cultural.*

I – Introduction

Since the first studies, different expressions (water use efficiency, crop water productivity) have been proposed and discussed (among others, Feddes, 1985; Pereira *et al.*, 2002; Zwart and Bastiaanssen, 2004). In general, water use efficiency (*WUE*) can be written as following:

$$WUE \text{ (kg m}^{-3}\text{)} = \text{yield / water consumption} \quad (1)$$

In Eq. (1), if an agronomic approach is chosen (Katerji *et al.*, 2008), the term "yield", can indicate two parameters: i) Global dry matter yield expressed in kg m^{-2}; ii) Marketable crop yield expressed in kg m^{-2}. From applicative point of view, it is worthwhile to mention another important index to estimate the path of water productivity in time, given in term of the dry or fresh biomass per water consuming by evapotranspiration (WUE_b), evaluated during the whole growing season:

$$WUE_b \text{ (kg m}^{-3}\text{)} = \text{biomass / water consumption} \quad (2)$$

Regarding the water consuming, from the water used by crops during the growing season, 99% is released as water vapour toward the atmosphere. For this reason crop water use is considered approximately equal to actual evapotranspiration (ET_a) in mm or in m^3. This approximation, discussed by Feddes in 1985 is valid only at full crop canopy, thus when leaf area value is over 2 (Katerji and Perrier, 1985). Above this leaf area value, ET_a is nearly similar to crop water use, because evaporation is very low even when soil surface is wet (Ritchie, 1983). On plot scale, ET_a can be determined through different approaches; in particular, ET_a can be measured directly using weighing or drainage lysimeters or can be measured indirectly through micro-metrological methods (Bowen, aerodynamic). These methods result as the most precise to determine ET_a. However, in order to use these methods, precautions are necessary, mainly in the Mediterranean region (Katerji and Rana, 2008).

Moreover, ET_a can be measured through the calculation of soil water balance. This approach is however based on some hypothesis (the capillary rise, runoff and deep percolation are supposed insignificant, rainfall are all efficient). However, some hypotheses are not valid mainly under Mediterranean climatic conditions (Katerji and Rana, 2008).

By model, ET_a can be calculated according to many methods developed in the past decades by different authors (see Katerji and Rana, 2008 for an exhaustive review of the *ET* models).

Finally, in many studies ET_a is not measured, but it is replaced in the Eqs. (1) and (2) by the amount of water supplied by irrigation. The overestimation of water necessary for crops is one of the characteristics of irrigation practice in the Mediterranean region, and this makes difficult the understanding of the obtained *WUE* values (e.g. Shideed *et al.*, 2005).

From the applicative point of view, at plot scale, almost in all the scientific works, ET_a in *WUE* and WUE_b is deduced by models. Generally speaking, there are two different methods for estimating ET_a: the direct and the indirect methods, both based on the Penman-Monteith model. In particular, in the direct approach the measurements of meteorological variables must be done on the crop, while in the indirect one it is enough to measure the meteorological variables on a reference grass (to obtain the reference evapotranspiration, ET_0) and to estimate ET_a as product of ET_0 and a crop coefficient K_c. This latter can be calculated by means of two approaches: the single and the dual crop coefficient approaches.

Considering that an acceptable error of ±20% can be admitted in both numerator and denominator of Eqs. (1) and (2), than a total error of ±40% can be made in the evaluation of *WUE* of a crop with consequent misestimating of irrigation scheduling and programming. For the reasons above described, in this work ET_a is evaluated only when LAI≥2. Thus, here we evaluate the water use efficiency when LAI≥2 (WUE_2 and the WUE_{2b}) using the above mentioned methods of ET_a estimation (direct, single K_c, dual K_c) for a sugar beet crop cultivated in Capitanata Plain, in order to give indications about the best way to evaluate *WUE* at plot scale. The site is submitted to Mediterranean semi-arid climate.

II – Material and methods

1. Theory

The analysis of the crop actual evapotranspiration was made on the basis of the Penman-Monteith (PM) model. In this model, which is theoretically applicable only to the hourly time scale (index "h"), the ET_a is written as:

$$ET_{a,h} = \frac{1}{\lambda} \frac{\Delta A + \rho c_p D / r_a}{\Delta + \gamma \left(1 + r_c / r_a\right)} \tag{3}$$

where $A=R_n-G$ is the available energy (W m^{-2}), ρ is the air density (kg m^{-3}), Δ is the slope of the saturation pressure deficit versus temperature function (kPa C^{-1}), γ is the psychrometric constant (kPa C^{-1}), c_p is the specific heat of moist air (J kg^{-1} C^{-1}), D the vapour pressure deficit of the air (kPa), r_c is the bulk canopy resistance (s m^{-1}) and r_a is the aerodynamic resistance (s m^{-1}), λ is the latent heat of evaporation (J kg^{-1}). The aerodynamic resistance r_a was calculated between the top of the crop and a reference point z located in the boundary layer above the canopy, following Perrier (1975a; 1975b), as:

$$r_a = \frac{\ln \frac{z-d}{z_0} \ln \frac{z-d}{h_c - d}}{k^2 u} \tag{4}$$

where u (m s^{-1}) is the wind speed measured 2 m above the crop; d (m) is the zero plane displacement estimated as $d=0.67h_c$, with h_c mean height of the crop (m); k is the von Kármán constant and z_0 (m) is the roughness length estimated as $z_0=0.1h_c$.

2. The direct method at hourly and daily scale

For calculating ET_a in the Eq. (3), the canopy resistance r_c has to be previously determined. In the present work, the hourly variation of r_c is simulated starting from a relationship taking into account the associated effects of solar radiation, air vapour pressure deficit and wind speed. Katerji and Perrier (1983) proposed to simulate the resistance r_c by the following relation:

$$\frac{{}_c}{r_a} = a \frac{r^*}{r_a} + b \tag{5}$$

where a and b are empirical calibration coefficients which require experimental determination. r^* (s m^{-1}) is given as:

$$r^* = \frac{\Delta + \gamma}{\Delta \gamma} \frac{\rho c_p D}{A} \tag{6}$$

This resistance r^* can be considered as a "climatic" resistance, because it depends only on weather variables. Moreover, r^* represents a "critical" value for the evaporative process, because it is a threshold between the situation, $r_c < r^*$, for which ET_a increases with increasing wind speed, and the situation, $r_c > r^*$, in which ET_a decreases with wind speed.

This model has been used to calculate ET_a for different species (alfalfa, rice, grass, lettuce, sweet sorghum, sunflower, grain sorghum, soybean, clementine orchard, sloping grassland) as reported by Katerji and Rana (2006). It has also been adapted to soil water stress conditions, but this subject will not be discussed here.

The daily values of ET_a were calculated, considering in this direct method (index "d") the sum of hourly values in the time interval between 8 a.m. and 6 p.m.:

$$ET_{a,d} = \sum_{h=8}^{18} ET_a \tag{7}$$

3. The indirect method

From the application point of view, the calculation of the crop ET_a is usually made by the formulation of Allen *et al.* (1998). Actually, this method refers to the maximum evapotranspiration, i.e. when the crop is in well watered conditions, which is the present case. The same methodology has been used by many other authors (i.a. Katerji and Rana, 2006; Testi *et al.*, 2004; Amayreh and Al-Abed, 2005). It is an indirect calculation (index "i"), in fact ET_a is determined by the following relationship:

$$ET_{a,i} = K_c ET_0 \tag{8}$$

In this formulation, ET_0 is the reference evapotranspiration and K_c is the crop coefficient. The recent FAO no. 56 paper (Allen *et al.*, 1998) well defined the concept of ET_0 and adopted the Penman-Monteith equation adapted to a grass crop. Anyway, the authors simplified the procedure to calculate the resistance r_c for the grass. In fact, this was considered constant in all climatic conditions and takes a fixed value in the Penman-Monteith formula. The formula used for the daily values of ET_0 in this work is (all the details in Allen *et al.*, 1998):

$$ET_0 = \frac{0.408\Delta A + \gamma \dfrac{900}{T+273} uD}{\Delta + \gamma (1 + 0.34u)} \tag{9}$$

The accuracy of the ET_a values determined by the Eq. (8) depends on two factors. Firstly, it depends on the accuracy of the determination of ET_0 as carried out by the users in different geographical sites; then, on the accuracy of the K_c values used in Eq. (8). These values were given by Allen *et al.* (1998) for three stages of crop growth cycle (initial, middle and end) for the main cultivated crops. The hypothesis of a constant resistance r_c in the determination of ET_0 for the grass could be a possible source of error. However, some studies showed that this hypothesis gave acceptable estimation of ET_0 in different regions of the world (Smith *et al.*, 1991; Allen *et al.*, 1994a, 1994b). Other studies, mainly carried out in semi-arid and arid regions, showed opposite results: the previously mentioned hypothesis underestimated the values of ET_0 as measured by lysimeters, except for a few cases (see the results obtained by Steduto *et al.*, 1996 in Morocco). The underestimation ranged between 2 and 18% (see Katerji and Rana, 2006 for details). Anyway, since the experimental error of the direct measurement of ET_0 by the lysimeter is about 15% (Rana and Katerji, 2000), the performance of this method seems to be reasonable. Therefore, the approach proposed by Smith *et al.*, (1991) and Allen *et al.*, (1998) merits the attention of researchers.

The second source of possible error concerns the values of K_c, as indicated by Allen *et al.*, (1998). Actually, these values showed more or less important differences with respect to the experimentally determined values of the relationship ET_a/ET_0. Actually, many papers can be found on this subject in the scientific literature. Also if we consider only the more recent literature, it is possible to find differences of ±40% between the K_c values reported by Allen *et al.*, (1998) and the values experimentally obtained, especially during the middle growth cycle (see Katerji and Rana, 2006; 2008). These big differences are mainly due to the complexity of the coefficient K_c, which actually integrates several functions (Testi *et al.*, 2004): aerodynamic factors linked to the height of the crop, biological factors linked to the growth and senescence of the surface leaves, physical factors linked to the evaporation from the soil, physiological factors linked to the response of the stomata to the vapour pressure deficit of the air and agronomical factors linked to the crop management (distance between rows, using mulch, irrigation system, etc.). For this reason, Allen *et al.*, (1998) recommended that the evaluation of K_c values in local climatic conditions by observed data using lysimeters is necessary. Nevertheless, the simple local determination of K_c is not enough if general values of K_c are required. Therefore, it is necessary to search for the relationships between K_c and more or less complex parameters, such as the surface area of the leaves, the humidity of the soil surface and the 3D energy balance (Testi *et al.*, 2004 among many others). This last approach was called "dual K_c" in the FAO56 book. In this case the actual evapotranspiration is called $ET_{a,\text{i-dual}}$.

4. Site, crop and measurements

This study was carried out at a site of Southern Italy (Capitanata plain) in 2006 and 2007 during two experimental field campaigns planned for the Italian project AQUATER. The data here presented were acquired in two private farms ("Forte" during 2006 and "De Lucretis" during 2007), on a very large field (5 hectares) of sugar beet (*Beta vulgaris L.*) maintained in well watered conditions; the irrigation was supplied by the "Consorzio di Bonifica della Capitanata (Foggia)", by aspersion method, following the local usage tending to maximize yield. The climate is semi-arid Mediterranean.

The actual evapotranspiration of the crop was measured by the eddy covariance method (EC) (Kaimal e Finnigan, 1994). A three-dimensional sonic anemometer (USA-1, Metek, Germany) was used in these experiments, coupled with an open-path sensor for the fast acquisition of water vapour concentration (LI-7500, Li-Cor, USA). The sensors were connected to an industrial computer and acquired by software (MeteoFlux, Servizi Territorio S.r.l., Cinisello B. (Mi), Italy). In case of failure of the EC technique, the aerodynamic method (Katerji and Rana, 2008) is used for filling the gaps. In this last case wind speed and air temperature at three levels above the crop were measured by commercial sensors after accurate calibration in laboratory. The agrometeorological variables used for the calculation of ET_a were measured directly above the crop, by means of standard commercial meteorological sensors, including net radiometers and soil heat flux plates. The same kinds of sensors were used to measure the meteorological variables for calculating ET_0 by the indirect method: in this case the sensors were placed above a reference grass in an agrometeorological station a few kilometers far from the experimental field. For the micrometeorological measurement of variables and fluxes the fetch in the directions was large enough for being well below the adjusted internal crop boundary layer. The FAO56 tomato K_c was used in this study (1.15 in the mid- season stage).

III – Results and discussion

The calibration of the model, i.e. the calculation of the coefficients *a* and *b* in the Eq. (5) must be made by comparing the ratio r_c/r_a, with r_c deduced by the Eq. (3) once the ET_a is measured in the field above the crop, and the ratio r^*/r_a, with all the variables measured directly above the crop. The result of the calibration (Fig. 1) for the sugar beet has been made by using the data acquired in 2006 and, of course, they were not used for the validation of the model.

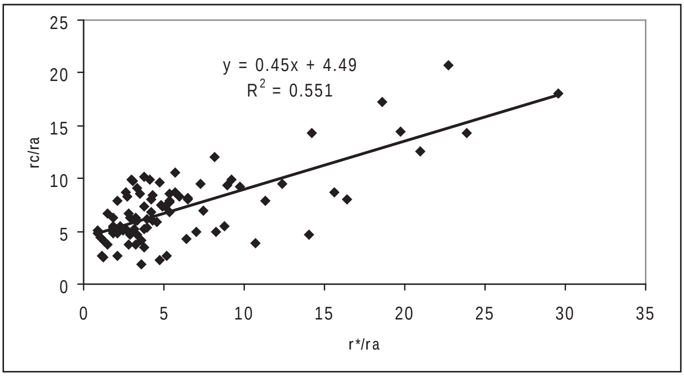

Figure 1. Calibration of the direct model (see text Eq. (5)) for sugar beet using the data acquired in 2006, directly above the crop.

In order to evaluate the performances of the three presented model of ET_a ($ET_{a,d}$ direct; $ET_{a,i}$ indirect and $ET_{a,i\text{-dual}}$ indirect with dual K_c), firstly we compare the daily evapotranspiration values calculated with evapotranspiration measured by eddy covariance method. In Figure 2, the comparison between $ET_{a,d}$ and evapotranspiration measured are presented at daily scale, using the data acquired in 2007. In this figure, 58 daily values of ET_a are reported, these data are relative to the whole crop growth season. The performance of the other two methods are reported in Table 1, by showing the values of the slope and intercept of the linear regression between ET_a measured and calculated together with the determination coefficient (r^2) and the standard error (STDE). From this table can be argued that the direct model had the best performances, both during 2006 and 2007; in fact, this method is accurate having a slope close to 1 and intercept negligible with a regression coefficient very high. Vice versa, the other two methods had bad performances, with high values of the intercept and low r^2. The method based on the dual K_c approach presented better results in both years.

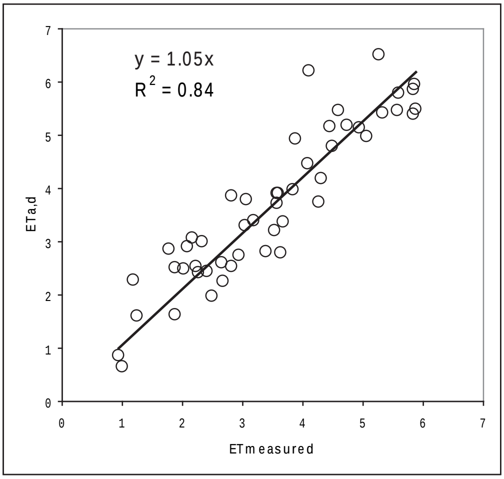

Figure 2. Comparison between daily values of ET_a modelled by the direct method and ET_a directly measured in the field by eddy covariance or aerodynamic method on sugar beet during 2007, when LAI≥2.

Table 1 Statistics of the performances of the ET_a presented model, calculated by the regression between measured and modelled values for the two years of experiment on sugar beet (STDE is the standard error; $ET_{a,d}$ is evapotranspiration calculated by direct method, $ET_{a,i}$ is evapotranspiration calculated by indirect method, $ET_{a,i\text{-}dual}$ is evapotranspiration calculated by indirect method with dual K_c).

Year	Model	slope	intercept	r^2	STDE
2006	$ET_{a,d}$	1.06	0.1	0.86	0.57
	$ET_{a,i}$	0.98	1.9	0.75	0.72
	$ET_{a,i\text{-}dual}$	0.99	1.2	0.74	0.71
2007	$ET_{a,d}$	1.05	0	0.84	0.58
	$ET_{a,i}$	0.94	2.2	0.74	0.89
	$ET_{a,i\text{-}dual}$	0.99	1.8	0.79	0.81

In Table 2 the values of the *WUE* in all the analysed cases is presented for the crop growth season when the sugar beet had a value of LAI≥2. In particular we presented the *WUEs* (both with yield and fresh biomass as numerator) obtained when ET_a is i) measured, ii) calculated by direct method, iii) calculated by indirect method with single K_c, iv) calculated by indirect method with dual K_c. From this table it is clear that the values of *WUEs* closest to that obtained with measured evapotranspiration are those obtained when ET_a is calculated by the direct method. In all other cases, the *WUEs* are underestimated from -12.9% to -19.5%.

Since the two *WUEs* had different values for the two years of the experiments, an attempt of normalising them, dividing by the water vapour deficit, has been carried out in order to establish a suitable univocal relationship between the crop production and the water losses. The results of this normalization gave ambiguous not clear results, maybe due to the particular structure of this crop (big roots and small epigeous parts), thus they are not presented here. Another comment can be made about the underestimation of ET_a with indirect models: this is linked to K_c values used for the estimation, which is lower than the one obtained with local calibration (data not shown).

Table 2. Summary of the *WUE* (Eqs. (1) and (2) in the text) calculated in the growth season when LAI≥2 up to the harvest of sugar beet (i.e. between 13 April and 28 June 2006; between 1 April and 14 April 2007). Var. is the variation in percentage of the *WUE* calculated with the cumulated evapotranspiration following the three methods described in the text: $ET_{a,d}$ direct method, $ET_{a,i}$ indirect method, $ET_{a,i\text{-}dual}$ indirect method with dual K_c.

Year	Indicator	$ET_{measured}$	$ET_{a,d}$	Var.	$ET_{a,i}$	Var.	$ET_{a,i\text{-}dual}$	Var.
2006	WUE^2	19.7	19.1	-3.2%	16.2	-17.7%	17.2	-12.9%
	WUE^2_b	33.1	32.0		27.2		28.8	
2007	WUE^2	15.1	14.5	-3.9%	12.5	-19.5%	12.5	-17.2%
	WUE^2_b	19.8	19.0		15.9		16.4	

IV – Conclusions

In semi-arid environments the ET_a evaluation poses big problems (Katerji and Rana, 2008) that can be reflected in the evaluation of *WUE* at plot scale. In this work, we analysed the performances of three methods to calculate ET_a by using data acquired directly in the field (ET_a direct model) and data acquired in a reference grass (indirect single K_c and indirect dual K_c models) by using the K_c approach as tabulated in the Allen et al (1998) FAO56 book for sugar beet. The results showed that a very small error is found in the calculation of *WUEs* (both when marketable yield and fresh biomass is used) when the direct ET_a model is used. The other two ET_a models produced big (around 15-20%) errors in the quantification of *WUE*.

Acknowledgements

This work was supported by the Italian Ministry of Agriculture, Food and Forestry Policies (AQUATER project, contract nr. 209/7303/05).

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Evaluation of different water content measurement methods to analyze soil water dynamics

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Abstract. Many agronomic and hydrological investigations depend on accurate measurement of soil water content (SWC). Accuracy, precision, facility and speed, including the capability to carry out measurements at different depths, are essential characteristics for monitoring SWC in the agronomical experiments. At the present, common systems use sensors based on capacitance (FDR) or time domain reflectometry (TDR) principles. Both the methods introduce advantages and disadvantages.

In the framework of AQUATER Project (Decision support systems to manage water resources at irrigation district level in Southern Italy using remote sensing information), the main objective of this study has been to monitor the SWC dynamics in a tomato (Foggia) and watermelon (Castellaneta - TA) field cultivations, both located in Southern Italy, by using: (1) the Diviner 2000 (Sentek Pty. Ltd., South Australia), (2) the TDR-100 (Campbell Sci. Shepshed, UK), (3) ThetaProbe Soil Moisture Sensor-ML2x (Delta-T Devices Ltd) and (4) the typical gravimetric methods.

In the field experiment of Foggia the SWC was continuously monitored (from the flowering stage until harvest time) by means of TDR probes installed at three depth (15, 30 and 45 cm). The probe signals were controlled by a TDR-100 (Campbell Sci. Shepshed, UK) and stored every hour in a CR1000 data logger. Moreover, SWC was measured with Diviner 2000 into five PVC access tubes vertically installed, by means of a portable probe (scanning length of 1.6 m) collecting reading at 10 cm depth intervals in soil profiles of 1.3 m. In the field of Castellaneta, on watermelon cultivation, the SWC was monitored by using TDR method and ThetaProbe with four 5-cm steel rods. The TDR probes were installed horizontally and vertically below the plant row and between crop rows. SWC has been continuously monitored and stored every hour into a CR10X. Moreover, for both the experiments, the SWC was also measured at two different depth (0-20 and 20-40 cm) with the typical thermo-gravimetric method.

The soil water dynamic was accurately individuated with the TDR methodology, while the DIVINER allowed to characterize the plant water uptake along the soil profile. However, accurate measurements of surface SWC were obtained by using the Thetaprobe sensor.

Keywords. Volumetric water content – Soil moisture sensors – TDR – FDR.

Évaluation de différentes méthodes de mesure de la teneur en eau pour analyser la dynamique de l'eau du sol

Résumé. *Plusieurs investigations agronomiques et hydrologiques dépendent de la mesure précise de la teneur en eau du sol (TES). L'exactitude, la précision, la facilité et la vitesse, y compris la possibilité d'effectuer des mesures à différentes profondeurs, sont des caractéristiques essentielles pour la surveillance de TES au niveau des expériences agronomiques. Actuellement, les systèmes communs utilisent des sondes basées sur les principes de la réflectométrie dans le domaine fréquentiel (FDR) ou de réflectométrie dans le domaine temporel (TDR), deux méthodes que présentent des avantages et des inconvénients.*

Dans le cadre du projet AQUATER (systèmes d'aide à la décision pour contrôler les ressources en eau des zones irriguées en Italie méridionale, utilisant l'information de télédétection), une étude a été mené en plein champ, dans la zone de l'Italie méridionale, son objectif principal été de surveiller la dynamique de TES de la culture de tomate (cultivé à Foggia) et de pastèque (à Castellaneta - TA), en utilisant: (1) le Diviner 2000 (Sentek Pty. Ltd., South Australia), (2) le TDR-100 (Campbell Sci. Shepshed, UK), (3) la sonde Thétaprobe ML2x (Delta-T Devices Ltd) et (4) les méthodes gravimétriques typiques.

Dans le champ expérimental de Foggia la TES a été surveillée d'une manière contenue (à partir de la phase de floraison jusqu'à la récolte) au moyen des sondes TDR insérées à trois profondeurs (15, 30 et 45 cm). Les signaux de sonde ont été commandés par le TDR-100 (Campbell Sci. Shepshed, UK) et stockés, chaque heure, grâce à un système d'acquisition de données CR1000. D'ailleurs, la TES a été mesurée avec le dispositif Diviner 2000 dans cinq tubes d'accès en PVC installés verticalement, au moyen d'une sonde portative (longueur de balayage de 1,6 m) rassemblant la lecture à des intervalles de profondeur de 10 cm le long d'un profils du sol de 1,3 m.

Sur la culture de pastèque, cultivée dans le champ de Castellaneta, la TES a été surveillée en employant la technique TDR et celle de Thétaprobe avec quatre tiges d'acier de 5 cm. Les sondes de TDR ont été installées horizontalement et verticalement sur la ligne, entre les plantes, et dans l'interligne. La TES a été surveillée sans interruption et les données ont été stocké chaque heure dans un CR10X.

En outre, pour les deux expériences, la TES a été également mesurée à deux profondeurs différentes (0-20 et 20-40 cm) avec la méthode thermogravimétrique typique.

La dynamique de l'eau du sol a été mesurée exactement avec la méthodologie de TDR, alors que le Devinier a permis de caractériser la captation des ressources en eau par la plante le long du profil du sol. Cependant, des mesures précises de la surface de TES ont été obtenues en utilisant la sonde de Thétaprobe.

***Mots-clés.** Contenu volumétrique en eau – Sondes d'humidité du sol – TDR – FDR.*

I – Introduction

Many plant-soil-water and hydrological investigations depend on accurate measurement of SWC. The field-measurements of soil water content (SWC) are of fundamental importance to study the soil water balance with particular reference to several components like the plant water uptake, the infiltration, the water re-distribution in the soil profile and the capillary rise.

In general, accurate measurements of the lower limit (also known as the permanent wilting point, PWP) and the drained upper limit (also known as the field capacity, FC) are required to estimate the totally or readily available soil water as critical inputs required by hydrological models base on simplified balance approaches.

However, some techniques, as irrigation deficit and drip irrigation, require great accuracy of soil water measurements in order to obtain high values of water use efficiency. SWC of shallow soil layers are very crucial also for hydrological study based on remote sensing information.

Figure 1. The six farms monitored in the study.

Accuracy, precision, facility and speed, including the capability to carry out measurements at different depths, are essential characteristics for monitoring the SWC in the agronomical experiments and applications.

Common systems actually use, mainly, sensors based on capacitance (frequency domain reflectrometry, FDR) or time domain reflectometry (TDR) principles. The FDR sensors use an oscillator to generate an AC field applied to the soil for detecting changes in soil dielectric properties linked to variations in SWC. Capacitance sensors consist essentially of a pair of electrodes which form a capacitor with the soil detecting changes in the operating frequency as influenced by variations in SWC. The theory has been discussed in Dean *et al.* 1987. In particular, the Diviner 2000, a capacitance probe, uses the same SWC sensing technology as the EnviroSCAN (Sentek Pty. Ltd., South Australia). It's a portable system designed to be moved from site to site and it's consists of one capacitance sensor at the end of a rod. As the rod is passed down the access tube the handheld display unit automatically records the SWC at each 10 cm depth increment.

Table 1. Experimental layouts

F arm	TDR probes		
	Geometric configuration	**Characteristics**	**Position**
F1	horizontal position at depths of 15, 30 and 45 cm	three-rod (25 cm long)	interrow
F2	vertical position at 0, 15, 30 and 60 cm from the row	three-rod (25 cm long)	row and interrow
F3	horizontal position at depths of 10-30-50-70 cm ; vertical position in the interrow	five-rod (15 cm long)	row

TDR determines the dielectric permittivity of a medium by measuring the time it takes for an electromagnetic wave to propagate along a transmission line that is surrounded by the medium. The transit time for an electromagnetic pulse to travel the length of a transmission line and return is related to the dielectric permittivity of the medium, κ, proportional to the square of the transit time. The time and speed of travel of reflected signal from the end of the probe varies with the dielectric of the soil, which is related to the water content of the soil. The theory and the relationship between κ and the volumetric SWC is described in detail in Topp *et al.* (1980).

In order to monitor the surface SWC, we also used the Moisture Meter Type HH2 with a ThetaProbe Soil Moisture Sensor-ML2x (Delta-T Devices Ltd), hereafter referred to as ThetaProbe. This probe provides a measure of the superficial volumetric SWC (about 60-70 mm in depth), by the well established method of responding to changes in the apparent dielectric constant. These changes are converted into a DC voltage, virtually proportional to soil moisture content over a wide working range. The pins act as a transmission line and detect changes in the soil's dielectric constant by monitoring changes in the way radio frequency energy is transmitted into and reflected by the soil. Handheld display is available and outputs either raw voltage readings or volumetric water content using the two generalised calibrations. For particular soils, a specific calibrations is recommended to achieve an high accuracy. The probe can be either inserted into the soil surface to make one-off readings or buried for continual in situ readings. In order to obtain distributed measurements of surface SWC, we have chosen the first approach.

The Diviner 2000 presents some potential limitations and the measurements are very sensitive to access tube installation. An accurate soil water measurement based into a previously installed PVC access tube and requires careful installation procedure, to prevent formation of air gaps along the sensor or alteration of soil properties within the sensor's zone of influence (approximately, 10 cm in length along the axis of the probe). Moreover, the effect of salinity is still unclear. To the opposite, it's an economical method for covering many sites and it allows a rapid and easy

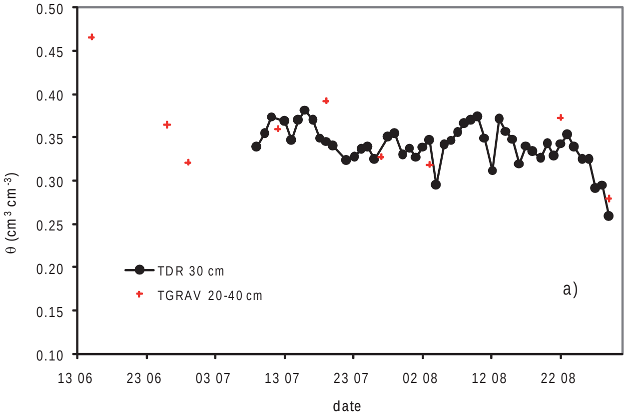
SWC measurement; compared to TDR method, no specific knowledge of analysing wave-forms is required.

TDR method provides important advantages as accurate and continuous measurements, no need for calibration, relatively insensitive to salinity. However, present some limitations because of complex electronics and high cost.

In the framework of AQUATER Project (Decision support systems to manage water resources at irrigation district level in Southern Italy using remote sensing information), the main objective of this study has been to monitor the SWC dynamics in a tomato (Foggia) and watermelon (Castellaneta - TA) field cultivations located in Southern Italy, by using: (i) the Diviner 2000, (ii) time domain reflectometry (TDR), (iii) ThetaProbe and (iv) the typical gravimetric methods.

II – Materials and methods

The data used in this paper came from field monitoring of 2006 and 2007 carried out in order to link the soil/plant water status to satellite information. In general, the SWC has been continuously monitored by means of TDR, while the other methods were applied at every satellite over passing.



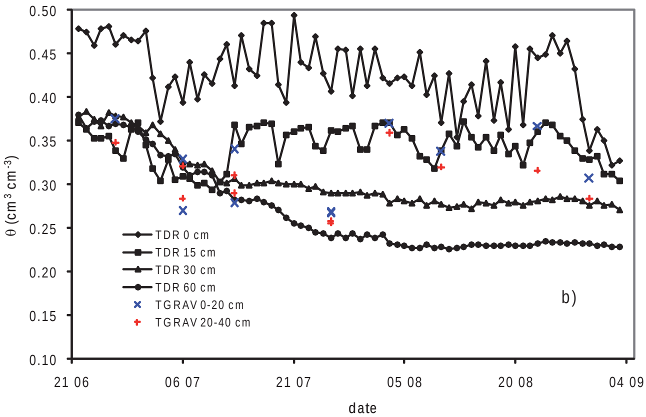


Figure 2. Variation of soil water content, θ, observed in F1 (top) and F2 (bottom) farms with both TDR and thermo-gravimetric method (TGRAV) during the tomato growing season.

A field experiment has been carried out in two farms located in Foggia (F1 and F2), in the Northern part of Puglia region (Southern Italy), and related to cultivation of tomato (Fig. 1). In these farms, the SWC was continuously monitored, from the flowering stage until harvest time, applying the TDR method described in Table 1 that reports the details of the experimental set-up, i.e. the probe geometric configuration, the characteristics and the position (row or interrow).

The probe signals were controlled by a TDR-100 (Campbell Sci. Shepshed, UK) and stored every hour in a CR1000 data logger.

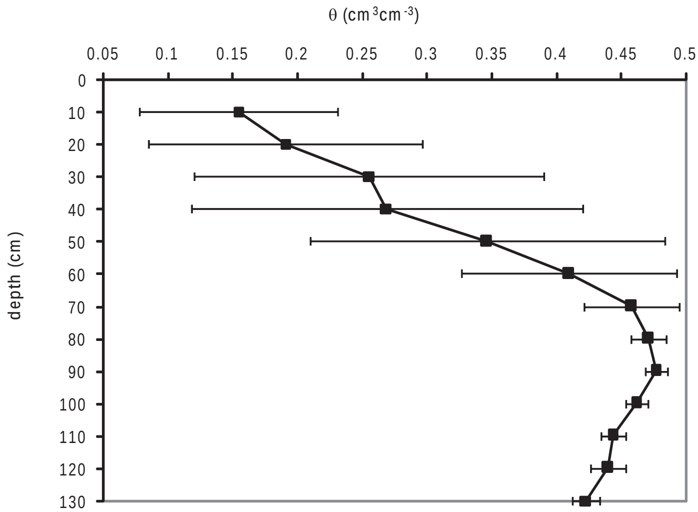


Figure 3. Variability of soil water content, q, during the tomato growing season, along the soil profile (0-130 cm), observed in F1 farm. Bars indicate standard deviation.

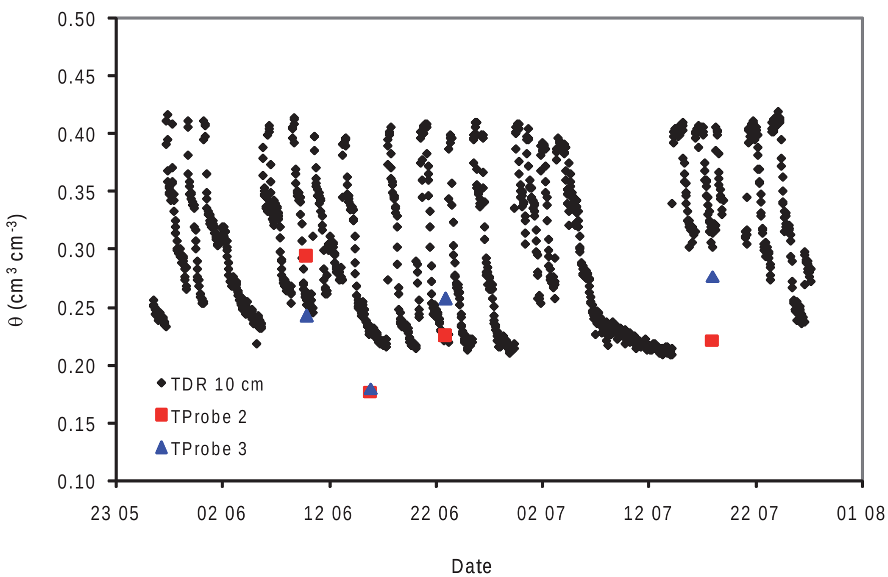


Figure 4. Variation of soil water content, θ, observed in F3 farm with both TDR and ThetaProbe (TProbe), under plastic mulch, during the watermelon growing season (2006).

Moreover, the SWC was also measured by means of Diviner 2000 with five PVC access tubes vertically installed in the soil, by using a portable probe (scanning length of 1.6 m) collecting reading at 10 cm depth intervals in soil profiles of 1.3 m. In the field, the access tubes were installed on crop rows.

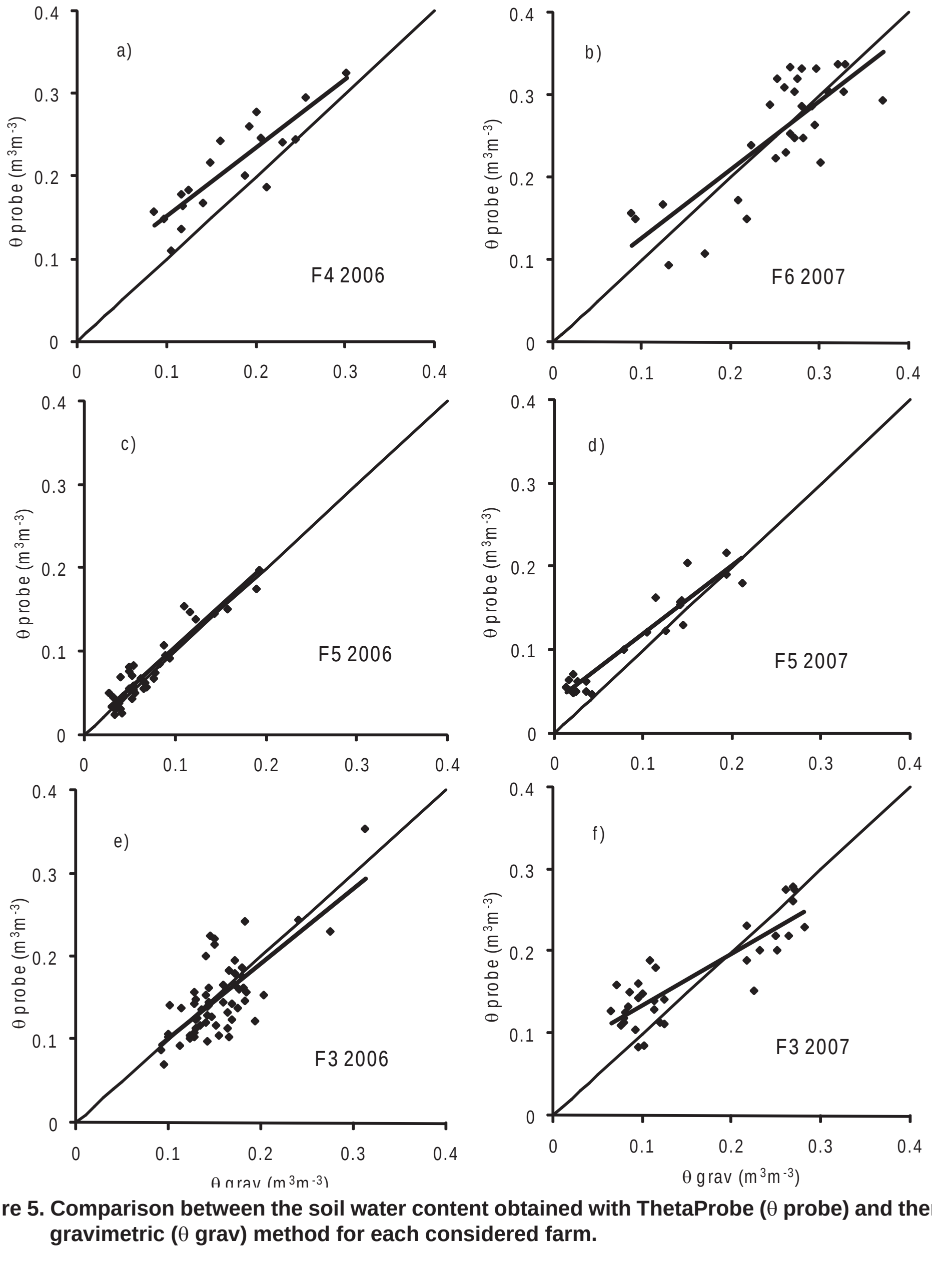


Figure 5. Comparison between the soil water content obtained with ThetaProbe (θ probe) and thermo-gravimetric (θ grav) method for each considered farm.

Another field experiment has been carried out in a farm (F3) located in Castellaneta (TA) close to the Jonical coastal area of Puglia region, on watermelon cultivation. SWC has been continuously monitored, along the soil profile, by using TDR method and stored every hour into a CR10X. The set-up of the TDR probes is described in Table 1.

Moreover the SWC of the shallowest layer of 5 cm was measured using ThetaProbe. For every measurement the probe was inserted into the soil surface on the plant row under the plastic mulch used by farmer in order to prevent the weed growth.

Finally, in order to estimate the volumetric SWC and bulk density by thermo-gravimetric method, undisturbed soil samples (steel cylinders with D=5 cm and H=5 cm) were collected from the surface layer of soil. The samples were weighed and dried in a ventilated oven at 105°C, until constant weight. For each undisturbed soil sample, four measurements were carried out by inserting, vertically in the soil, the ThetaProbe around the sampling points. This "calibration procedure" of ThetaProbe was also applied in other three farms localized in Jonical coastal plain ((F4, F5 and F6).

Moreover, for both of the field experiments, the SWC was also measured at two different depth (0-20 and 20-40 cm) with the typical thermo-gravimetric methods.

Water content estimates from ThetaProbe were compared with those obtained with the thermo-gravimetric method. For this purpose a systematic regression analysis, utilizing the SAS (1988) package, was performed by site and year testing three hypotheses concerning the coefficient of determination (R^2), the intercept (a=0) and slope (b=1).

III – Results and discussion

Figure 2 shows the dynamics of SWC as measured by TDR in two farms compared to measurements obtained in several days with the thermo-gravimetric method. Even if the comparison is not homogeneous, because of different soil sample volumes, it is possible observe a qualitatively good agreement among the two methods with one exception (i.e. in July 19, we observed a difference of 0.044 m^3 m^{-3}).

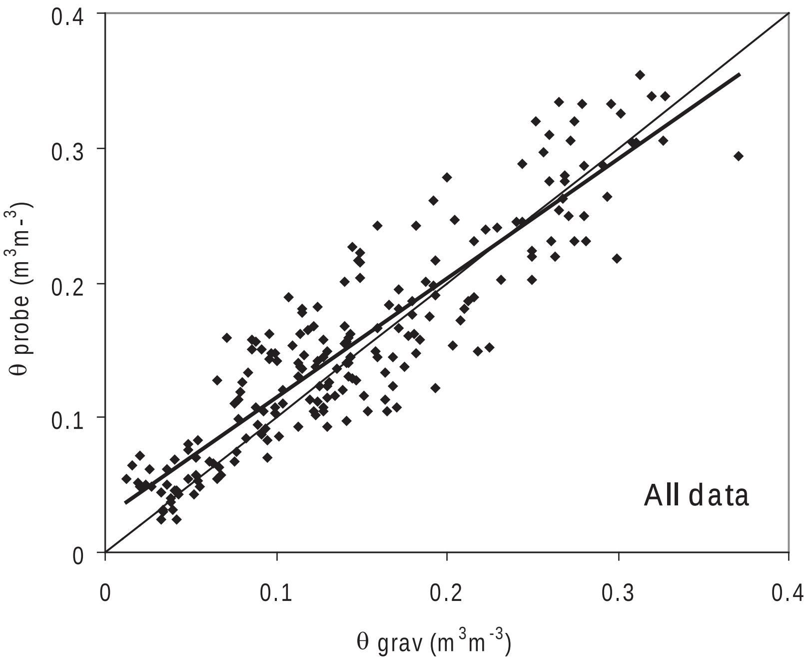


Figure 6. Comparison between the soil water content obtained with ThetaProbe (θ probe) and thermo-gravimetric (θ grav) method.

Below the dripper lines, the surface layer presented the largest temporal fluctuations due to irrigations, soil evaporation and plant water uptake. However in the interrow positions the SWC gradually decreased up to be constant beginning from the end of July around values of 0.25 and 0.30 at 30 and 60 cm from the plant-row, respectively.

Figure 3 reports the variability of SWC observed during the tomato crop season along the soil profile as observed by means of Diviner 2000. As expected, large differences in terms of standard deviation (corresponding to eight different measurements), were observed during the crop season in the topsoil (about 0-50 cm) and relatively constant water content below 90 cm.

In figure 4 we report the temporal variations of surface SWC measured at hourly scale by means of TDR during the watermelon growing season. In the same diagram we also show the ThetaProbe measurements carried out under plastic mulch. Several discrepancies (more than 0.05 m^3 m^{-3}) were detected on June 16 and July 18.

The results of the comparison between the Theaprobe instrument and thermo-gravimetric method are reported in Fig. 5 and 6 with the regression analysis statistics shown in Table 2. For any combination of year and site, the relationship among the two methods has been always highly significant with coefficients of determination, R^2, higher than 0.74 in four data-set on 6. Considering all the data in a pooled analysis, the R^2 was higher than 0.8 with a root mean square error of 0.03.

Table 2. Number of data points (N), intercept (a), slope (b) and coefficient of determination (R^2) of the linear regression analysis among the SWC measured with ThetaProbe and thermo-gravimetric methods

	N	a	b	R^2
Farm		**2006**		
F3	59	0.010 ns	0.907 ns	0.54***
F4	19	0.068**	0.833 ns	0.77***
F5	39	0.006 ns	0.990 ns	0.89***
		2007		
F3	33	0.072***	0.627***	0.74***
F5	22	0.038***	0.820 **	0.90***
F6	31	0.045 ns	0.831 ns	0.64***
All data	203	0.026***	0.885***	0.82***

Symbols: ns=not significant; *,**,***=significant at P<0.5, 0.01 and 0.001. a Significantly different from 0 (P=0.05). The tested hypothesis about intercept and slope are a=0 e b=1, respectively.

The intercept values, a, were close to 0 even if in three data-set the deviations from 0 were significant . However in four cases on six the coefficient b was significantly not different from the optimal value of 1.

IV – Conclusion

With the TDR it was possible to characterize with high precision the temporal evolution of the SWC at hourly and daily scale. Because of soil water fluxes of infiltration, redistribution in soil profile, evaporation and plant water uptake, in the shallow layer and below the dripper lines, we detected the largest fluctuation that were damped down on depth. In interrow position, the SWC stayed low and almost constant.

The DIVINER instrument proved to be an useful tool to estimate the soil water status along the profile giving important indication about the vertical root concentration. Thanks also to its low cost, the tool can usefully be employed for irrigation scheduling.

Finally, by means of ThetaProbe the shallow SWC was measured with precision and accuracy as demonstrated by the good results obtained with the regression analysis performed to compare the measurements of this instrument with the traditional thermo-gravimetric method. However, our data indicate that deviations from the line 1:1 can be significant and consequently preliminary calibration procedures have to be recommended if absolute values of SWC are required. In any case the TetaProbe is a very useful tool for studies and/or applications concerning the SWC estimation by remote sensing information.

Acknowledgements

This work was supported by the Italian Ministry of Agriculture, Food and Forestry Policies (AQUATER project, contract nr. 209/7303/05).

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Terrain and climate change impact on WUE of durum wheat in a semi-arid hilly catchment

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Abstract. The effects of climate change on agriculture are widely investigated by means of the support of crop simulation models, which can be useful to evaluate the efficacy of probable mitigation and adaptation strategies for improving the sustainability of crop growing in future scenarios. Even if wheat yield could benefit from increasing atmospheric CO_2, which could mitigate limited water availability in dry conditions, the interaction between climate, water and CO_2 concentration is still unclear with respect to its effect on crop yield. Moreover, any simulation model has investigated in detail the terrain effects (slope, elevation and azimuth effects) on the crop growth in function of climate changes.

The focus of this paper is to relate predicted yields of wheat crops to topographic characteristics, analysing the vulnerability in future scenarios with respect to crop cultivated in plane in a semi-arid region in South Italy. The presented simulation is based on the model STAMINA, which is the result of a European project (EU-QLK-5-CT-2002-01313) where a risk assessment for arable agriculture in hilly landscape has been done in detail in the final report of the project. This complex cropping system model, integrating spatial information, simulates agro-meteorology, hydrology, crop development and photosynthesis in hilly terrain, deriving, among others variables, Agro-Ecological Indicators (AEI) for aiding decision makers to improve sustainable farming at the catchment scale. Among the AEI indicators obtainable by STAMINA model, the WUE, defined by the ratio of yield and cumulative actual evapotranspiration, has been analysed to show how the spatial heterogeneity of the landscape affected its distribution in time and space. Moreover, a study on how management practices could mitigate negative impacts of climate change and topography is done.

Keywords. Agricultural practice – Slope – Exposition – Azimuth – Regional scale.

Influence du terrain et des changements climatiques sur l'efficience d'utilisation de l'eau (WUE) du blé dur dans une région collinaire semi aride

Résumé. *Les effets du changement climatique sur l'agriculture ont été largement étudiés avec l'aide des modèles de simulation des cultures, capables d'évaluer l'efficacité des stratégies de mitigation et d'adaptabilité pour améliorer la durabilité des cultures dans les scénarios futurs. Même si le blé bénéficie de l'augmentation du* CO_2*, qui peut mitiger la limitation de l'eau en condition de sécheresse, l'interaction entre le climat, l'eau et le* CO_2 *n'est pas encore claire pour ce qui concerne le rendement. En revanche, aucun modèle de simulation n'a exploré en détail les effets du terrain (pente, exposition et azimut) sur la croissance des plantes en fonction des changements climatiques.*

Ce travail focalise l'attention sur la prévision du rendement du blé en fonction des caractéristiques topographiques, en analysant sa vulnérabilité dans les scénarios futurs dans une plaine de l'Italie du sud. La simulation présentée se base sur un modèle (STAMINA) développé dans le cadre d'un projet européen (EU-QLK-5-CT-2002-01313), où la prévision des risques pour les cultures en terrain collinaire a été élaborée. Ce modèle intègre un système cultural, des informations spatiales, l'agro météorologie, l'hydrologie, la croissance et la photosynthèse en terrains en pente, pour fournir des indicateurs agro écologiques (AEI) afin de contribuer à l'amélioration de l'agriculture à l'échelle régionale. L'efficience d'utilisation de l'eau (WUE), définie comme le rapport entre le rendement et l'evapotranspiration réelle cumulée, a été analysée pour montrer comment sa distribution dans le temps et l'espace est influencée par l'hétérogénéité du terrain. En revanche, les pratiques culturales pour mitiger les effets du changement climatique et de la pente ont été étudiées.

Mot-clés. *Pratiques culturales – Pente – Exposition – Azimut – Échelle régionale.*

I – Introduction

Many scientific papers (i.a. Maracchi et al, 2005) and reports (IPCC, 2001, 2007) state increases in global average air temperature and increasing variability in precipitation patterns, with rainfall decreasing in most subtropical land, especially in the Mediterranean regions. Climate change will affect agricultural productivity (i.a. Harrison *et al.*, 1995a, 2000; Olesen and Bindi 2002). In particular, studies report positive effects on wheat production due to increasing in atmospheric CO_2 (i.a. Nonhebel, 1996) and this CO_2 – fertilization effect could mitigate other limiting factors such as water and nutrients (Lawlor and Mitchell, 1991), for example water more efficiently used will be beneficial in dry conditions (Chaudhuri *et al.*, 1990; Kimball *et al.*, 1995; Bunce, 2000). However, the interactive effects of drought and CO_2 concentration increasing on crop production in relation to climatic conditions is still an open problem (Ewert *et al.*, 2002). In northern latitudes, agriculture is likely to benefit from both, warming, which increases the length of the growing season, and elevated CO_2, which enhances resource use efficiency of plants (Mela, 1996). For the Mediterranean basin, lower yields are expected due to shorter growing seasons, heat and water stress (Rosenzweig and Tubiello, 1997; Harrison *et al.*, 2000) due to water shortage in the arid and semi-arid environment (Olesen and Bindi, 2002).

On the other hands, arable agro-ecosystems located in hilly regions may be particularly vulnerable to climate change due to the already significant impact of topography on water and energy fluxes changing the physical environment of crops. This vulnerability needs to be investigated at an ecologically and practically relevant scale using simulation models. However, there are few attempts (Nouvellon *et al.*, 2001; Zhang and Liu, 2005) to include terrain effect in modelling plant productivity. Process-based models to forecast yields under future climate usually simulated the interactions between weather, soil water availability and plant physiology (Tubiello *et al.*, 2000; Tubiello and Ewert, 2002).

In areas of greater hydrological forcing, like the Mediterranean, the impacts of terrain could be greater. However, none of the current models has investigated the terrain effects on climate change impacts by explicitly accounting for the atmospheric, soil and topographic effects on crop growth. In complex terrain, the actual energy fluxes and exchange processes, which drive plant growth, are affected by topographic characteristics such as slope, azimuth and elevation (Raupach *et al.*, 1992). Simulating the impact of topography on micrometeorological processes have progressed greatly, however, the complexity of these models (e.g. Kaimal and Finnigan, 1994) makes it difficult to use them for operational applications and for scenario studies.

Recently, Rana *et al.* (2007) developed a physically-based model to describe the effect of terrain on the energy balance as part of a European project (STAMINA; QLK-5-CT-2002-01313), which aimed to improve the impact assessment for arable ecosystems in hilly terrain (Richter *et al.*, 2006). The developed simulation model STAMINA has been used to carry out the analysis reported here. In particular, the focus of this paper is to relate predicted Water Use Efficiency (WUE) of wheat crops to topographic characteristics in a Mediterranean hilly terrain by using the algorithms developed by Rana *et al.* (2007) in the STAMINA model. In detail, our objectives were to quantify the relative increase of vulnerability of a wheat crop in hilly lands under future scenarios compared to cultivation in the plain using long-term data for the past/present and future climatic scenarios. Moreover, possible adaptation strategies have been analysed in order to mitigate the effect of climate change on crop growing in hilly landscapes.

II – Material and methods

1. The STAMINA model

The STAMINA modelling system is composed of three linked physically-based sub-models:

i) A micrometeorological model (Rana *et al.*, 2007) which has the purpose to estimate meteorological variables for each cell of a catchment in a complex terrain, following classical approach with the addition of a correction term to the energy balance in order to take into account the influence of the slope on atmospheric stability.

ii) A soil water balance based on the force-restore theory on 2 or 3-layers of the ISBA (Interaction Soil Biosphere Atmosphere) approach (Noilhan and Planton, 1989).

iii) A crop model based on net carbon assimilation as a balance of gross CO_2 assimilation and maintenance and growth respiration. This crop model is derived from the "School of de Wit" models (van Ittersum *et al.*, 2003) and it is similar to SUCROS (van Keulen *et al.*, 1982), and WOFOST (Boogaard *et al.*, 1998). All modification are extensively described in Richter *et al.* (2006).

The STAMINA model simulates in detail the crop development and interaction with the environment at small temporal and spatial intervals. It is, therefore, able to derive specific and aggregated, simple and complex Agro-Ecological Indicators (AEI), which can be used as both site- and crop-specific probabilistic indices. In particular, here, we focus on the future impact of terrain on Water Use Efficiency defined as the ratio between yield and cumulative actual evapotranspiration.

2. The catchment, climate scenarios and crop system

The selected catchment is located in Volturino (Foggia, Apulia region) in the south-east of Italy. The reference point at the bottom of the catchment has geographical coordinates of Latitude 41°29'N, Longitude 15° 07' E, altitude 365 m a.s.l.. The catchment area was 40 ha and was divided into 122 cells with a spatial resolution of 75 m. Side slopes ranged from 1° to 14° and minimum and maximum elevation was 365 and 470 m, respectively. The soil was classified as a silt loam. The predominant aspects of the field were north-east. The climate is semi-arid.

The weather inputs used for the baseline scenario (1961-1990) came from time series of meteorological data available for the site. The climate change scenarios B2 (environmental stewardship) (Hulme *et al.*, 2002) were derived from the 3rd simulation of the Hadley Centre global circulation model HadCM3, regionalized for Europe for the period 2071-2100. Atmospheric CO_2 concentrations were set at 330 and 562 ppm for baseline and B2 scenarios respectively.

The analysis on the meteorological data used for the simulations (Ferrara *et al.*, 2008) showed a significant increase of annual daily temperature from 1961 to 1990 (0.029 °C/year; $P<0.01$) and a trend in decreasing of the total annual precipitation. Moreover, this trend is confirmed by predictions in the future: predicted mean annual temperature increase is roughly 3 °C, while predicted mean annual precipitation is likely to decrease of 38% when comparing B2 scenario to the baseline one, with days with minimum threshold rainfall (> 5 mm) significantly decreasing (Ferrara *et al.*, 2008).

For the scenario analysis, we selected the predominant arable rainfed winter crops of the region: Durum Wheat (DW). The simulations have been made by selecting a sowing date according to the variety of DW and, for all the 30 years of each simulation run, the sowing date has been kept constant. Moreover, the simulations were run considering one crop at time and no irrigation was applied.

III – Results and discussion

An analysis of the distribution relative to yield, cumulative evapotranspiration and WUE for the Volturino catchment in the baseline and future scenario shows that in the flat land, the reference point of the catchment, the simulation with future scenario gives an increase of the yield with an unchanged evapotranspiration that produces an increasing in the WUE of about +6%. On the other hand, at the maximum elevation of the catchment, the simulated reduction of the yield and the increasing in the future evapotranspiration generates a significant decreasing in the WUE of about -30%. In particular, Figure 1 shows the distribution of the WUE inside the catchment, considering the average on the 30 years scenarios simulations. During the baseline scenario, the impact of the terrain on the yield and evapotranspiration reduces the WUE of about -40% going from the flat to the top of the catchment. The same trend is observed in the future scenario, with a more significant terrain impact: around -60% of reduction in the WUE, going from plane to top hill.

In order to improve increasing in WUE and then in wheat yield, adaptation strategies have been tested. First of all, different sowing date have been simulated during the future scenario, considering a early sowing date with respect the typical one of the regions. Figure 2 shows the cumulative probability relative to the simulated yield obtained for the baseline and B2 scenarios using the some sowing date at the end of November, and for B2 using a sowing date at the end of October. It is clear that the shift of the sowing date has a positive effect on future yield, reducing the risk of future failure of crop (yield < 1t/ha) from about 70% to 25%. The relative improvement in the WUE is reported in Figure 3 that shows the cumulative probability of WUE in the above-mentioned simulations. By changing the traditional management practices in terms of sowing date, the drastic reduction of WUE simulated in the B2 scenario, seems to be mitigated, reducing of 50% the probability to have a WUE less than 1 g/l. These strategy has been chosen considering the rainfall distribution variation in the future climate scenario with respect to the baseline one: even if there is a general decreasing in future rainfall, the beginning of autumn shows the more moisture conditions for sowing. Moreover, the decreasing in future simulated yield is due to the increase in temperature and the reduction of growing season.

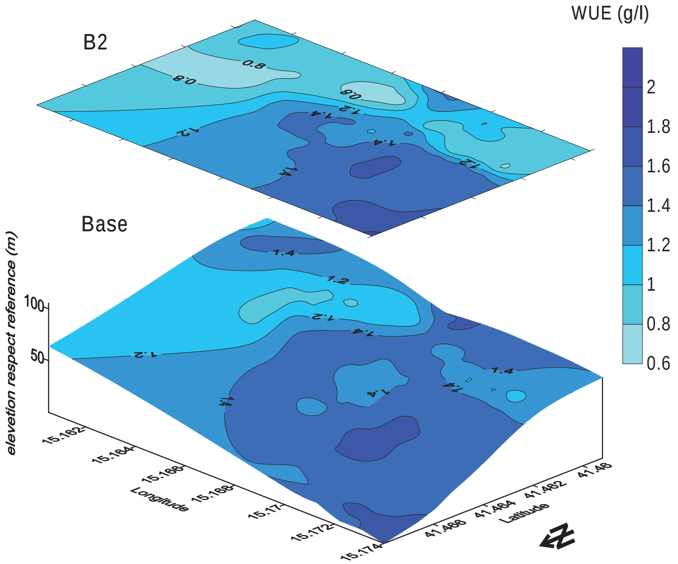

Figure 1. Distribution of the simulated WUE in the Volturino catchment during the baseline and the B2 scenarios.

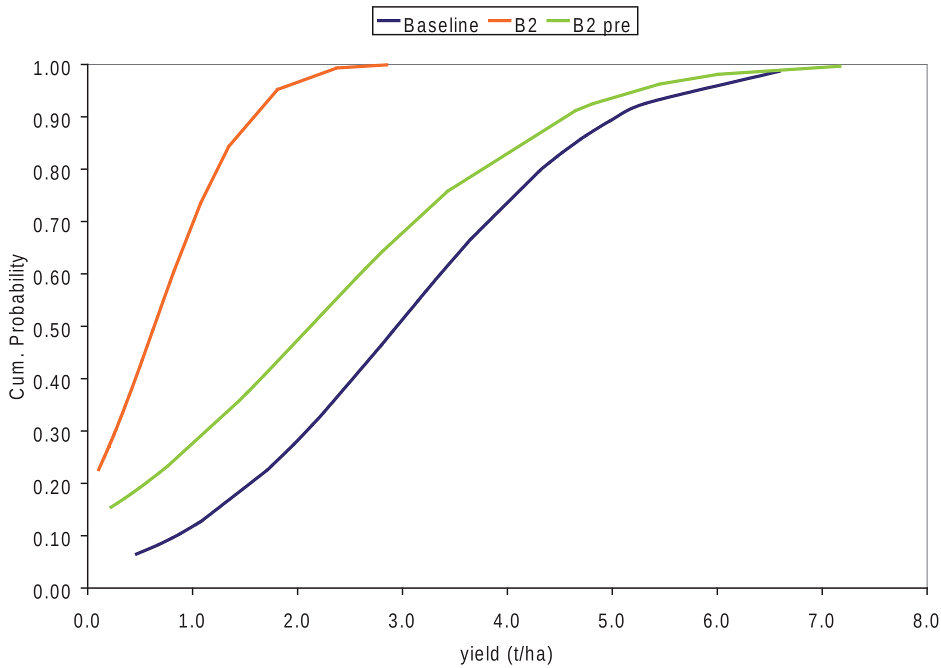

Figure 2. Cumulative probability of simulated yield for baseline and B2 scenarios, considering the traditional sowing date and a early sowing date in the future scenario (B2 pre).

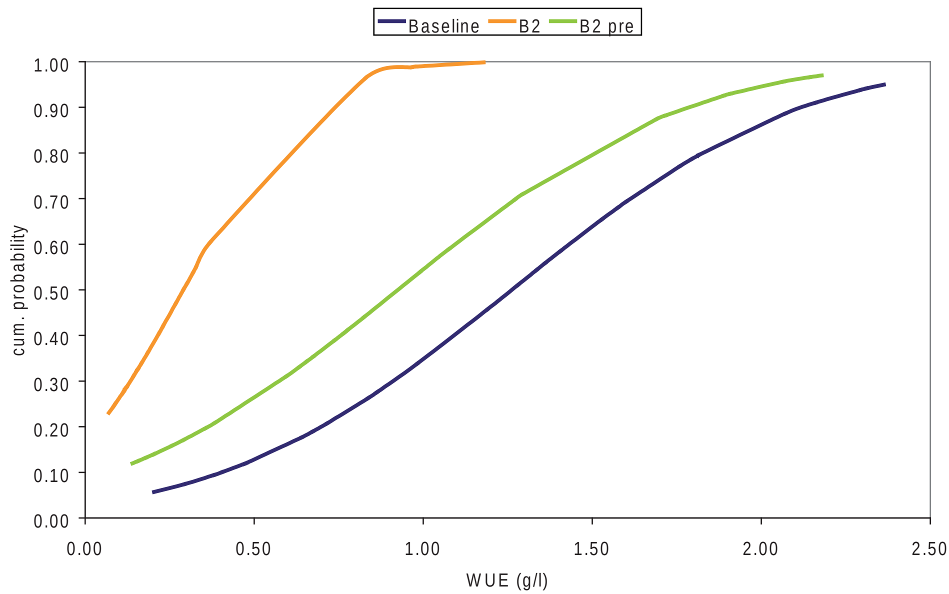

Figure 3. Cumulative probability of simulated WUE for baseline and B2 scenarios, considering the traditional sowing date and a early sowing date in the future scenario (B2 pre).

IV – Conclusions

In this work, we analysed the impact of complex topography on the rainfed wheat WUE in past and future climate scenarios for a catchment located in a semi-arid region of Mediterranean. The scenario analysis has been carried out using a newly developed model, STAMINA, obtaining results that show a significant increase in the negative impact of complex topography on WUE in view of future climate change. Increasing slope and elevation can explain great part of the variability of production and WUE in a complex field, even if the strongest effect is due to the climate projection.

From the results, the vulnerability of agriculture in hilly lands seems to be candidate to a substantial increase under future scenarios in semi-arid regions. Therefore, further research work on interaction between complex terrain and crop development, growth, production and water use efficiency is needed in arid and semi-arid environments, checking if management strategy, such as early sowing date, can improve the cereal production.

Acknowledgements

We acknowledge funding by the European Commission (QLK-5-CT-2002-01313).

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Water management of olive trees (*Olea europaea* L.) in a hilly environment of Central-South Italy

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Abstract. Olive tree is one of the most tolerant species to water stress. The experiment was carried out in Italy on five olive cultivars: Ascolana tenera, Nocellara del Belice, Itrana Maiatica e Kalamata. Four irrigation treatments were compared: a not irrigated control, a treatment fully irrigated during all season and two deficit irrigation levels that received an amount of water of 33 and 66% of ETc from pit hardening stage to fruit veraison. Results showed that a complete replacement of ETc would result in an averaged yield increase of 20% in comparison with 66%, though applying up to two times the seasonal water amount. So starting irrigation at the pit hardening stage supplying the crop with an amount of water of 66% of ETc is feasible for a water saving strategy in this experimental environment. The yield increase was primarily due to the higher fruit weight according to the enhancement in irrigation volume. Yield of the two years was 'off' for all cultivars probably for the high density of plantation that caused difficulties in air circulation. Plantation density was planned under the hypothesis to cut one plant after another within the row after 15–18 years to obtain a final density of 277 plant ha^{-1}. After 15 years of growth this hypothesis become reasonable.

Keywords. *Olea europaea* L. – Deficit irrigation – Irrigation scheduling – Yield.

Gestion de l'eau des oliviers (Olea europea L.) dans un environnement collinaire de l'Italie du Sud

Résumé. *L'olivier est l'une des espèces qui mieux supportent le stress hydrique. Cette expérimentation a été menée en Italie sur cinq cultivars: Ascolana tenera, Nocellara del Belice, Itrana Maiatica et Kalamata. On a comparé quatre régimes d'irrigation: une parcelle témoin non irriguée, une parcelle totalement irriguée pendant toute la saison, deux parcelles recevant respectivement un apport d'eau égal à 33 et 66% de l'ETc à partir du stade de durcissement du noyau jusqu'à la véraison. Si l'on compare la production obtenue et l'eau reçue par la parcelle totalement irriguée et celle recevant 66% de l'ETc on constate que, malgré un apport en eau jusqu'à deux fois supérieur à l'apport saisonnier, la production des plantes totalement irriguées n'augmente que de 20%. En conclusion, dans notre milieu expérimental, un régime d'irrigation apportant 66% de l'ETc pendant la phase de durcissement du noyau s'est démontré faisable et a permis une économie d'eau. L'augmentation de la production a été principalement causée par une augmentation du poids des drupes correspondant à l'augmentation du volume d'irrigation. La production des deux années a été «off» pour tous les cultivars, ce qui probablement dépend de la haute densité de la plantation empêchant une bonne circulation de l'air. La densité de plantation a été conçue se basant sur l'hypothèse que, après 15-18 ans, on effectuerait une coupe alterne dans chaque rangée aboutissant à une densité finale de 277 plantes par ha^{-1}. Cette hypothèse peut être prise en considération après 15 ans de vie des arbres.*

Mots-clés. *Olea europaea L. – Irrigation déficitaire – Pilotage de l'irrigation – Rendement.*

I – Introduction

Mediterranean climate is characterized by dry and hot summers and cold and humid winters. Abiotic stresses combined with climate variability are the limiting factors for quality and yield of agricultural production. Recent previsions of global change climate predict that in the Mediterranean region winter precipitation will increase near the year 2050, while summer precipitation will decrease by 10 to 15%. In addition, the agricultural sector should also bear an increase in water rates caused by the increase in demand, energy costs and distribution. This general situation makes crucial to study irrigation scheduling models that allow avoiding water losses and improving water use efficiency.

It is recognized that olive tree is one of the most drought tolerant fruit trees, but water responses of this species to good soil water supply is higher compared with other fruit species (Xiloyannis *et al.,* 1999) in terms of efficient use. In addition, studies demonstrated that irrigation strategies partially satisfying water consumption in fixed phenological stages (RDI) minimize detrimental effect on fruit yield and on vegetative development (Alegre *et al.,* 2000, Goldhamer *et al.,* 1999, Girona *et al.,* 2002). In Spain, the *cv*. Arbequina showed that irrigation volumes of 75 and 50% of ETc supplied from pit hardening to the beginning of fruit ripening resulted in no significant yield reductions compared with the control, while the water saving was 24 and 35%, respectively. In the same trial 25% of ETc restitution caused a 16% yield loss and a 47% water saving compared with the control due to a lower number of fruit per tree and a lower fruit fresh mass (Alegre, 2001). Thus a rationale irrigation scheduling is essential to reach high quality standard of final production and high and stable yield. Drought adaptations of olive trees depends on several anatomic characteristics such as leaf cuticular waxes, stomata present only in the abaxial position and covered by trichomes and physiological mechanisms such as the ability to withstand low water content and water potential in the tissues. This ability allows establishing a gradient between leaves and roots systems and soil that allows water uptake below the conventional wiling point. This characteristic of olive trees, as reported by Xiloyannis *et al.*, (1999) and Dichio *et al,.* (1994), permits to utilize soil water also at water potential of -2.5 MPa. Under water stress conditions the canopy transpiration rate is higher than root water uptake during the morning independently of soil water conditions (Gucci, 2007). Consequently, the water content in the plant tissues is reduced to satisfy the transpiration flux. Tissues could loss about 60% of water showing high capacitance that permits transpiration when the evaporative demand of the environment is high (Xiloyannis *et al.,* 1999). As a consequence of high water stress, olive tree stops vegetative growth by increasing stomatal resistances and reduce gas exchange to a very low rate. Although, since the fruit yield depends on the time course of vegetative development and reproductive phases during its biennial cycle, the effects of water stress allow negative impacts not only during the season but also in the subsequent years.

The present study summarizes field experiment results of five olive tree cultivars growing in a hilly area of Central-South Italy. The aim of the work was to test the hypothesis that irrigation applied from pit hardening to fruit veraison, in the study area, would allow good crop yield while saving water.

II – Material and methods

The field trial was carried out in the period 2006-2007 in a typical area of southern Italy at CNR-ISAFoM experimental farm (Benevento, 41°06’, 14° 43’; 250 m above sea level). The orchards was established in 1992 and trees were planted to a density of 555 plant per hectare (6 x 3 m).

The soil texture is sandy-loam and the soil has a volumetric water content of 35.6% at field capacity (-0.03 MPa) and 21.2% at wilting point (-1.5 MPa), an organic matter content of 1.76%, a CaCO3 of 1% and a pH of 7.2. The experimental orchard was planted in 1992 with one-year-old trees grafted in a nursery on DA-12-Io clonal rootstock (Fontanazza *et al.,* 1992) - patent IRO-CNR no. 1164/NV. Trees were trained using the central leader training system (Fontanazza, 1993) with a planting density of 6 x 3 m. The plantation density was proposed at field establishment as ‘dynamic’ since after 15th – 18th years of growth one plant on the row should be cut and the final density should become 277 plant ha-1 (6 x 6 m). At field establishment and during the first two years after planting, all trees were irrigated equally to guarantee uniform development. Differentiation of irrigation treatments started in 1994. Irrigation water was delivered daily, using a system with 4 drip nozzles (two per side) of 4 l h^{-1} per tree set in a line along the rows at a distance of 0.50 and 1.00 m from the trunk.

Five olive cultivars for table consumption and double aptitude were tested: Ascolana tenera, Nocellara del Belice, Itrana Maiatica e Kalamata. Four irrigation treatments were applied: a not irrigated control (T0), a treatment fully irrigated (100% of maximum evapotranspiration, ETc) during the all season (T100) and two deficit treatments that received 33 and 66% of ETc (T33 and T66) irrigated from pit hardening to fruit veraison. Reference (ETo) evapotranspiration was estimated adopting Penman-Monteith model and data were adjusted with a crop coefficient equal to 0.65 and a tree ground coefficient of 0.85.

The experimental design was a split-plot, replicated four times with irrigation treatments in the main plots and cultivars in the sub-plots. Each sub-plot consisted of 7 trees.

To assess water regime effect on plant growth, trunk diameter was measured at regular intervals at 0.4 m above the soil level and at pruning time removed wood was collected and weighted. Dry matter of pruned material was determined on a sample after oven dry.

Fruits of each elementary plot were harvested when the cultivars were suitable for table consumption. Yield components were analyzed by determining fruit weight (fresh and dry weight), flesh-to-pit ratio and fruit diameters (longitudinal and equatorial) on a sample of 50 fruits per elementary plot.

Data were analysed using the SAS statistical package. Analysis of variance (ANOVA) was applied by cultivar since the variance was not homogeneous. The interaction between years and irrigation levels was not significant therefore, data presented are means of the two years. Means separation between irrigation treatments was performed with the Least Significant Differences test (LSD) at the 0.05 level.

III – Results and discussion

The climatic conditions of the experimental site were characterized by a mean annual precipitation of 736 mm (1984 - 2007 average) mainly occurring in fall and spring months, while scarce or no rainfall events were generally detected from mid-June to mid September. The yearly mean reference evapotranspiration was about 1233 mm. Differences between the two experimental years were essentially due to precipitation amount and seasonal distribution that influenced the irrigation volume, while temperatures were near the poliannual mean. In the first year, rainfall during the irrigation season accounted for 54.4 mm, with rainy events that occurred at the end of July and first decade of August (Tab. 1).

Table 1. Irrigation volume, crop evapotranspiration (ETc)) and useful rainfall (> 5 mm within 24 h) during the irrigation period of each experimental year.

Treatment	Irrigaton period		ETc	Useful rain	Irrigation volume
	beginning	end			
				mm	
33	27/07/06	14/09/06	117	54.4	21
66	27/07/06	14/09/06	117	54.4	41
100	26/06/06	14/09/06	217	58.0	159
33	24/07/07	07/01/07	191	10.6	57
66	24/07/07	07/01/07	191	10.6	115
100	20/06/07	07/01/07	307	10.6	297

By contrast the second year was drier and only 10.6 mm of useful rain were detected during the all season. Irrigation of T100 started when the soil water content was about the 50% of the total available water for a soil layer of 1.40 m (Fig. 1). These conditions were detected on 20 and 26 June of 2006 and 2007, respectively. For the other two deficit irrigated treatments water was delivered from 27 and 24 July of 2006 and 2007 respectively, when the beginning of pit hardening phase was monitored. Soil water content showed value below 50% of available water at the end of May in all years, while at the time of starting irrigation for treatment T33 and T66 (doy 207) soil water content was near the wilting point. Subsequently the soil profile was gradually replenished by rainfall, with different patterns among years according to the amount of precipitation. Irrigation supply ended in the mid of September in the first year since rainfall replenished the soil layer explored by the root systems while in the second year was necessary to deliver irrigation water until 7 October.

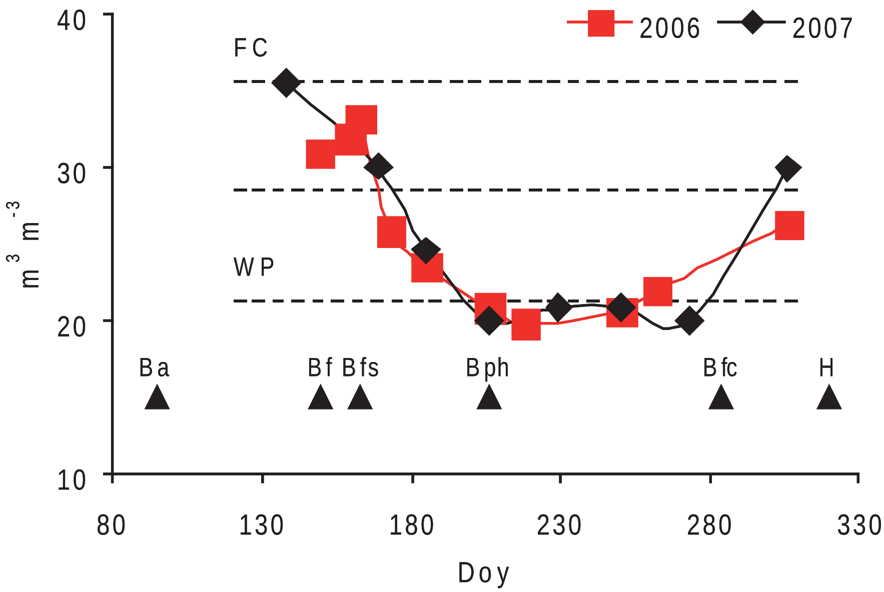

Figure 1. Volumetric soil water content in the top 1.40 m soil layer of rainfed control treatment during the irrigation season of two experimental years (Doy = day of year). Main phenological stages of the cultivars are reported: FC = field capacity, WP = wilting point, Ba = blossom appearing, Bf = beginning of flowering, Bfs = beginning of fruit set, Bph = beginning of pit hardening, Bfc = beginning of fruit veraison, H = harvest.

Across years, cultivars and treatments, stomatal conductance was exponentially related to water potential (Fig. 2).

Stomata are integrators of all environmental factors affecting plant growth, resulting in a wider scattering of stomatal conductance than water potential. These olive trees were able to restrict water loss by modulating stomatal closure at different irrigation levels. The sensitivity of stomata to irrigation might have also reduced the impact of water stress on fruit yield.

Growth patterns of the tested cultivars showed similar behaviour in response to water regime. Pruned wood evaluated as the mean weight of dry matter (DM) removed in the two years, increased according to the increase in irrigation levels (Fig. 3).

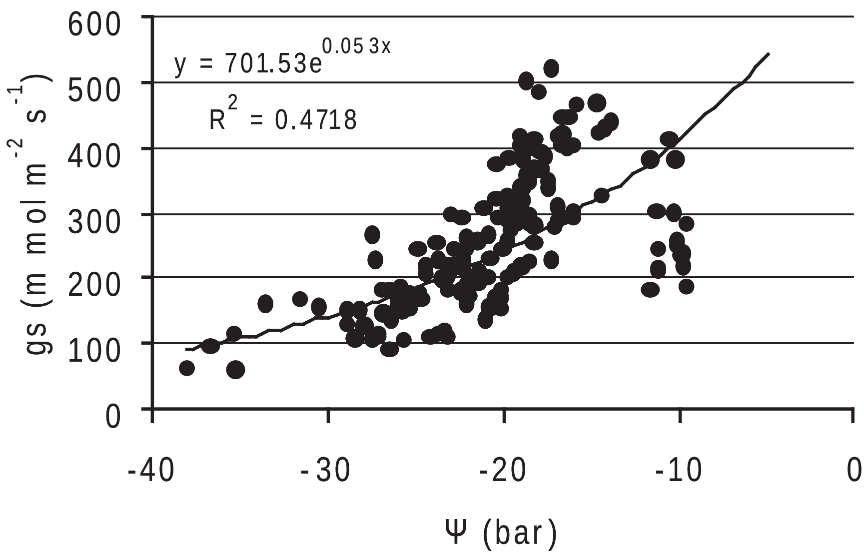

Figure 2. Exponential relation between stomatal conductance (gs) and water potential (?). Relationship between water potential and stomatal conductance for pooled data collected in 2006 2007. Regression parameters of exponential function fitted to data are also reported.

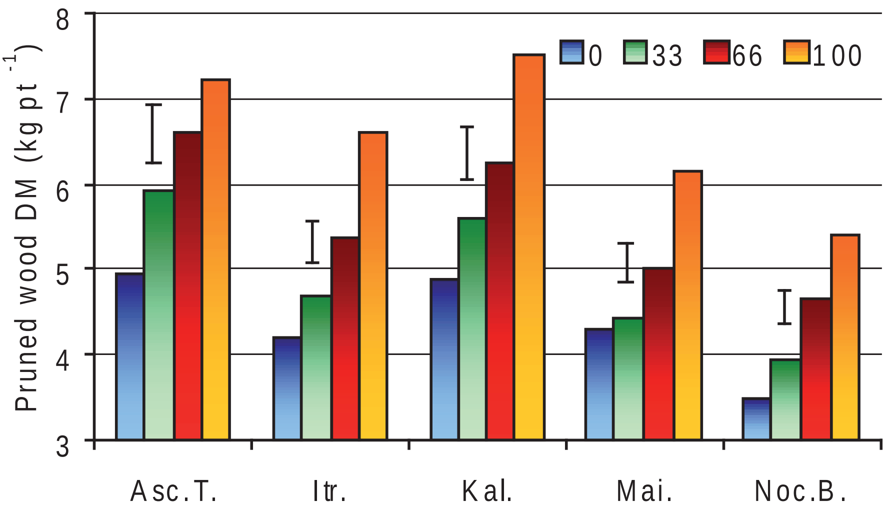

Figure 3. Mean weight of dry matter (DM) of pruned wood removed in the two years as a function of treatments and cultivars. Bars represent LSD value at P = 0.05.

Differences between treatments were significant in all cultivars, while only a trend was found between T0 and T33 for cv. Maiatica. Similar response to watering regime was reported by Magliulo *et al.* (2003) in the same environment for cultivar Frantoio and Leccino and by d'Andria *et al.* (2004) on the same cultivars of the present experiments. In these experiments deficit irrigation (replacing 33% of ETc during the all irrigation season) environment did not show significant increments in comparison with rainfed treatments. These findings are related to present environmental conditions with sufficient spring rainfall that guarantees enough water throughout the vegetative development. By contrast, a restitution of 66 and 100% of water consumption allows significant increments of canopy development. This aspect could have an economic impact since pruning expenses for olive trees generally account for 20-30% of annual cultural costs, being second only to harvesting. Accordingly, the optimisation of deficit irrigation strategy may be economically profitable further limiting tree size and vegetative development with the central leader training system (Gucci and Cantini, 2000). Similar findings were found for trunk area and crown volume (data not shown). Nocellara and Maiatica were the least vigorous cultivars.

Yield of the two years were 'off' for all cultivars (Fig. 4). This behavior was probably due to the high plantation density that caused difficulties in air circulation and high humidity within the canopy, allowing the diffusion of pathogen fungi such as cycloconium. In addition, solar radiation within the canopy was scarce. Itrana, Maiatica and Nocellara del Belice were the most sensitive cultivars to experimental conditions. Plantation density was planned under the hypothesis to cut one plant after another within the row after 15–18 years to obtain a final density of 6 x 6 m (277 plant ha^{-1}).

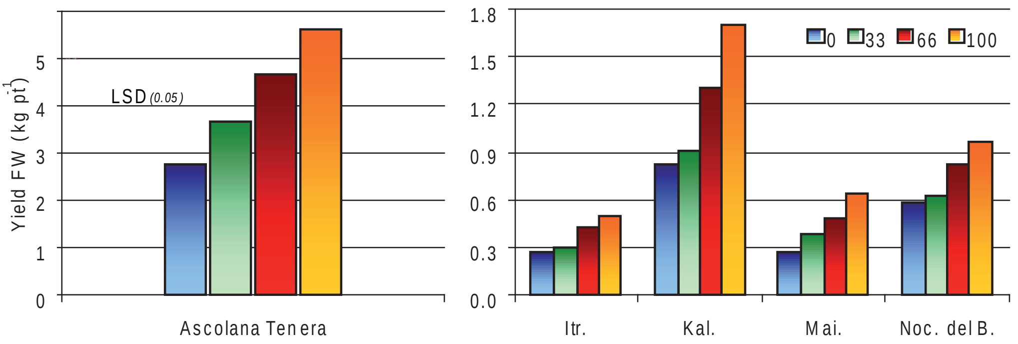

Figure 4. Mean yield of the two years as a function of treatments and cultivars. Bars represent LSD value at P = 0.05.

Besides, yield significantly increased with the increase of irrigation amounts in the most productive cv., Ascolana tenera. Fully irrigated plants during the all season had higher yield than T66 treatment, only for Ascolana tenera and Kalamata. However, in Kalamata, yield was not significantly different between T0 and T33. Itrana, Maiatica and Nocellara del Belice showed effects of irrigation only between T0 and T100. The lack of irrigation effects in these three cultivars was probably due to the generally low productivity in the two experimental years.

The yield increase was primarily due to the higher fruit weight and number according to the enhancement of irrigation volume (Tab. 2). Fruit fresh and dry weights were affected by irrigation treatments, showing marked differences between irrigation levels in all cultivars.

The greatest fruit weight of T100 resulted from the increase in both width and length of fruits, while the shape (polar – equatorial ratio) was not affected by the irrigation regime.

Irrigation favoured the development of fruit flesh. This pattern was due to the increase in flesh–to-pit ratio in all cultivars. In particular, the highest increment was shown by Ascolana tenera between T0 and T100.

Table 2. Fresh and dry weight of fruit, flesh-pit ratio and shape (polar-equatorial diameter ratio) as a function of treatments and cultivars. Data are the mean of two experimental years. The LSD value at P = 0.05 is reported.

Cultivar	Treatment	fresh weight	dry weight	flesh-pit ratio	Diameter pol.-equat. ratio
		g			
Ascolana T.	0	5.03	1.61	3.82	1.29
Ascolana T.	33	5.87	1.82	3.94	1.32
Ascolana T.	66	6.73	1.87	4.91	1.30
Ascolana T.	100	7.73	2.17	5.43	1.24
	LSD (0.05)	0.82	0.22	1.03	ns
Itrana	0	3.68	1.35	2.65	1.19
Itrana	33	3.83	1.38	2.91	1.18
Itrana	66	4.67	1.72	2.80	1.18
Itrana	100	4.79	1.77	2.90	1.16
	LSD (0.05)	0.38	0.17	ns	ns
Kalamata	0	3.64	1.33	3.72	1.45
Kalamata	33	3.91	1.45	3.86	1.51
Kalamata	66	4.57	1.62	3.63	1.46
Kalamata	100	5.48	1.97	4.48	1.46
	LSD (0.05)	0.53	0.14	0.54	ns
Maiatica	0	2.19	0.64	2.53	1.30
Maiatica	33	2.86	0.79	2.86	1.31
Maiatica	66	3.45	0.94	3.15	1.30
Maiatica	100	4.24	1.24	3.57	1.30
	LSD (0.05)	0.35	0.13	0.63	ns
Nocellara B.	0	3.93	1.42	3.21	1.15
Nocellara B.	33	4.54	1.62	3.85	1.16
Nocellara B.	66	5.03	1.78	4.51	1.11
Nocellara B.	100	5.74	1.98	4.09	1.18
	LSD (0.05)	0.53	0.19	0.76	ns

IV – Conclusions

The increase in fruit size with increasing irrigation levels was primary determined by dry matter accumulation in both endocarp and mesocarp, following similar patterns in each treatment. Bigger fruits had greater equatorial and longitudinal diameter or area; therefore, the overall fruit shape was only marginally affected by deficit irrigation. The yield increase with irrigation was due primarily to a higher fruit weight (d'Andria *et al.* 2004) and fruit number in both cultivars (data not shown).

Between others, one important aspect of irrigation delivered only in the most sensitive phenological phases was a better control of vegetative development, thus reducing plant strength and pruned wood, without high detrimental effects on fruit yield, which should lead to a considerable increase in water use efficiency. This was evident in the most irrigated treatment that yielded a higher vegetative development as compared with T66.

Results implied that a complete restitution of ETc (T100) would result in an average yield increase of 20% in comparison with T66, though applying up to two times the seasonal water amount. This suggests that starting irrigation at pit hardening, supplying the crop with a water amount of 66%

of ETc, is feasible for a water saving strategy in these experimental conditions. In these pedo-climatic conditions, delaying water supply could be achieved particularly considering management costs, such as water, energy and pruning.

Training system adopted (central leader) and plant density (555 plants per hectare) of this olive plantation should be strongly revised according to the present results. After 15 years of growth the hypothesis to cut one plant after another within the row become reasonable, to avoid detrimental effects on yield performances and plant pathology. The central leader training system could be still grantable, in terms of management costs for the varieties of the present experiment.

Acknowledgment

The Ministero delle Politiche Agricole e Forestali supported this research within the project “Ricerca ed innovazione per la filiera olivicola Meridionale – RIOM”. We acknowledge the technical expertise of Davide Calandrelli and Fulvio Fragnito for ecophysiological measurements.

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Effects of deficit irrigation on two cherry tomato cultivars in hilly areas

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Abstract. In the last years the cultivation of cherry tomato significantly increased in the hilly areas of Campania region. Generally in the Campania hilly areas the species is cultivated under rainfed conditions to improve some quality parameters. The cultivation without irrigation is feasible thanks to the resistance to abiotic stress of cherry tomato and because climatic conditions of hilly areas of the region are characterized by erratic rainfall during the summer. The aim of the present work was to evaluate the response to deficit irrigation scheduling based on critical plant growth stages to ensure good productivity of two cultivars of cherry tomato (Altavilla cv. standard and Mignon hybrid). The trial was carried out in 2005 and 2006 at the experimental station of the CNR-ISAFoM, in Piano Cappelle (BN). The two cultivars were subjected to four irrigation regimes: T0 (rainfed), T1 (one irrigation at beginning of flowering), T2 (one irrigation at beginning of flowering and another at 50% of fruit set) and T3 (at beginning of flowering, at 50% of fruit setting and, after, every 15 days). Results showed that, in the area of the experiment, a limited water supply is useful to increase yield depending on the climate of the year and that it is possible to obtain high quality cherry tomatoes yield also with a limited irrigation water supply.

Keywords. Cherry tomato – Deficit irrigation – Hilly areas – Critical phonological stages – Productivity.

Effets de l'irrigation déficitaire sur deux cultivars de tomate cerise dans les zones collinaires

Résumé. *Dans les années récentes, la culture de la tomate cerise a remarquablement augmenté dans les zones caires de la Région Campania. En général, dans les zones collinaires de la Campania ces espèces sont cultivées sans irrigation afin d'en améliorer les paramètres qualitatifs. La culture sèche est faisable grâce à la résistance de la tomate cerise au stress abiotique et aux conditions climatiques des collines de la région, caractérisées par des pluies estivales inconstantes. Le but de cette étude est d'évaluer la réponse à un schéma d'irrigation déficitaire se basant sur les stades critiques du développement de la plante pour assurer une bonne productivité de deux cultivars de tomate cerise (Altavilla cv. standard et Mignon hybrid). L'étude a été menée en 2005 et 2006 dans la station expérimentale du CNR-ISAFoM, située à Piano Cappelle (BN). Quatre régimes d'irrigation ont été administrés aux deux cultivars: T0 (sans irrigation), T1 (une irrigation en début de floraison), T2 (une irrigation en début de floraison et une autre à 50% de la nouaison) et T3 (en début de floraison, à 50% de la nouaison et, ensuite, tous les 15 jours). Les résultats ont montré que, suivant le climat de l'année dans la zone de l'expérimentation, un apport d'eau limité fait augmenter la production tout en permettant d'obtenir des tomates cerises de haute qualité.*

Mots-clés. *Tomate cerise – Irrigation déficitaire – Zones de colline – Stades phénologiques critiques – productivité.*

I – Introduction

Tomato (Lycopersicon esculentum Mill.) is important worldwide, both for fresh and processing markets (Opiyo and Ying, 2005). It is grown wherever climatic conditions are favorable. In 2005, the world production of tomato reached about 126,090.74 (10^3) Mg, 18,227.53 (10^3) Mg of which in the European Union (EU). In Italy, 7,187 (10^3) Mg of tomato were produced, that is roughly 40% of the entire EU tomato production (Mori *et al.*, 2008).

Italy is the greatest European tomato producer for processing market: approximately 70,000 hectares are cultivated and about 4 million tons are intended for processing. The tomato production is mainly located in Puglia, Emilia-Romagna, Campania and Sicily (Tei *et al.,* Spigno *et al.,* 2003).

In Campania about 5,000 farms produce tomatoes for the processing industry, on an area covering 2,832 hectares (35.8% of the total area planted with tomatoes). In the last years the cultivation of cherry tomato significantly increased in the hilly areas of Campania region since the favorable climatic conditions allow a high-quality product. Generally in the Campania hilly areas, the species is cultivated under rainfed conditions that improve fruit sugar and soluble solids content and other quality parameters (Pentangelo *et al*., 2003).

The cultivation without irrigation is possible due to the species resistance to abiotic stress (high temperatures and water deficit) and to climatic conditions of hilly areas, characterized by erratic rainfall during the summer. Nevertheless this practice is very risky for farmer's income, because it becomes strictly dependent on the occurrence of useful rainfall during the most important phenological stages of the crop (fruit set and fruit growth). Furthermore, climate global change models forecast a decrease of about 10 to 15% of summer precipitation that makes crucial the study of sustainable irrigation scheduling in the area of the experiment.

The aim of the present work was to evaluate the response to deficit irrigation scheduling based on critical plant growth stages to ensure good productivity and quality.

II – Material and methods

The field trial was carried out in 2005 and 2006 at the CNR - Institute for Agricultural and Forest Mediterranean Systems (ISAFoM) research station located in Piano Cappelle, Benevento (41°06' Nord, 14°43' East; 250 m a.s.l.), an hilly areas of southern Italy.

The experiment involved two cultivars of cherry tomato (Altavilla cv. standard and Mignon hybrid) in a factorial combination with four irrigation regimes to partially satisfy the crop water consumption: T0 (rainfed), T1 (one irrigation at beginning of flowering), T2 (one irrigation at beginning of flowering and another at 50% of fruit set) and T3 (at beginning of flowering, at 50% of fruit setting and every 15 days onwards).

Watering volume was estimated as to replenish the soil profile to 50% of field capacity for a soil layer of 0-0.60 m. The irrigation water was distributed using a localized system with on-line drip nozzles delivering 2 L h^{-1} set in line equally spaced between the twin rows. Table 1 reports the amount of waterings along with the seasonal water volumes for all irrigation regimes for both experimental years.

Table 1. Irrigation volumes, useful precipitation (> 5 mm) and seasonal water of the two experimental years.

Irrigation date	Water volume mm			
	T0	**T1**	**T2**	**T3**
2005				
Irrigation volume	0.0	37.0	81.2	154.9
Rainfall > 5mm	29.8	29.8	29.8	29.8
Seasonal volume	29.8	66.8	111.0	184.7
2006				
Irrigation volume	0.0	20.0	50.9	95.8
Rainfall > 5mm	186.8	186.8	186.8	186.8
* Seasonal volume	186.8	206.8	237.7	282.6

*A relevant rainfall of 70,2 mm occurred in the first decade of June 2006

During the crop cycle the soil water content of each treatment was gravimetrically measured for a soil layer of 0-0.60 m with 0.20 m increments; this was monitored before and 24-h after each watering and at the beginning and at the end of the growing season.

The experimental design consisted in a randomized complete block with four replicates where the irrigation variable was in the main plots and cultivars in the sub-plots.

Tomato plants, grown in greenhouse in plastic cellular containers, were transplanted on May 17th and May 10th in 2005 and 2006, respectively. In the conventionally tilled plots of 30 m^2 (5 by 6 m) plants were placed on twin rows to reach a density of 40.000 plants ha^{-1} (1.20 m row spacing and 0.30 m between the twin rows). The crop was cultivated adopting the traditional agronomic management for the area. At planting, all plots were equally supplementary irrigated to guarantee uniform plant development, thereafter irrigation level differentiation started. The harvest was made manually when the plants reached 90% of fruits ripening on the 18th and the 25th of August for cultivars Mignon and Altavilla in the first year and on 23 August for both cultivars in the second year. At harvest, in a sampling area of 20 m^2 per plot, marketable yield components (fruit mean weight, biomass yield and waste yield) as well as main quality characteristics were determined.

Data were analyzed by analysis of variance (ANOVA) using the SAS (SAS Institute inc., Cary, N.C.) statistical package, and means were compared using Least Significant Difference (LSD).

III – Results and discussion

Environmental conditions were typical of a sub-humid Mediterranean area characterized by a mean precipitation of about 740 mm, a potential evapotranspiration of 1,240 mm (23-year mean data) and scarce summer precipitation. In the experimental area the daily mean temperature increased from 10.7°C in April to 22.4°C in July, decreasing to 18.2°C in September, while the reference evapotranspiration increased from about 3 mm day^{-1} in April to about 8 mm day^{-1} in July, starting to decrease in August.

The climatic conditions during the two experimental years differed for the precipitation amount and distribution (Fig. 1).

The first year was dryer than the second one and, during the whole crop cycle, 29.8 mm rainfall occurred. In this year a rainfall event of 34 mm occurred during the harvest and it was not included in the seasonal water budget since it was not useful for yield formation. In the second year the seasonal amount of useful rainfall (> 5 mm in 24 hours) was 186.8 mm. In this year several precipitations occurred in the first decade of June when a total amount of 70.2 mm was monitored. Minimum and maximum air temperatures were generally lower than poli-annual mean value, while in the third decade of June values showed a peak of about 2.5°C higher than the poli-annual means in both years.

Evaporation pan showed values generally near to the poli-annual mean in both year, but for the first decade of June of the second year when it decreased as a consequence of a rainy period. In addition, the second decade of July 2006 was characterized by a daily evaporation of about 1 mm higher than the first year.

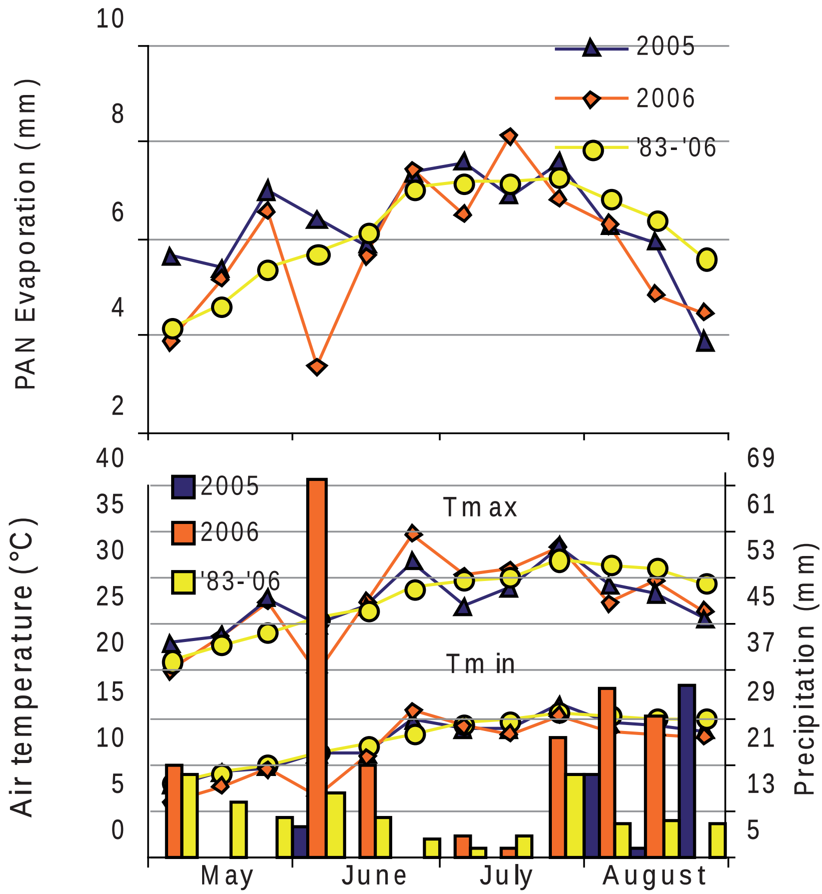

Figure 1. Time course of some climatic parameters in the two experimental years compared with the 23 - years mean values. PAN evaporation (10 days mean), minimum and maximum air temperatures (T min and T max - 10 days mean) and precipitations (10 days sum) are reported.

In 2005 the soil water content (Fig. 2) monitored before each watering showed a gradual reduction of soil water content during the crop cycle always showing values below wilting point for T0 treatment. Soil water content in irrigated treatments also reached a level near to the wilting point before each watering. This behavior points out that, in all treatments, both cultivars consumed the whole amount of the given water. In 2006 soil water content for T0 treatment showed values near to the wilting point and this trend increased during the plant growing. Only in the first decade of June 2006 soil water content reached a value near to field capacity because of a 70.2 mm rainfall.

After the beginning of watering the available soil water content clearly varied in different treatments. In the second year, the wetter year, irrigated treatments showed a soil water content higher than in 2005 and treatment T3 reached about 50% of available water content in the last two irrigation dates. In the 2006 watering volumes were lower than in 2005 (Tab. 1): as a consequence of the very rainy period occurred in the first decade of June soil water content during plant growing was higher.

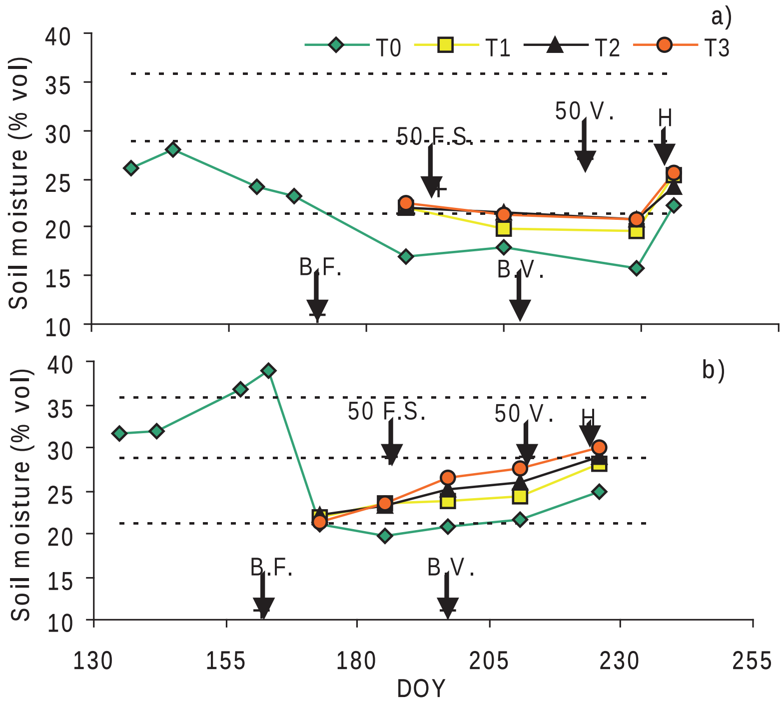

Figure 2. Volumetric soil water content of 2005 (a) and 2006 (b) in the top 0-0.60 m soil layer for the three irrigation levels. The main phenological stages are also reported: B.F.= beginning of flowering; 50 F.S. = 50% of fruit set; B.V. = beginning of fruit veraison; 50 V. = 50% of fruit veraied; H = harvest. F.C = field capacity; 50% A.W. = 50% of available water; W.P. = wilting point.

The statistical data analysis showed the significance of the three way interaction of cultivars x treatments x year for yield and vegetative parameters monitored (Fig. 3). As a general rule, for these two cultivars a higher water supply makes the yield to increase for both years although this was more evident in the first year.

Especially in 2005 - the drier year - the marketable yield obtained by T0 and T1 treatments was significantly lower than the one obtained by the two more irrigated treatments for both cultivars. Moreover, treatment T3, that received an irrigation volume of about 155 mm during the crop cycle, performed significant higher yield than T2 in cv. Mignon. If we compare cultivars, the most irrigated treatment (T3) of Mignon yielded a higher marketable yield than the same treatment for Altavilla (Fig. 3a) thanks to a more efficient use of irrigation water.

In the wet year (2006), due to rainfalls occurred from June to August (186.8 mm), the yields of the two cultivars receiving same treatments did not differ. Furthermore, climatic conditions determined a reduction of yield differences between treatments in both cultivars and significant differences were detected only between treatment T0 and T2.

The marketable yield enhancement of the two cultivars, as a consequence of irrigation volumes, was mainly determined by the increase of mean fruit weight that showed similar behavior described for marketable yield. The trend showed by waste yield and vegetative biomass (Fig. 3 c,d) was similar to marketable yield, but the waste yield was higher in 2005 Mignon because of a 34 mm rainfall occurred during the harvest.

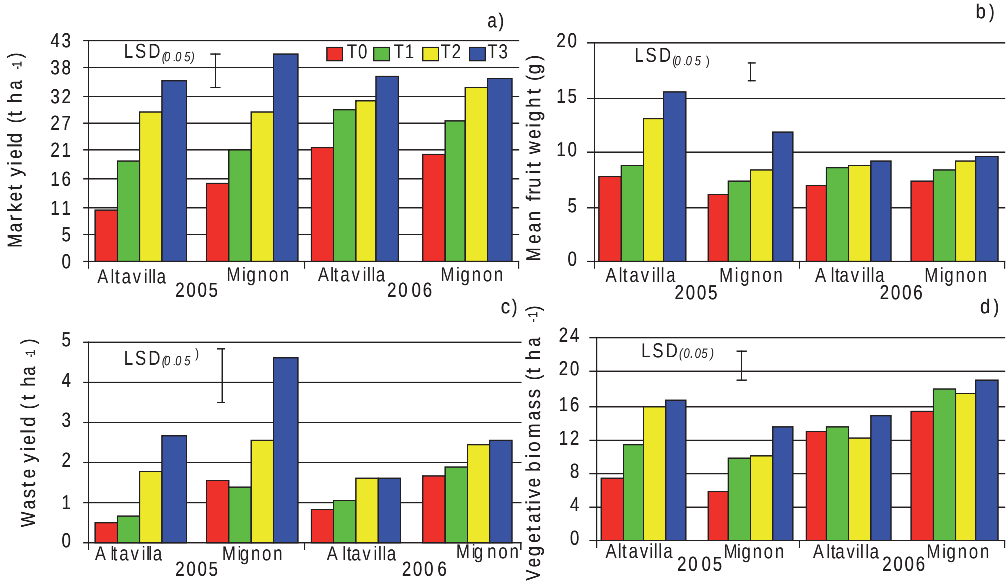

Figure 3. Marketable yield (a), mean fruit weight (b), waste yield (c) and vegetative biomass (d): interaction cultivars x irrigation level x year. Last Significant Difference (LSD) at 0.05 level is also reported.

Table 3 lists the fruits biometric parameters showing that in both years water supply influenced in the same way the polar and equatorial diameter so the fruits shape was not modified.

The harvest index (HI), calculated as marketable yield to vegetative biomass ratio, showed higher values for irrigated treatments against the control (T0). In the first year, Altavilla showed a significant increase of harvesting index between T0 and the irrigated treatments, while only a trend was evident among irrigation levels. In the second year this cultivar showed a significant increase of this parameter between T0 and T2 and similar values were monitored for the two most irrigated treatments. Similar response to irrigation was observed for Mignon. In the drier year, Altavilla recorded lower values respect to Mignon, while in 2006 the differences were less evident.

Quality parameters (Tab. 4) like high solid soluble (optical residue) and high sugar content, pH and fruits color (values> 2.1 Hunter Color) underlined a good yield quality.

According to previous experience (Giordano *et al*., 2005) irrigation influenced some chemical and technological parameters of tomato. Water, especially, administered at the end of the growing cycle may lead to a significant reduction of solid soluble and sugars content and total acidity. In this trial the decrease in soluble solids was evident among the non-irrigated and irrigated treatments. Instead fruits color and pH were not influenced by irrigation schedule.

Mignon showed good quality parameters and was suitable for industrial processing while Altavilla had some negative aspects, such as the low level of acidity (<0.4 g%) and a pH value slightly higher than the limit for industrial processing. However, a pH value of 4.5 is critical in food processing because pH pathogenic microorganisms are unable to growth below this level. Processed tomato with ph>4.5 can be adjusted by adding acidifying products - i.e. citric acid - that reduce pH to below 4.5 with obvious negative impact on the product quality. This trial emphasized the different response of two varieties in response to irrigation scheduling. In particular the optical residue and sugar content recorded a higher reduction with irrigation for Altavilla than for Mignon.

Table 3. Longitudinal and equatorial diameter and Harvest Index (HI) for both cultivars as a function of irrigation treatments. Last significant difference (LSD) at 0.05 level and Standard Deviation (Std. Dev.) are also reported.

	Longitudinal diameter		Equatorial diameter		HI
	Mean	*Std Dev.*	*Mean*	*Std. Dev*	
			cm		
2005			**Altavilla**		
T0	24.8	±1.6	22.4	± 2.2	55.7
T1	25.7	± 2.1	23.3	± 2.7	61.8
T2	29.5	± 2.9	26.9	± 3.1	61.5
T3	31.6	± 3.1	28.8	± 3.7	63.5
2006					
T0	24.9	± 1.9	20.4	± 2.2	68.8
T1	25.8	± 2.2	22.4	± 2.3	72.4
T2	26.2	± 3.1	22.3	± 2.0	76.1
T3	26.9	± 2.5	22.4	± 3.2	76.3
2005			**Mignon**		
T0	22.7	± 2.3	21.6	± 1.2	67.1
T1	24.1	± 2.5	22.8	± 1.8	65.4
T2	25.3	± 2.6	24.3	± 2.2	69.4
T3	28.2	± 2.8	26.6	± 2.9	67.1
2006					
T0	22.5	± 1.8	22.0	± 1.6	64.9
T1	23.8	± 1.7	23.0	± 1.8	66.1
T2	23.9	± 1.5	23.8	± 1.6	72.7
T3	24.7	± 1.8	24.0	± 1.5	72.2
LSD *(0.05)*	1.17		1.08		5.36

Table 4. Main quality parameters. OR=optical residue, Ac.=acidity (citric acid), Gluc=glucose, Fruct=fructose, Treat=irrigation treatment.

	OR	Ac.	Sugar			Ratio		pH	Hunter Color		
			Gluc.	Fruct.	Total	Ac.	Sugar		a	b	a/b
	%	*g %*	*g %*	*g %*	*g%*	*%*	*%*				
Year											
2005	7.65 a	0.54 b	2.30 a	2.42 a	4.72 a	7.1 b	61.8 a	4.33 a	24.9 b	10.9 b	2.28 a
2006	7.07 b	0.66 a	1.86 b	2.03 b	3.89 b	9.4 a	54.9 b	4.24 b	29.5 a	12.7 a	2.34 a
Cv											
Mignon	7.49 a	0.71 a	2.09 a	2.25 a	4.34 a	9.4 a	57.8 a	4.18 b	28.6 a	11.8 a	2.42 a
Altavilla	7.23 a	0.50 b	2.07 a	2.20 a	4.27 a	7.0 b	58.9 a	4.39 a	25.8 b	11.8 a	2.20 b
Treat.											
T0	8.16 a	0.68 a	2.30 a	2.46 a	4.76 a	8.4 a	58.1 a	4.28 a	27.7 a	11.9 a	2.32 a
T1	7.40 ab	0.63 a	2.12 a	2.27 a	4.39 a	8.6 a	59.0 a	4.29 a	27.2 a	11.7 a	2.33 a
T2	7.13 b	0.57 a	1.99 a	2.10 a	4.09 a	8.0 a	57.0 a	4.30 a	27.6 a	11.9 a	2.33 a
T3	6.74 b	0.53 a	1.91 a	2.08 a	3.99 a	7.9 a	59.1 a	4.26 a	26.3 a	11.7 a	2.25 a
Mean	7.36	0.60	2.08	2.23	4.31	8.20	58.3	4.28	27.2	11.8	2.3

IV – Conclusions

Results showed that, in the area of the experiment, a limited water supply is useful to increase yield depending on the climate of the year. In both cultivars marketable yield values showed a significant yield increase by T3 against T1, while T2 and T3 did not differ. Moreover, in the wet year cultivars responded similarly to irrigation levels.

The quality parameters showed that in the experimental area it is possible to obtain high quality cherry tomato yield also with a limited irrigation water supply.

In conclusion, in the year characterized by little or no rainfall during the growing cycle two (T2) or four (T3) waterings were necessary to ensure good yield and quality, depending of water cost, while in the years with useful precipitations during critical phenological stages one watering at the beginning of flowering may be sufficient to achieve good yield for Mignon, the less sensitive cultivar to drought. The tolerance to water stress of cultivars must be considered to optimize the water management.

Acknowledgements

Project supported by: "Ministero delle Politiche Agricole e Forestali" within the project "Analisi e Valutazione di Ordinamenti Produttivi Alternativi nelle Aree a Riconversione del Tabacco – Co.Al.Ta.

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Response of woad (*Isatis tinctoria* L.) to different irrigation levels to optimise leaf and indigo production

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Abstract. *Isatis tinctoria* L. (woad) is a potential new crop for southern European countries as source of natural indigo. Water represents an important factor for woad leaf and indigo production, nevertheless few data are available in this respect. With the aim to assess the crop coefficient (Kc), the seasonal crop water requirement (CWR) and the effects of irrigation on vegetative production and indigo yield, six irrigation levels (T100, T80, T60, T40, T20 that received a seasonal water amount equivalent to 100, 80, 60, 40, 20% of ETc and a rain-fed control T0) have been compared in a field experiment. The trials have been carried out in Central Italy during two growing seasons characterized by exceptionally rainy (2002) and dry summer conditions (2003) in comparison with the typical ones. Results outlined differences in the daily maximum evatranspiration (ETc) and in the seasonal CWR that differed significantly between the two years being significant higher (+37%) in the dry than in the rainy season. Kc values ranged from 0.30 to 0.47 in relation to plant development. Leaf dry production and indigo yield were unaffected by the level of irrigation both in 2002 and in 2003. Even if *I.tinctoria* appeared to be drought tolerant, going from T0 to T40 a +16% increment in dry leaf and indigo yield has been observed in the driest growing season. In such conditions it is useless to supply a seasonal irrigation volume over 40%ETc i.e. 1330 m^3 per hectare.

Keywords. Isatis tinctoria – Kc – ETc – Irrigation requirement – Leaf – Indigo – Yield.

La réponse du Isatis tinctoria L. (pastel) à l'irrigation différente nivelle pour optimiser la production de feuille et d'indigo

Résumé. *Isatis tinctoria L. (pastel) est une nouvelle culture potentielle pour les pays européens méridionaux comme source d'indigo. L'eau représente un facteur important pour la production de feuille et d'indigo de pastel, néanmoins peu de données sont disponibles à ce regard. Pour le but d'évaluer le coefficient de culture (Kc), le besoin de l'eau saisonnier (CWR) et les effets de l'irrigation sur la production de l'indigo, six niveaux d'irrigation (T100, T80, T60, T40, T20, qu'ont reçu une quantité saisonnière d'eau équivalente a 100, 80, 60, 40, 20% de ETc, et T0 sans irrigation) ont été comparés. Les épreuves ont été effectuées en Italie centrale pendant deux ans caractérisées par les états particulièrement pluvieux (2002) et secs (2003) en comparaison des états typiques. Les résultats ont décrit des différences dans l'evatranspiration maximum quotidien (ETc) et dans le CWR saisonnier qui a différé de manière significative entre les deux années, étant significatives plus haut (+37%) dans la saison sèche que dans la saison pluvieuse. Les valeurs de kc se sont étendues de 0.30 à 0.47 par rapport au développement du plant. La production de feuilles sèches et le rendement d'indigo n'étaient pas changés par le niveau de l'irrigation en 2002 et en 2003. Même si I.tinctoria a semblé être sécheresse tolérant, allant de T0 à T40 on a observé un incrément de +16% dans le rendement sec de feuille et d'indigo en l'année la plus sèche 2003. En telles conditions, il est inutile d'assurer un volume saisonnier d'irrigation au-dessus de 40%ETc, équivalent à 1330 m^3 par hectare.*

Mots-clés. *Isatis tinctoria – Kc – ETc – Condition d'irrigation – Feuille – Indigo – Rendement.*

I – Introduction

Isatis tinctoria L. (woad) is a potential new crop for southern European countries as source of natural indigo (Gilbert and Cooke, 2001; Angelini, 1999). It is a biennial member of the family *Cruciferae*, cultivated in Europe extensively up to XVIII and then abandoned due to the discovery of indigo by synthetic way (Balfour-Paul, 1998). The blue dyestuff was obtained from the leaves, by water extraction of their indoxyl precursors, isatans and indican, followed by alkali precipitation of the blue powder (Epstein *et al*., 1967; Gilbert *et al*., 2004; Angelini *et al*., 2007). Recently, there is an increasing demand for natural dyes of vegetal origin, included indigo, as renewable materials for industrial textiles dyeing.

To make possible the re-introduction of this crop into the agricultural systems it is necessary to provide new scientific information regarding the agronomic aspects of its cultivation in order to develop efficient and sustainable cultivation methods. Water represents an important factor for leaf production and indigo yield, nevertheless few data are available in this respect (Sales *et al*., 2006; Campeol *et al.*, 2006). For an efficient use of water resource, the knowledge of crop coefficient (Kc) in the different plant growth stages, is of vital importance in order to estimate the seasonal crop water requirements (CWR). Therefore, the aim of the present work is to assess the Kc values for this specific crop and location, the crop water requirements and the effects of irrigation on both production quantity and quality.

II – Material and methods

1. Field trials

Trials were conducted during the two growing seasons 2002 and 2003 at the Experimental Centre of DAGA-University of Pisa (Pisa countryside, Central Italy 43°41' N; 10°23' E; altitude 5 m a.s.l). *I.tinctoria* seeds were sown in paper pots on March and incubated in germination cabinets under controlled air temperature (20°C) until transplanting in the field in the spring (8th May 2002 and 18th April 2003). The plants were transplanted at 4th-6th true leaf stage with 30 cm inter-row and 10 cm intra-row distances and a crop density of 330,000 plants ha^{-1}. Soil was a typical Xerofluvent of the low Arno river plain, characterized by a superficial water table 120 cm deep in dry conditions. At the beginning of the experimental season, soil was sampled along the profile and physical and chemical characteristics, as well as wilting point and field capacity were measured (Table 1).

Table 1. Chemical and physical characteristics of the soil used for the field trial in 2002 and 2003. Soil was sampled at 20 cm depth in February before planting. Bulk density was averaged on 0-30 cm soil layer.

Parameter	Unit	2002	2003
Sand (2-0.05 mm)	%	36.8	25.8
Silt (0.05-0.002 mm)	%	45.5	46.2
Clay (<0.002 mm)	%	17.7	28.1
pH		8.0	7.9
Organic matter	(%)	1.7	1.3
Total nitrogen	(g kg^{-1})	1.2	1.2
Available phosphorus	(mg kg^{-1})	4.8	15.3
Exchangeable potassium	(mg kg^{-1})	112.2	105.8
Field capacity	% weight	21.0	21.5
Permanent wilting point	% weight	9.6	9.6
Bulk density	g cm^{-3}	1.3	1.3

Fields had been previously cultivated with wheat, and soil was ploughed to a depth of 35 cm in November 2001 and 2002. Ploughing was followed by a superficial disk harrowing in March to a fine tilth to prepare the sowing bed.

Throughout the two experimental periods plants were maintained under identical fertilisation conditions. Mineral fertiliser was applied at pre-planting at rates of 100/100/100 kg ha^{-1} of N/P_2O_5/K_2O. Further 50 kg N ha^{-1} were supplied after the first and the second harvest of the leaves.

Weeds were mechanically controlled by hand weeding. Diseases and insects were kept controlled using commercial pesticides.

2. Irrigation treatments

During the first week of growth in the field, water was supplied in equal amounts to all plots to facilitate post-transplanting recovery. Subsequently, six irrigation levels (T100, T80, T60, T40, T20 that received a seasonal water amount equivalent to 100, 80, 60, 40, 20 % of ETc and a rain-fed control T0) were compared in a randomised block design experiment with four replications. Each plot was 6 m^2 size with 199 plants per plot. The crop evapotraspiration (ETc) during the growing season was estimated by two microlysimeters while monitoring the climatic parameters and the phenological crop development (Bertolacci and Megale, 1991).The microlysimeters consisted of two prismatic containers (1.20 m x 1.20 m x 0.50 m deep) buried in the soil within the crop layout, leaving two centimeters emerging from the ground. Plants growing in the inside area were therefore perfectly integrated in the crop, thus avoiding advection. The portion of crop confined in the microlysimeters was water fed from a proper artificial water table, placed at the bottom of the containers that were equipped with an automatic device for management and control. The device ensured prompt water replenishment for daily implementation of the automated drip irrigation system, in order to deliver water to the crop at a rate matching water consumption, i.e. water amounts equivalent to 100% ETc rate. Daily meteorological data and daily ETc data were automatically collected and recorded. The water was delivered daily by an automated drip irrigation system equipped with a pressure-compensated and non-leakage dripper line, with emitter flow rate of 2.3 $l \cdot hr^{-1}$ and emitter spacing of 30 cm. To calculate the reference evapotranspiration (ET0), climatic parameters were monitored by a meteorological station and daily measures taken by a Class A pan evaporation placed near the experimental field. ET0 was estimated by the following equation: ET0 = Kp Epan [ET0 = evapotranspiration for grass reference crop, mm day^{-1}; Kp = pan coefficient by Doorenbos and Pruitt, 1977; Epan=pan evaporation, mm day^{-1}].

ETc was calculated by adding any rainfall of significance to the microlysimetric daily water requirement. Therefore, ETc represents the maximum crop evapotraspiration. The ratio between ETc and ET0 within time intervals gives the crop coefficient Kc (Kc = ETc/ET0).

The seasonal crop water requirement (CWR, m^3 ha^{-1}), ETc (mm day^{-1}) and Kc were evaluated.

3. Environmental parameters

Changes in air temperature, rainfall, global radiation and Photosynthetically Active Radiation (PAR) were recorded throughout the growing season by using a weather station, properly equipped to the purpose. Cumulative sums of PAR (mE m^{-2}; 1E = 1 moles of photons) and global radiation (KJ m^{-2}) on hourly and daily basis from sowing to harvesting were calculated by a data logger Campbell CR10X. Sensors were mod. Rg19 by Silimet Quantum Sensor system.

4. Plant productive determinations

During the crop cycle the vegetative crop development was followed. Plants were harvested by cutting them at 2 cm above soil level when the diameter of the leaf rosette reached 30 cm and 25 cm plant height. Subsequent harvests were taken when inter-row closure was complete and the same plant height had been regained. Plants grown on the same area were harvested four times in each season: in June (1st harvest), August (2nd harvest), September (3rd harvest) and October (4th harvest). Production measurements (plant fresh and dry yield) were performed on total plot area, excluding the outer rows. Fresh weight was measured, and plants subsequently allowed to dry, first in a greenhouse and later into a ventilated oven at 80°C, for dry weight determination. Measurements made on individual harvest (leaves and total fresh and dry plant yield in t ha^{-1}) were summed to estimate crop seasonal yield.

5. Leaf indigo quantification

To quantify indigo yield from plant samples a modification of Stoker *et al.* (1998) method was adopted for the determination of leaf total indigo. From each plot, 10 medium-sized leaves were randomly chosen. Leaf disks (1 cm) from the middle part of the leaves were taken, weighted and put into a glass tube. 2 ml of deionised water was added and samples were incubated in a boiling water bath for 5 min. Then, the extracts were rapidly cooled to 25°C on ice before removing the leaf discs. 200 µl of a saturated solution of $Ca(OH)_2$ was added and the mixture was aerated for 30 sec at least. An aliquot (500 µl) was transferred into a clear tube and 30 µl 19% HCl were added and the solution gently shaken. Further 2 ml of deionised water and an equal volume of ethyl acetate were added to the solution and shaken to allow a complete partition of the two phases. The blue upper phase of Ethyl Acetate was taken and the indigo concentration of each sample was determined from their absorbance at 600 nm by using an algorithm previously obtained. The measured absorbance was plotted against a calibration curve obtained solving synthetic indigo from Sigma in Ethyl Acetate and measuring the absorbance of a series of diluted solutions.

6. Statistical analysis

All measured and derived data were analysed separately for each year by analysis of variance (ANOVA) using the CoStat software, version 6.201. In all cases, means were separated on the basis of least significant difference (LSD) only when the F-test of the ANOVA treatment was significant at the 0.05 or 0.01 probability level (Gomez and Gomez, 1984).

III – Results and discussion

1. Weather conditions

Total rainfall per month and monthly mean air temperature in 2002 and 2003 are presented in Figure 1. The two growing seasons were characterised by contrasting rainfall distributions during spring and summer in comparison with long-term trend. Considerable variability in rainfall amount and distribution was observed between the two years (468 mm and 59 mm from April to October in 2002 and 2003 respectively) as well as in comparison with the typical long-term trend (426 mm from April to October). In particular, 2003 was characterised by a very dry summer, with rainfall amount significantly lower than the previous year and the typical one. Summer 2002 (June to August) was exceptionally rainy, with a total rainfall of 164.4 mm against 6.3 mm in 2003 and 113.4 mm in the long term.

Mean air temperatures showed the typical long-term trend. Mean monthly temperatures increased from March to the end of July, with a decreasing trend observed thereafter. The 2003 peak value was higher than the 2002 one (33°C vs 29 °C respectively). In particular, higher mean summer temperatures were due to higher maximum temperatures. Cumulative daily PAR (Σ mean values per month in mE m^{-2}) and cumulative Global Radiation (Σ mean values per month in KJ m^{-2}) are reported in Figure 2. PAR showed the typical increasing trend from April to July thereafter it decreased slowly until September. In 2002 weather conditions were unstable throughout summer, with no sustained periods of high irradiance. Global Radiation and PAR summer 2002 values were lower than 2003 ones.

In Figure 3 the trend of ET0 daily values from April/May to October 2002 and 2003 is reported. The values recorded are those typical of the Tyrrhenian coast with peak values at the end of spring and summer when dry windy and sunny conditions occurred. ET0 values in 2003 were always higher than 2002.

2. Seasonal crop water requirement (CWR), crop evapotraspiration (ETc) and crop coefficients (Kc)

The seasonal CWR from April/May to October/November differed significantly between the two years being significantly higher (+37%) in 2003 than in 2002, the wetter season (3327 vs 2080 m^3 ha^{-1}). The seasonal trend of ETc calculated in the two years, is showed in the Figure 4.

To evaluate the ETc and the crop coefficients in the different stages of development, it's useful to keep in mind the phenological development of *Isatis tinctoria*. This species produces an increasing number of leaves organized in shape of a rosette up to when its diameter reaches the size of 20 cm, to pass then to a phase of prevailing growth of the leaf laminas reaching at maturity a plant rosette diameter over 30 cm. Subsequently to the first cutting, the plant develops new leaves reaching again the same diameter. The leaf production after every cutting has the tendency to decrease during the season, mainly as consequence of the diminution of day-length, PAR as well as air temperatures.

The ETc values were different in the two years according with the different trend of the ET0. During the growing season 2002, the medium values of ETc fell in the range 1.3-2.3 mm/day, except in the last month of the season, when they decreased to 0.5 mm/day. This behaviour can be explained by the unusual 2002 cloudy and rainy summer conditions. In particular the abundant rainfalls brought frequently the soil to the field capacity, so plants had much available water and consequently the water supply to the microlysimeters was limited. On the contrary, the 2003 ETc trend was much more irregular than 2002, with the maximum values of 4 mm/day, due to the high sunshine and temperatures during summer with the minimum values immediately after each harvesting.

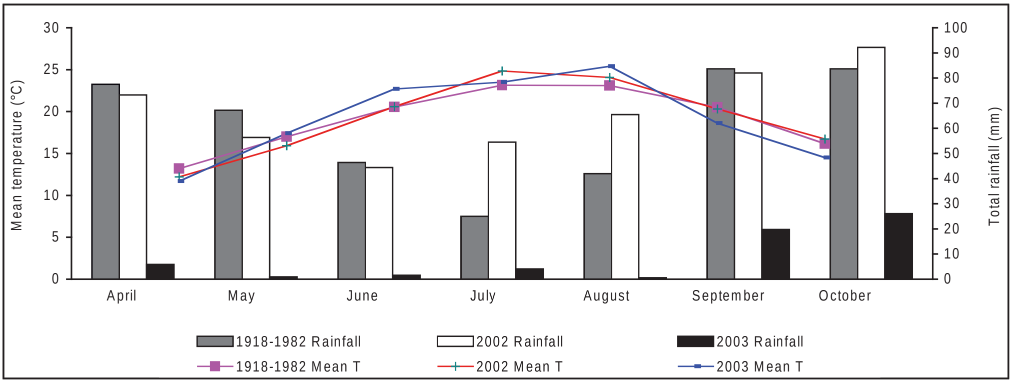

Figure 1. Total rainfall (mm) and mean air temperature (°C) from April to October in 2001 and 2002 growing seasons in comparison with long term 1918-1982 data for the same site.

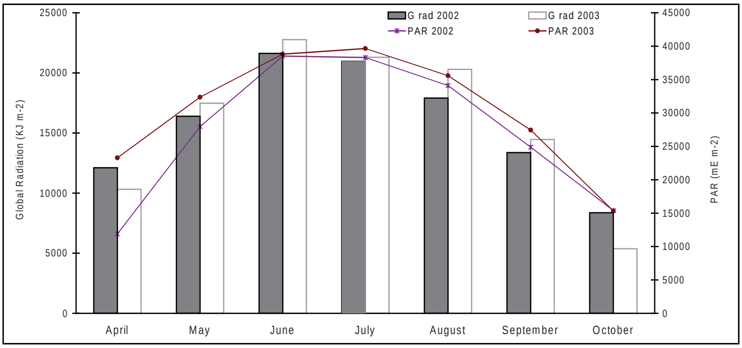

Figure 2. Mean monthly values of Global Radiation (KJ m^{-2}) and Photosynthetically Active Radiation (PAR mE m^{-2}; 1E = 1 moles of photons) measured from April to October in 2002 and 2003 growing seasons.

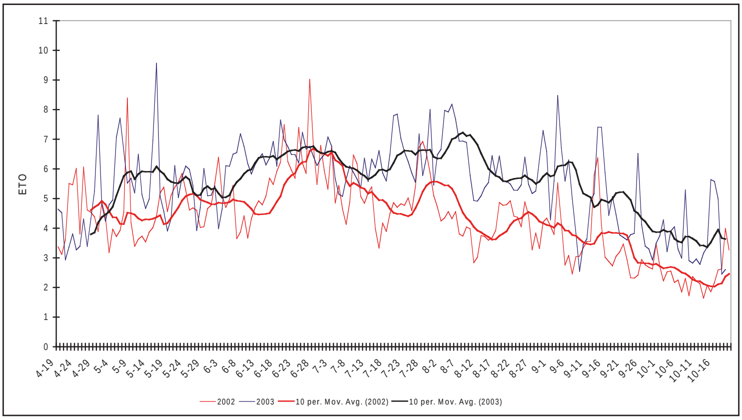

Figure 3. Trend of ET0 (mm/day) daily values from April/May to October 2002 and 2003. Data averaged every 10 days (moving average) represented by the bold lines.

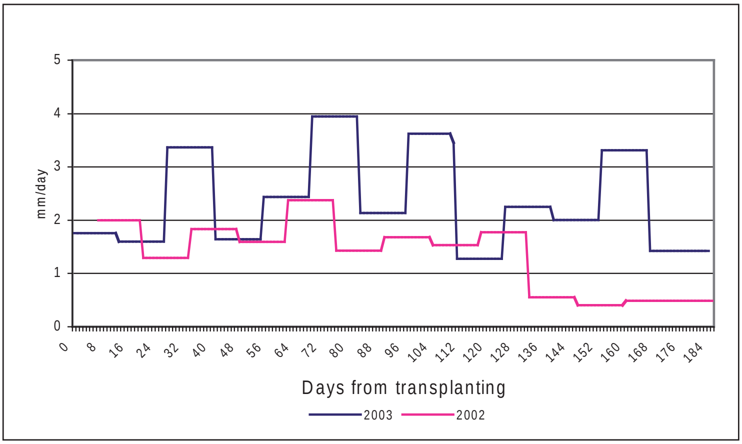

Figure 4. ETc mean values (mm /day) in 2002 and 2003 seasonal course. Values were averaged over 14 days.

The Kc values measured in the two experimental seasons are illustrated in Figure 5. Kc values were more affected by crop stage of growth than by the contrasting climatic conditions observed between the two years. As expected crop coefficients varied by crop stage of growth. When the crop is fully developed Kc reached the maximum values, whereas in the initial period of vegetative growth and after each harvest, the values were low. The coefficients ranged from about 0.30 at the beginning of plant development (C1= plant with leaf rosette with diameter over 20 cm) to 0.47 at full development (=C2 plant with leaf rosette with diameter over 30 cm). The crop has been harvested four times during the growing season therefore the Kc at full plant development varied among the four cutting-cycles. The plants fully developed and ready for the second cutting in August showed the higher crop coefficients (0.46 and 0.47 in 2002 and 2003). Leaf production after every harvest decreased during the season, mainly as consequence of the diminution of day-length, PAR as well as air temperatures. Consequently before the fourth cutting in Autumn the plants showed the lowest Kc values (0.32 in 2002 and 2003) due to the reduced leaf mass development.

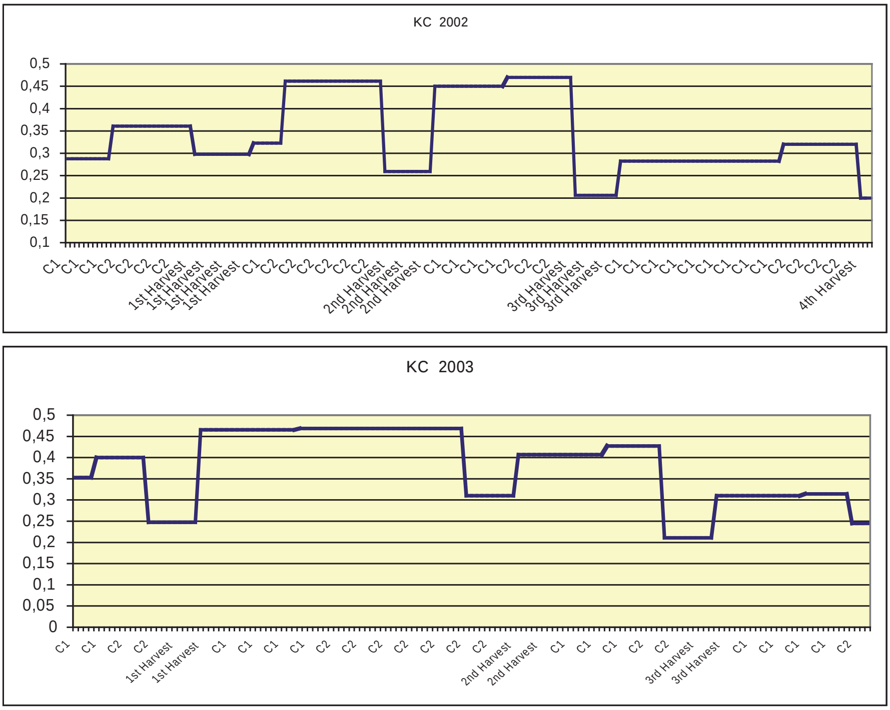

Figure 5. Crop Coefficients (Kc) in the different woad vegetative growth stages in 2002 and 2003 growing seasons. C1= plant with leaf rosette with diameter over 20 cm; C2= plant with leaf rosette with diameter over 30 cm.

Regarding leaf and indigo production, in 2002 the irrigation levels did not affect seasonal fresh and dry leaf production and indigo yield due to the exceptional rainy summer season (Table 3). In the driest 2003 season the irrigation influenced significantly leaf fresh yield and indigo production. The results showed that 40%ETc supply was enough to obtain a fresh leaf yield (t ha^{-1}) higher than T0 and T20. On the other hand, water restitution higher than 40%ETE (T60, T80 and T100) did not give further yield increment (Table 3). Therefore, by a practical point of view, it is useless to supply a seasonal irrigation volume over 40%ETc i.e. 1330 m^3 per hectare.

Table 3. Effect of different irrigation levels on mean fresh (t FW ha^{-1}), dry leaf yield (t DW ha^{-1}) and indigo (kg ha^{-1}) productions on Isatis tinctoria in 2002 and 2003 growing season.

Irrigation Treatments	2002[1]			2003[2]		
	Leaf t FWha^{-1}	Leaf t DW ha^{-1}	Indigo kg ha^{-1}	Leaf t FW ha^{-1}	Leaf t DW ha^{-1}	Indigo kg ha^{-1}
T_0	94.92	8.90	162.73	52.66 b	8.14	59.62
T_{20}	107.94	10.48	174.12	61.52 ab	8.08	64.90
T_{40}	101.29	8.99	149.76	71.34 a	9.46	69.10
T_{60}	99.70	9.40	139.66	67.04 a	8.64	76.40
T_{80}	101.75	9.77	168.77	65.12 a	8.52	75.70
T_{100}	99.61	9.03	143.24	63.23 a	8.27	82.30
Mean	100.87	9.43	156.38	63.48	8.52	71.34
Significance (LSD)	NS	NS	NS	(10.02)	NS	NS

(1) Harvest dates: 17 June; 29 August; 09 Sept.; 11 Nov. 2002;

(2) Harvest dates: 04 June; 04 August; 11 Sept.; 19 October 2003.

IV – Conclusion

This study provides original information on the water requirements for growing *Isatis tinctoria* under irrigated conditions, particularly with regard to increasing its vegetative growth and the production in its leaves of indigo dyes. Leaf dry production and indigo yield were unaffected by the level of irrigation both under rainy and dry summer conditions. *I.tinctoria* appeared to be drought tolerant in fact it features a deep taproot system and hairy leaves, allowing the plant to withstand water stress. Therefore it is recommended to supply a seasonal irrigation volume not over 40%ETc when severe drought occurred.

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Irrigation strategies to optimise water use efficiency and production in *Polygonum tinctorium* Ait., a new indigo delivering crop

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Abstract. *Polygonum tinctorium* Ait. (dyer's knotweed) is an annual plant of the Family *Polygonaceae*, very popular in Japan and China, where it has been employed for large-scale indigo production until 19th century. Today there is increasing interest toward this species as new crop for indigo production but until now, no research has been carried out on its irrigation requirements. With the aim to assess the crop coefficient (Kc), the seasonal crop water requirement (CWR) and the effects of irrigation on vegetative production and indigo yield, six irrigation levels (T100, T80, T60, T40, T20 that received a seasonal water amount equivalent to 100, 80, 60, 40, 20 % of ETc and a rain-fed control T0) have been compared in a randomised block design experiment with four replications. The trials have been carried out in Central Italy during two growing seasons characterized by exceptionally rainy (2002) and dry summer conditions (2003) in comparison with the typical ones. Results outlined that the concentration per unit of leaf weight of the indoxyl indigo precursor indican, determined by HPLC-ELSD, was not influenced by irrigation, whereas it was increased by temperatures and light intensity. On the other hand irrigation significantly influenced seasonal plant dry and fresh yield as well as indigo production in both years. A significant decrement of yield was observed with T0 and T20 treatments in comparison with T40, T60, T80 and T100. Irrigation rates higher than 40%ETc did not enhance significantly plant and indigo production. The seasonal CWR recorded from April/May to October 2003, corresponding to 4767 m^3 ha^{-1}, was significantly higher (+98%) than 2002. Kc values differed significantly with the crop growth stage reaching the maximum value of 0.7-0.8 at full vegetative development when the plants were ready to be harvested for the first time at the beginning of July. The maximum Kc values of 0.5-0.6 were regained at beginning of September before the crop second harvest.

Keywords. *Polygonum tinctorium* – Indoxyl β-D-glucoside – Irrigation – Kc – ETc – Crop – Yield.

Stratégies d'irrigation pour optimiser l'efficacité d'utilisation de l'eau et la production de Polygonum tinctorium Ait., une nouvelle culture pour la production de l'indigo

Résumé. *Polygonum tinctorium Ait. est un plant annuel de la famille de Polygonaceae, très populaire en Japon et Chine, où elle a été utilisée pour la production à grande échelle d'indigo jusqu'au 19ème siècle. Aujourd'hui l'intérêt augmente vers cette espèce pour la production d'indigo, mais jusqu'au moment, aucune recherche n'a été effectuée sur ses conditions d'irrigation. Pour le but d'évaluer le coefficient de culture (kc), le besoin de l'eau (CWR) et les effets de l'irrigation sur la production de l'indigo, six niveaux d'irrigation (T100, T80, T60, T40, T20, qu'ont reçu une quantité saisonnière d'eau équivalente a 100, 80, 60, 40, 20% de ETc, et T0 sans irrigation) ont été comparés. Les épreuves ont été effectuées en Italie centrale pendant deux ans caractérisées par les états particulièrement pluvieux (2002) et secs (2003) en comparaison des états typiques. Les résultats ont décrit que la concentration par unité du poids de feuilles du précurseur d'indigo indican, déterminé par HPLC-ELSD, n'a pas été influencée par irrigation tandis qu'elle a été augmentée par les températures et intensité de la lumière. D'autre part l'irrigation a influencé de manière significative le rendement sec et frais, et aussi la production d'indigo en les deux années. On a observé une décroissance significative de rendement avec les traitements T0 et T20 en comparaison de T40, de T60, de T80 et de T100. Niveaux d'irrigation plus haut que 40% ETc n'a pas augmenté de manière significative la production du plant et d'indigo. Le CWR saisonnier enregistré à partir d'avril-de mai à l'octobre 2003, correspondant à 4767 m^3 ha^{-1}, était sensiblement plus haut (+98%) que 2002. Les valeurs de Kc ont différé de manière significative avec l'étape de croissance atteignant la valeur maximale de 0.7-0.8 au plein développement végétatif au début de juillet. Les valeurs du maximum Kc de 0.5-0.6 ont été regagné au début de septembre avant de la deuxième récolte.*

Mots-clés. *Polygonum tinctorium – Indoxyl β-D-glucoside – Irrigation – Kc – ETc – Culture – Rendement.*

I – Introduction

Indigo used in the dyeing industry mainly for denim, is currently synthesized from by-products of fossil fuels. However, several plants are able to synthesize indigo precursors such as *Polygonum tinctorium* Ait. (dyer's knotweed) an annual plant of the Family *Polygonaceae*, very popular in Japan, China and Russia, where it has been employed for large-scale indigo production until 19th century. The plant has large dark bluish-green leaves which contain some glycosides as secondary metabolites, the major one is a colourless glucoside called indican (indoxyl β-D-glucoside). When the plant cells are put in water, indican is extracted and it is degraded to indoxyl and glucose. A dimerization of this indoxyl by air oxidation follows and indigo is formed, which is commonly used as a blue dye since ancient time (Minami, 1997). Today there is increasing interest toward this species as new crop for indigo production in Europe but until now, no research has been carried out on its irrigation requirements.

Aim of the present study was to analyze the crop coefficients (Kc), the crop water requirement (CWR) and the response to irrigation of this new crop grown under field conditions.

II – Material and methods

1. Field trials

Trials were conducted during the two growing seasons 2002 and 2003 at the Experimental Centre of DAGA-University of Pisa (Pisa countryside, Central Italy 43°41' N; 10°23' E; altitude 5 m a.s.l). *P. tinctorium* seeds were sown in paper pots on March and incubated in germination cabinets under controlled air temperature (20°C) until transplanting in the field in the spring (8th May 2002 and 18th April 2003). The plants were transplanted at 4th true leaf stage with 30 cm inter row and 30 cm intra row distances and a crop density of 120.000 plant ha^{-1}. Soil was a typical Xerofluvent of the low Arno river plain, characterized by a superficial water table 120 cm deep in dry conditions. At the beginning of the experimental season, soil was sampled along the 0-30 cm profile and physical and chemical characteristics as well as wilting point and field capacity were measured (Table 1).

Table 1. Chemical and physical characteristics of the soil used for the field trial in 2002 and 2003. Bulk density was averaged on 0-30 cm soil layer.

Parameter	Unit	2002	2003
Sand (2-0.05 mm)	%	36.8	25.8
Silt (0.05-0.002 mm)	%	45.5	46.2
Clay (<0.002 mm)	%	17.7	28.1
pH		8.0	7.9
Organic matter	(%)	1.7	1.3
Total nitrogen	(g kg^{-1})	1.2	1.2
Available phosphorus	(mg kg^{-1})	4.8	15.3
Exchangeable potassium	(mg kg^{-1})	112.2	105.8
Field capacity	% weight	21.0	21.5
Permanent wilting point	% weight	9.6	9.6
Bulk density	g cm^{-3}	1.3	1.3

The field used for the experiments had been previously cultivated with wheat. The soil was ploughed to a depth of 35 cm in November 2001 and 2002 and ploughing was followed by a superficial disk harrowing in March to a fine tilth to prepare the sowing bed.

Throughout the two experimental periods plants were maintained under identical fertilisation conditions. Mineral fertiliser was applied before planting at rates of 100/100/100 kg ha^{-1} of N/ P_2O_5/K_2O. Further 50 kg N ha^{-1} were supplied after the first and the second harvest of the leaves. Weeds were mechanically controlled by hand weeding. No diseases and insects occurred.

2. Irrigation treatments

During the first week of growth, water was supplied in equal amounts to all plots to facilitate post-transplanting recovery. Subsequently, six irrigation levels (T100, T80, T60, T40, T20 that received a seasonal water amount equivalent to 100, 80, 60, 40, 20% of ETc and a rain-fed control T0) were compared in a randomised block design experiment with four replications. Each plot was 12 m^2 size with 144 plants per plot. The crop evapotraspiration (ETc) during the growing season was estimated by two microlysimeters while monitoring the climatic parameters and the phenological crop development (Bertolacci and Megale, 1991). The microlysimeters consisted of two prismatic containers (1.20 m x 1.20 m x 0.50 m deep) buried in the soil within the crop layout, leaving two centimeters emerging from the ground. Plants growing in the inside area were therefore perfectly integrated in the crop, thus avoiding advection. The portion of crop confined in the microlysimeters was water fed from a proper artificial water table, placed at the bottom of the containers that were equipped with an automatic device for management and control. The device ensured prompt water replenishment for daily implementation of the automated drip irrigation system, in order to deliver water to the crop at a rate matching water consumption, i.e. water amounts equivalent to 100% ETc rate. Daily meteorological data and daily ETc data were automatically collected and recorded. The water was delivered daily by an automated drip irrigation system equipped with a pressure-compensated and non-leakage dripper line, with emitter flow rate of 2.3 $l \cdot hr^{-1}$ and emitter spacing of 30 cm. To calculate the reference evapotranspiration (ET0), climatic parameters were monitored by a meteorological station and daily measures taken by a Class A pan evaporation placed near the experimental field. ET0 was estimated by the following equation: ET0 = Kp Epan [ET0 = evapotraspiration for grass reference crop, mm/day; Kp = pan coefficient by Doorenbos and Pruitt (1977); Epan=pan evaporation, mm/day]. ETc was calculated by adding any rainfall of significance to the microlysimetric daily water requirement. Therefore, ETc represents the maximum crop evapotraspiration. The ratio between ETc and ET0 within time intervals gives the crop coefficient Kc [Kc = ETc/ET0]. The seasonal crop water requirement (CWR) (m^3 ha^{-1}), ETc (mm day^{-1}) and Kc were evaluated.

3. Environmental parameters

Changes in air temperature, rainfall, global radiation and photosynthetically active radiation (PAR) were recorded throughout by using a weather station, properly equipped to the purpose. Cumulative sums of PAR (mE m^{-2}; 1E = 1 moles of photons) and global radiation (KJ m^{-2}) on hourly and daily basis from sowing to harvesting were calculated by a data logger Campbell CR10X. Sensors were mod. Rg19 by Silimet Quantum Sensor system.

4. Plant productive determinations

During the crop cycle the phenological crop development was followed. Plants were hand-cut at 10 cm above soil level at the beginning of the flowering phase when they had reached their maximum height. Subsequent harvests were taken when inter-row closure was complete and maximum height had been regained. In 2002 *P.tinctorium* plants were harvested on July 4th for the first time, and on October 3rd for the second time; in 2003 plants were harvested on July 5th, September 3rd and October 28th for the first, second and third time respectively. Measurements made on individual harvests (leaves, stems, and total fresh and dry plant yield in t ha^{-1}) were summed to estimate crop seasonal yield. Samples were taken from an area of 5 m^2 on each plot excluding the plants on the two outer rows of each plot.

5. HPLC indican analysis and indigo quantification

Ten leaf samples from each field experimental plot were taken before harvesting. Leaf discs (1cm diameter) were obtained from the central part of the leaf (excluding veins) and immediately transferred into a glass tube with deionised water in a 1:10 weight/volume ratio. Indican water extraction was carried out at 100°C in a boiling bath for 7 min. Leaf water extracts were diluted 1:10 (v/v) with water and 20 ml aliquots injected into the HPLC system (Jasco PU980) coupled with an Evaporative Light Scattering Detector (ELSD 2000, Alltech), according to Angelini *et al.* (2003 and 2004). The theoretical indigo amount obtainable from the complete reaction of indoxyl was predicted by stoichiometric calculations. The method, fully described by Angelini *et al*. (2003), allowed a sensitive and reproducible resolution of samples in a short running time (5 min).

6. Statistical analysis

All variables were analyzed by ANOVA using a randomized block experimental design to test the significance of differences associated to irrigation treatments separately for each year. Significantly different means were separated at 0.05 probability level by Last Significant Difference (LSD) test (Gomez and Gomez, 1984).

III – Results and discussion

1. Weather conditions

Total rainfall per month and monthly mean air temperature in 2002 and 2003 are presented in Figure 1. The two growing seasons were characterised by contrasting rainfall distributions during spring and summer in comparison with long-term trend. Considerable variability in rainfall amount and distribution was observed among the two years (468 mm and 59 mm from April to October in 2002 and 2003 respectively) and in comparison with the typical long-term trend (426 mm from April to October). In particular, 2003 was characterised by a very dry summer, with rainfall amount significantly lower than the year before and in comparison with the long-term trend. Summer 2002 (June to August) was exceptionally rainy, with a total rainfall of 164.4 mm against 6.3 mm in 2003 and 113.4 mm for the long term. Mean air temperatures showed the typical long-term trend. The mean monthly temperatures increased from March to the end of July, and decreased thereafter. The peak value in 2003 was higher than in 2002 (33°C vs 29 °C respectively) due to higher maximum temperature values. Cumulative daily PAR (Σ mean values per month in mE m^{-2}) and cumulative Global Radiation (Σ mean values per month in KJ m^{-2}) are reported in Figure 2. PAR showed the typical increasing trend from April to July, thereafter it decreased slowly until September. In 2002 weather conditions were unstable throughout summer, with no sustained periods of high irradiance. As a consequence global radiation and PAR summer values in 2002 were lower than in 2003.

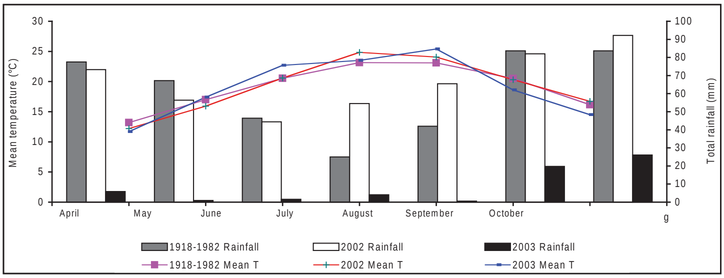

Figure 1. Total rainfall (mm) and mean air temperature (°C) from April to October in 2001 and 2002 growing seasons, in comparison with long term 1918-1982 data for the same site.

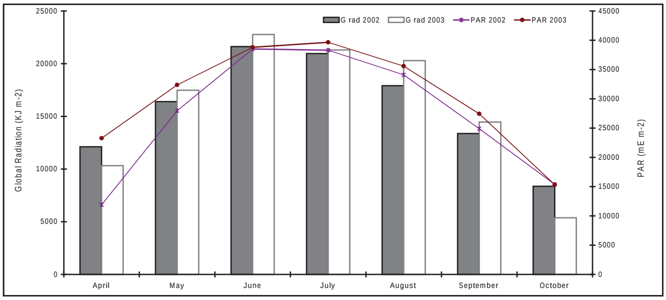

Figure 2. Mean monthly values of Global Radiation (KJ m^{-2}) and Photosynthetically Active Radiation (PAR mE m^{-2}; 1E = 1 moles of photons) measured from April to October in 2002 and 2003 growing seasons.

In Figure 3 the trend of ET0 daily values from April/May to October 2002 and 2003 is reported. The values recorded are those typical of the Tyrrhenian coast with peak values at the end of spring and summer when dry windy and sunny conditions occurred. It is evident that ET0 values in 2003 were always higher than 2002.

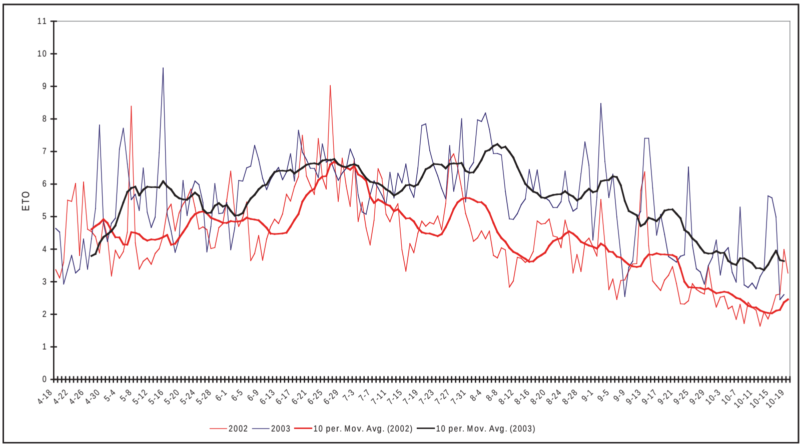

Figure 3. Trend of ET0 (mm/day) daily values from April/May to October 2002 and 2003. Data averaged every 10 days (moving average) represented by the bold lines.

2. Seasonal crop water requirement (CWR), crop evapotraspiration (ETc) and crop coefficients (Kc)

The seasonal CWR from April/May to October differed significantly between the two years being significant higher (+97%) in 2003 than in 2002, the wetter season (4767 *vs* 2413 m^3 ha^{-1}).

The seasonal trend of ETc calculated in the two seasons, is showed in the Figure 4.

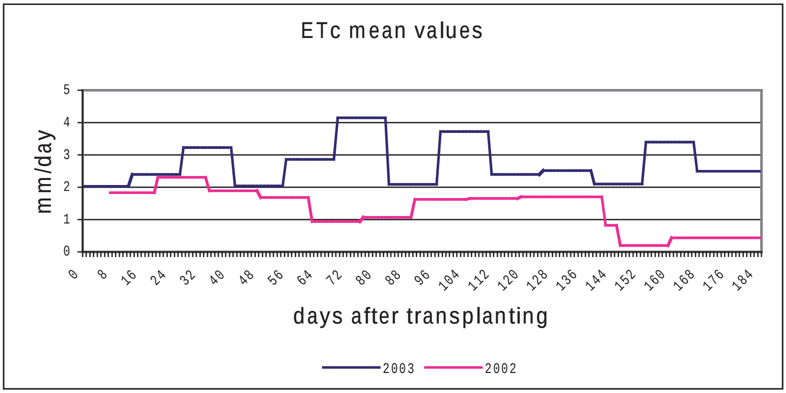

Figure 4. ETc mean values (mm /day) in 2002 and 2003 seasonal course. Values were averaged over 14 days.

To evaluate the ETc and the crop coefficients in the different phases of development, it's useful to keep in mind the development of *Polygonum tinctorium*. This species begins the vegetative development with beginning of branching about 45 days after sowing, thereafter the main stem lengthens, reaching 20 cm height about three months after sowing and 40 cm height about three and half months after sowing. In this phase a large amount of leaves were formed. The stems are free of indigo precursor, which is confined to the leaves. For this reason harvesting is best done before the end of the vegetative growth period. Therefore the best time for the first harvest is reached when the ratio between leaves and stalks is about 1:1 when the crop rows are closed by the developing *Polygonum* plants.

Subsequently to the first harvest, the plant re-growths and develops new stems and leaves. The plant production after every harvest has the tendency to decrease during the season, mainly as consequence of the diminution of day-length, PAR as well as air temperatures.

The ETc values were different in the two years according with the different trend of the ET0. During the 2002 growing season, the medium values of daily ETc fell in the range 1.0-2.3 mm/day, except in the last month of the season, when they decreased to 0.2 mm/day. This behaviour can put in relation with the unusual 2002 cloudy and rainy summer conditions. In particular the abundant rainfall took frequently the soil to the field capacity, so plants had much available water and consequently the water supply to the microlysimeters was limited. On the contrary, the 2003 ETc reached the maximum values over 4 mm/day, due to the high sunshine and temperatures during summer with the minimum values of about 2 mm/day immediately after each harvesting (Figure 4).

The trend of Kc values measured in the two experimental seasons is reported in Figure 5.

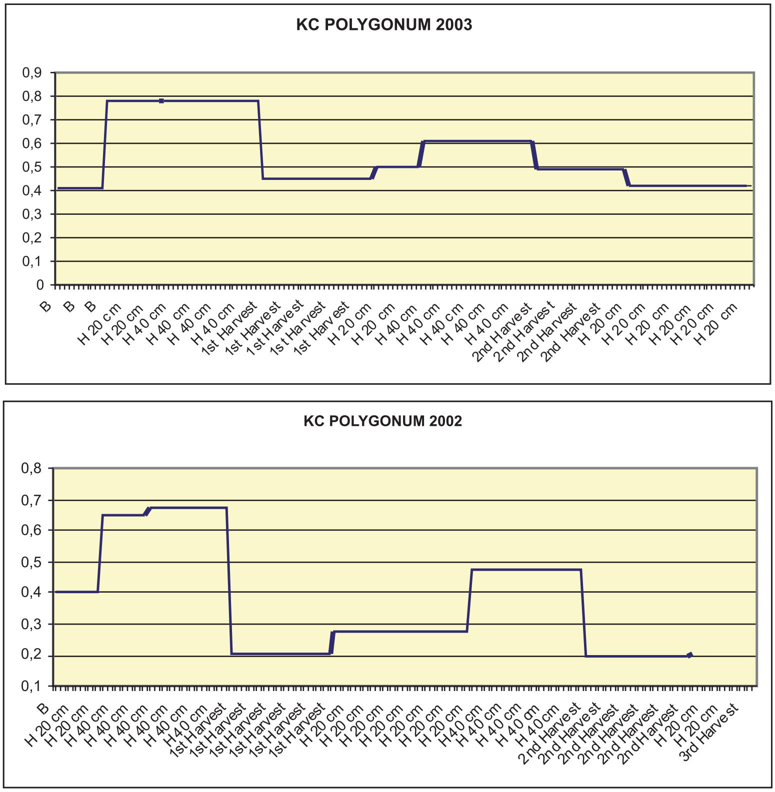

Figure 5. Crop Coefficients (Kc) in the different *P.tinctorium* phenological phases in 2002 and 2003 growing seasons. B= Beginning of stem branching; H 20 cm= plant with stem height of 20 cm; H 40 cm= plant with stem height of 40 cm.

Kc values varied by crop growth stage reaching the maximum value of 0.7/0.8 at full vegetative development when the plants were ready to be harvested for the first time. The plants reached this stage with full soil cover at the beginning of July. Cutting creates a ground surface with less than 10% vegetation cover. Therefore the plant re-growth and the maximum Kc values of 0.5/0.6 were regained at beginning of October (2002) or September (2003) before the crop second harvest. The Kc of the first growth cycle are higher than those of the second growth cycle due to the lower temperature that reduced crop growth activity. The higher values were found in the 2003 driest growing season.

Regarding the final yield of indigo it is a result of two major factors: the indigo content of the leaves, and the yield of leaves. The first of these two factors is increased by temperatures and light intensity reaching the highest values in the leaves before the first harvest in July and the lowest ones before the harvest in October (Table 2). Furthermore indigo precursor indican was in general not affected/enhanced by water stress conditions. In fact the long drought spell observed in 2003 summer did not significantly affect indigo content per unit leaf fresh weight, showing values which were not significant different between plants grown without irrigation and those fully irrigated (Table 2). These results with field-grown *Polygonum* crops echo earlier experiments (Campeol *et al*., 2006) in which it was shown that the indigo concentration per unit of leaf weight in *Polygonum* is increased by exposure to higher light intensities prior to harvest.

Table 2. Effect of different irrigation levels on mean (standard deviation) leaf indigo concentration (g kg^{-1} FW) in the different harvests accomplished in 2002 and 2003 growing seasons.

Irrigation Treatments	2002		2003		
	4th July g kg^{-1}	24 Oct. g kg^{-1}	7th July g kg^{-1}	3rd Sept. g kg^{-1}	24th Oct. g kg^{-1}
T_0	12.16 a (0.20)	7.22 (0.20)	12.7 (0.53)	11.6 (0.38)	5.19 (0.53)
T_{20}	11.74 ab (0.09)	7.39 (0.25)	12.2 (0.56)	12.0 (0.35)	5.16 (0.55)
T_{40}	10.97 bc (0.10)	7.12 (0.10)	13.2 (0.65)	12.2 (0.33)	5.26 (0.89)
T_{60}	9.98 d (0.02)	7.05 (0.09)	13.7 (0.39)	12.3 (0.17)	5.09 (0.49)
T_{80}	11.08 bc (0.18)	7.83 (0.10)	12.8 (0.54)	11.9 (0.55)	4.95 (0.71)
T_{100}	10.80 cd (0.24)	7.27 (0.20)	12.5 (0.39)	12.3 (0.52)	4.97 (0.65)
Mean	11.12	7.31	12.85	12.05	5.01
Significance	*	N.S.	N.S.	N.S.	N.S.

Mean values within each column followed by the same letter are not significantly different for P<0.05 probability level according to LSD test. NS=Not Significant according to F test by ANOVA analysis.

The second factor, i.e. the yield of leaves, depends crucially on number of harvests taken in a season, which in turn depends, among other factors, on the rate of foliage re-growth between harvests. Environmental conditions, mainly temperature and water availability affect strongly yields of foliage and indigo production per hectare. Two and three harvests per year, from July to October were possible in year 2002 and 2003 respectively. Seasonal whole plant yield was higher in 2002, due to higher rainfall as well as higher air temperatures than 2003. Amounts of fresh leaves, representing the actual economic yield, were also greater in 2002 with a potential indigo yield of up to 298.7 kg ha^{-1} (Table 3).

Table 3. Effects of different irrigation levels on mean (standard deviation) fresh whole plant, leaf (t FW ha^{-1}) and indigo (kg ha $^{-1}$ FW) productions on Polygonum tinctorium.

Irrigation Treatments	2002[1]			2003[2]		
	Plant t ha^{-1}	Leaf t ha^{-1}	Indigo kg ha^{-1}	Plant t ha^{-1}	Leaf t ha^{-1}	Indigo kg ha $^{-1}$
T_0	48.2 c (3.6)	23.4 c (2.7)	214.6 b (16.6)	26.2 b (5.5)	10.7 c (2.1)	110.2 b (19.3)
T_{20}	71.8 b (6.7)	31.9 b (2.8)	293.2 a (18.4)	32.6 b (4.3)	15.6 bc (2.3)	158.8 b (15.7)
T_{40}	90.1 a (8.6)	36.8 a (3.4)	324.4 a (15.0)	55.6 a (6.2)	24.6 ab (3.3)	268.2 a (16.2)
T_{60}	90.8 a (3.2)	39.7 a (2.2)	327.1 a (14.8)	66.3 a (4.7)	29.3 a (4.1)	318.0 a (15.0)
T_{80}	84.5 ab (6.6)	35.1 ab (2.5)	325.2 a (18.3)	64.0 a (9.6)	27.4 a (4.2)	281.7 a (17.2)
T_{100}	89.8 a (7.3)	36.2 ab (2.7)	313.9 a (17.7)	73.0 a (11.9)	29.1 a (4.7)	307.0 a (18.7)
Mean	79.2	33.8	298.7	52.9	22.8	240.6
LSD 0.05	12.82	4.9	39.9	18.95	9.28	94.3

[1] Harvest dates: 04 July; 03 October 2002; [2] Harvest dates: 07 July; 3 September; 28 October 2003

Mean values within each column followed by the same letter are not significantly different for P<0.05 probability level according to LSD test.

Even if plant dry yield was not statistically different between the two years, averaging 14.25 t ha^{-1}, a lower production of dry leaves was observed in the driest 2003 growing season (Table 4). Furthermore, irrigation significantly influenced seasonal plant dry and fresh yield (t/ha) as well as indigo production (kg/ha) in both years (Table 3 and 4). In particular in the driest 2003 growing season plants grown in T0 showed over 64% and 63% plant and leaf fresh yield reduction in comparison with T100 as a consequence of the very stressful conditions which occurred in July and August 2003. A significant decrement of dry yield was observed with T0 and T20 treatments in comparison with T40, T60, T80 and T100 (Table 4). Irrigation rates higher than 40%ETc did not affect significantly plant and indigo production.

Table 4. Effect of different irrigation levels on mean (standard deviation) dry whole plant and leaf productions (t DW ha^{-1}) on *Polygonum tinctorium*.

Irrigation Treatments	2002[1]		2003[2]	
	Plant	Leaf	Plant	Leaf
	t ha^{-1}	t ha^{-1}	t ha^{-1}	t ha^{-1}
T_0	9.80 c (3.6)	4.66 d (2.7)	7.89 b (5.5)	2.85 b (2.1)
T_{20}	13.22 b (6.7)	5.82 c (2.8)	10.32 b (4.3)	3.72 b (2.3)
T_{40}	16.40 a (8.6)	6.86 a (3.4)	15.58 a (6.2)	6.71 a (3.3)
T_{60}	15.60 ab (3.2)	6.84 ab (2.2)	18.19 a (4.7)	7.23 a (4.1)
T_{80}	14.92 ab (6.6)	5.97 bc (2.5)	15.86 a (9.6)	5.99 a (4.2)
T_{100}	16.51 a (7.3)	6.61 abc (2.7)	16.72 a (11.9)	6.16 a (4.7)
Mean	14.40	6.13	14.09	5.44
LSD 0.05	2.86	0.89	1.78	0.88

[1] Harvest dates: 04 July; 03 October 2002; [2] Harvest dates: 07 July; 3 September; 28 October 2003

Mean values within each column followed by the same letter are not significantly different for $P<0.05$ probability level according to LSD test.

IV – Conclusion

P.tinctorium has the morphology of a marsh plant characterized by a rather superficial root development, which is responsible for great sensitivity to water stress. Therefore, *P.tinctorium* appears to be more productive in not limiting water conditions, thus making appropriate irrigation plans (*i.e.* 40%ETc corresponding to 1907 m^3 ha^{-1} in the driest season) necessary to achieve sustainable high yields.

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An evaluation of some drought indices in the monitoring and prediction of agricultural drought impact in central Italy

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Abstract. A comparative analysis of the performances of some drought indices in monitoring and predicting sunflower and sorghum crop yield in Central Italy is carried out. Considered drought indices include: Palmer drought indices (PDSI, Z, CMI), Standardized Precipitation Index (SPI) and a severity index (RS) derived from a Run theory applied to the soil water content time series. The indices were computed weekly using climatic data recorded from 1978 to 2003 in four sites for which also pedo-hydrological and crop data are available. An intra-seasonal correlation analysis enabled to identify the week during which each index shows the best correlation with the seasonal yield. Weekly indices cumulated in each growth stage were used for the implementation of the best crop yield-drought index models by a stepwise regression technique. Model's performances were evaluated using different goodness-of-fit measures. RS proved to be more suitable than other indices for the prediction of agricultural drought conditions. SPI, despite of the limited data requirement and the simple algorithm, leads to appreciable results similar to those obtained by using Z and CMI that. Finally PDSI models were sometimes not significantly related with crop yield and in general exhibit a lower reliability for crop yield prediction.

Keywords. Drought indices – Crop yield – Sunflower – Sorghum.

Evaluation de quelques indices de sécheresse pour le monitorage et la prévision de l'impact de la sécheresse agricole en Italie Centrale

Résumé. *Une analyse comparative a été conduite sur quelques indices de sécheresse afin d'étudier leur performance dans le monitorage et la prévision des rendements du tournesol et du sorgho en Italie Centrale. Les indicateurs de sécheresse considérés sont : les* indices *de* Palmer *(PDSI, Z, CMI), l'indice de précipitation standard (SPI), et un indice de sévérité (RS) calculé suivant une théorie de simulation appliquée à la série temporelle du contenu hydrique du sol. Les indices ont été calculés à échelle hebdomadaire en utilisant les données climatiques enregistrées de 1978 à 2003 pour quatre localités pour lesquelles les données pédo-hydrologiques et culturelles sont aussi disponibles. Une analyse de corrélation intra-saisonnière a permis d'identifier la semaine pendant laquelle chaque indice montre la meilleure corrélation avec le rendement saisonnier. Les valeurs hebdomadaires des indices, cumulées pour les différents stades de croissance, ont été utilisées dans une* régression *multiple progressive pour l'identification des modèles rendement-indice de sécheresse. Différents tests d'adéquation ont été utilisés pour évaluer la performance des modèles. L'indice RS s'est démontré le plus convenable pour la prévision des conditions de sécheresse agricole. Cet indice est plus robuste vue sa capacité de considérer les caractéristiques spécifiques des cultures même si cela demande un excés de données d'entrée. SPI, malgré le nombre limité des données d'entrée et son simple algorithme, a permis d'obtenir des résultats appréciables similaires à ceux de Z et CMI, qui dérivent d'algorithmes plus complexes. Les modèles PDSI ont présenté parfois des résultats qui ne sont pas significativement corrélés au rendement agricole, et, en général, leurs prévisions ont montré une moindre fiabilité.*

Mots-clés*. Indices de sécheresse – Rendement agricole – Tournesol - Sorgho.*

I – Introduction

As emphasized by Palmer (1965), drought is not an easily definable phenomenon because the term 'drought' assumes different meanings according to the context in which impacts are analyzed. Wilhite and Glantz (1985) distinguish four types of drought: meteorological, hydrological, agricultural and socio-economical. In the present paper the attention is focused on agricultural drought that occurs when the soil water availability for a specific crop is reduced to such a level that it adversely affects the cultivation production and therefore the corresponding profit (Panu and Sharma, 2002). Typically the drought indices enable to identify and to quantify the drought phenomena. Some indices are also valid tools for the drought event real time monitoring, useful to improve a proactive approach to drought management. With reference to agricultural drought the indices should be specific, since able to estimate the impacts on different crops of analogous climatic conditions. According to a generally accepted definition, the impact of the drought in agriculture can be quantified by the consequent yield reduction. Hence the goodness of an agricultural drought index can be evaluated by means of its ability to predict (and to monitor) the crop yield. In the paper this ability is tested with reference to two rainfed crops: sunflower (Helianthus annuus L.) and sorghum (Sorghum bicolor L.) grown in Central Italy. The considered drought indices are: three Palmer (1965; 1968) drought indices (PDSI, Z, CMI), the standardized precipitation index (SPI; McKee, 1993), and a severity index (RS; Mannocchi *et al.*, 1987). The Z and PDSI indices are considered able to characterize the conditions of short term water stress, which usually occur in the context of the agricultural drought. The CMI index, is considered a specific agricultural drought index. SPI, since the temporal scale can be varied, is suitable for the quantification of the various types of drought: for agricultural one, a temporal scale shorter than 3-4 months is suggested. Since RS is based on better description of the soil-crop-atmosphere interactions (Allen *et al.*, 1998), it has the potentiality to be a good agricultural index, also if more input data are required. In the next section a more detailed description of the selected indices is given underlining the differences in terms of required data input. Indices performances in crop yield prediction and monitoring will be evaluated by means of two different techniques: the former is based on an intra-seasonal correlation analysis between weekly values of the indices (during the crops growing seasons) and the seasonal experimental crop yield; the latter is based on the specification, for each index, of the best crop yield model by means of a stepwise regression technique.

II – Selected indices for the comparative performance analysis

In Table 1 are listed the indices selected for the performance analysis, to determine the most appropriate index for monitoring and for predicting the Sunflower and Sorghum crop yield in Central Italy. The indices have been selected among the most commonly used measures of agricultural drought. The main differences among them is the computational effort and the amount of input data required to quantify them (Table 1).

Table 1. Input data required by the indices. Rain: simple precipitation; ET0: reference evapotranspiration; ETm: crop maximum evapotranspiration; ETa: crop actual evapotranspiration.

	Index	DATA				
		Rain	ET0	ETm	ETa	Soil
Palmer Indices	Z (Anomaly Index)	√	√			
	PDSI (Palmer Drought Severity Index)	√	√			
	CMI (Crop Moisture Index)	√	√			
	SPI (Standardized Precipitation Index)	√				
	RS (Relative Severity)	√	√	√	√	√

1. Palmer Indices

Incorporated antecedent precipitation, moisture supply, and moisture demand into a hydrologic accounting system (Palmer, 1965). A two-layered model for soil moisture computations is used and certain assumptions concerning field capacity and transfer of moisture to and from the layers are made. Palmer applied Climatologically Appropriate for Existing Conditions (CAFEC) quantities to normalize his computations so he could compare the dimensionless index across space and time. This procedure enables the indices to measure abnormal wetness (positive values) as well as dryness (negative values), with persistently normal precipitation and temperature theoretically resulting in an index of zero in all seasons in all climates.

Anomaly Index (Z) The Palmer Z Index reflects the departure of the weather of a particular month from the average moisture climate for that month regardless of what has occurred in prior or subsequent months. The index can be quantified also at weekly time scale.

Palmer Drought Severity Index (PDSI) The Palmer PDSI Index determines the beginning, ending and severity of the drought periods. In PDSI computation, the drought severity for a month depends on the moisture anomaly for that month and on the drought severity for the previous and subsequent months. The index can be quantified also at weekly time scale.

Crop Moisture Index (CMI) The CMI (Palmer, 1968) index is designed as an agricultural drought index and depends on the drought severity at the beginning of the week and the evapotranspiration deficit or soil moisture recharge during the week. It measures both evapotranspiration deficits (drought) and excessive wetness (precipitation is more than enough to meet evapotranspiration demand and recharge the soil).

2. Standardized Precipitation Index (SPI)

In SPI computation (McKee, 1993) historical data are used to compute the probability distribution of the monthly and seasonal (the past 2 months, 3 months, etc., up to 48 months) observed precipitation totals, and then the probabilities are normalized using the inverse normal (Gaussian) function. The SPI methodology allows expression of droughts (and wet spells) in terms of precipitation deficit, percent of normal, and probability of non excedance as well as the SPI. The index can be quantified also at weekly time scale.

3. Relative Severity (RS)

The RS (Mannocchi *et al.*, 1987) is an index derived from a Run theory applied to the simulated (or measured) soil water volume dynamics (SWt) in the root zone with a truncation level SW0 (the soil water volume corresponding to the crop critical point). The drought runs occurs when both the following conditions occur: $dSWt/dt<0$ and $SWt<SW0$. The severity of the soil water deficit is quantified by the RS as the integral of the drought runs normalized with respect to the Total Available Water volume per unit surface in the root zone (TAW). RS can be quantified at any time scale.

III – Available data

For the selected crops (Sunflower and Sorghum) and for the soil-atmosphere units considered (Papiano, S.Apollinare, Osimo, Rieti) the following data were available (Monotti M. *et al.*, 1978-2003; Desiderio E. *et al.*, 1984-2003): a) agrometeorological data at daily time scale (precipitation, temperature) and at monthly time scale (wind speed, air humidity, solar radiation) from 1978 to 2003. In figure 1 mean weekly precipitation depths in the four sites during the growing season of sunflower and sorghum is shown. In table 2 mean seasonal precipitation depths and the corresponding standard deviation are given; b) hydrological soil data; c) phenological periods dates and growing seasons; d) experimental crop yield for sunflower and sorghum from 1978 to 2003. Some descriptive statistics are given in table 3.

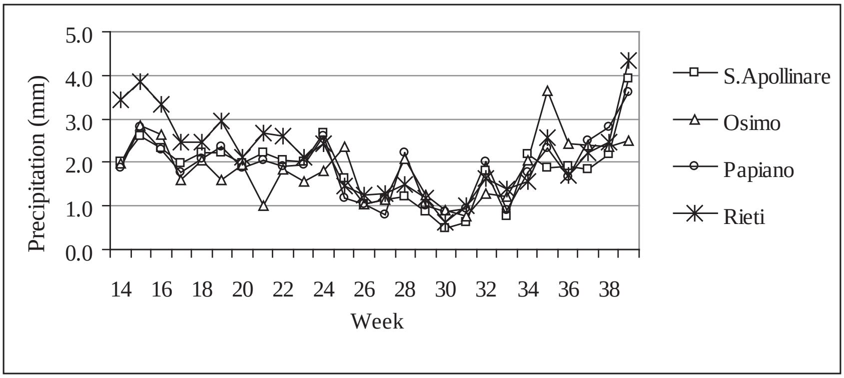

Figure 1. Mean precipitation depths of weeks from 14th to 39th for the selected sites (reference period: 1978-2003).

Table 2. Mean precipitation depths (*mean* $P_{apr\text{-}aug}$) for the period april-august and corresponding standard deviation $\sigma_{apr\text{-}aug}$ computed for the period 1978-2003 for the sites of the case study.

	Papiano	S.Apollinare	Osimo	Rieti
mean $P_{apr\text{-}aug}$ (mm)	266.6	263.2	265.7	320.2
$\sigma_{apr\text{-}aug}$ (mm)	81.6	90.0	109.2	76.5

Table 3. Yield experimental data number (*n*), mean seeding (*mean SD*) and flowering date (*mean FD*) and corresponding standard deviations σ_{SD} and σ_{FD}. Mean crop yield (*mean Y*)-(1978-2003).

	Sunflower			Sorghum		
	Papiano	S.Apollinare	Osimo	Papiano	S.Apollinare	Rieti
n	25	16	23	18	13	20
mean SD (day)	95	93	94	127	128	134
σ_{SD} (day)	5.8	4.1	7.6	3.6	3.3	8.3
mean FD (day)	180	181	177	202	203	211
σ_{FD} (day)	6.5	4.7	6.1	6.5	5.8	7.8
mean Y (t/ha)	3.52	3.59	3.03	6.55	6.93	8.31

IV – Intra-seasonal correlation analysis at weekly time scale

1. Correlation analysis

The indices have been quantified at weekly scale within however the crop growing season. For each week, the time series of the drought index value has been used within an analysis of correlation with the correspondent series of crop experimental yield. The same analysis has been performed for every index and for every unit. The values of the coefficient of correlation r for the different weeks, are given in the diagrams of the Fig. 2a for Sunflower and Fig. 2b for Sorghum.

In the figures growing season weeks were grouped in four growth stages according to FAO scheme (Allen *et al.*, 1998): 1st (initial), 2nd (development), 3rd (mid-season), 4th (late season). In the same diagrams have been also drawn the continuous lines that identify the extremes values of significance for r (α=0.05). In other words $|r| > |\text{extreme value}|$ the correlation is statistically significant. In particular r values are expected to be positive for PDSI, Z, CMI, SPI and negative for RS, as on the contrary of the other indices, it increases with the water deficit (i.e. when the yield decreases).

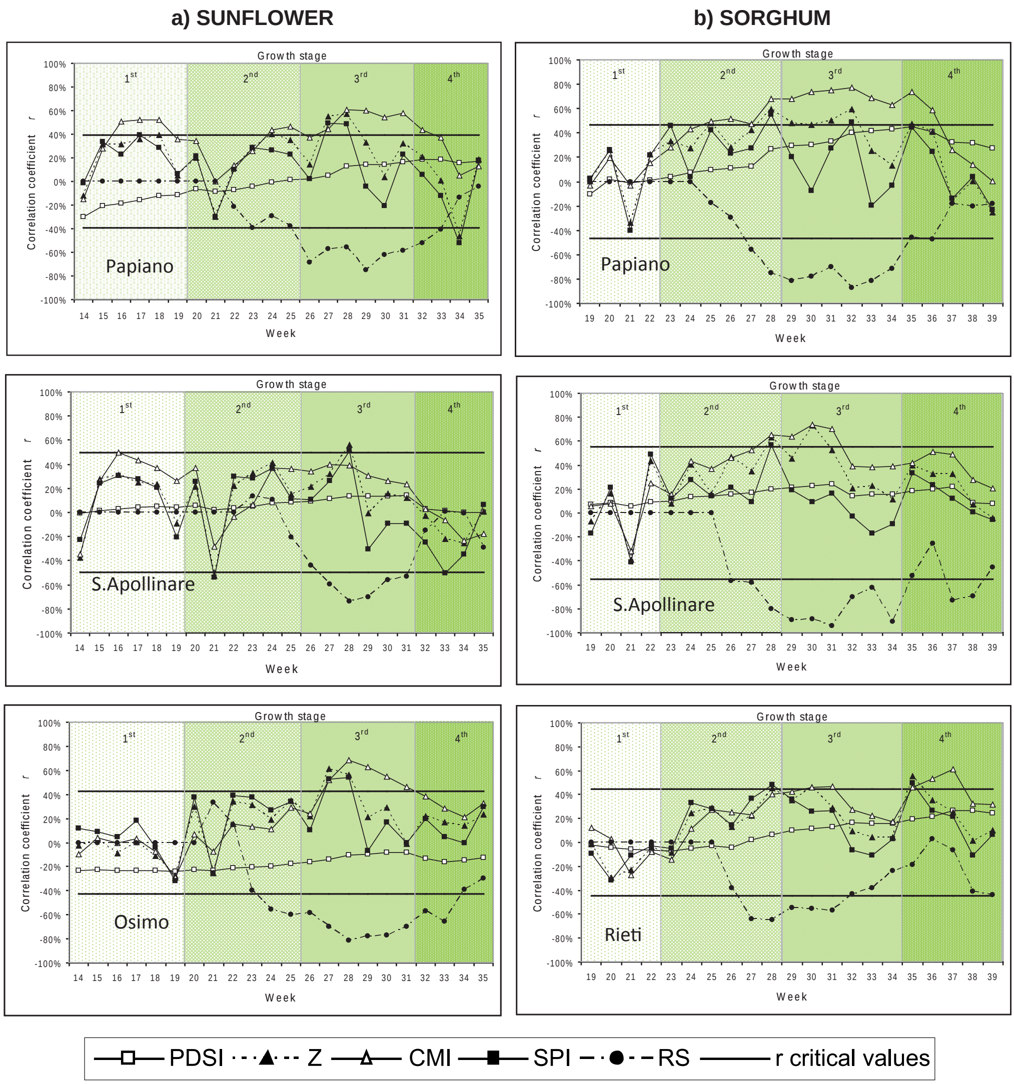

Figure 2. Correlation coefficients between weekly drought indices values and corresponding seasonal crop yield for sunflower and sorghum at different experimental sites.

2. Discussion of the results

For all the selected indices the correlation coefficient *r* increases until the 3rd growth stage, afterwards (4th and last stage) the correlation decreases. The increase is monotonic only for the PDSI, in the other cases the *r* value presents some off-hand oscillations particularly for the SPI, CMI and Z, anyway the increasing tendency is evident (Fig. 2a and Fig. 2b)

The sign of the correlation coefficient *r* is always negative for RS as this index quantify the stress of the crop that is inversely related to the crop yield.

The correlation typically becomes significant for few weeks in correspondence or in proximity of the 3rd stage, with the exception of the PDSI for which the correlation never becomes significant. The most correlated weeks are the 28th-29th for Sunflower and around the 30th for Sorghum. The index RS has the more evident correlation with the final yield both for the higher absolute value of the *r* and for the greater number of weeks when the correlation is significant. It is also possible to pinpoint weeks when correlation becomes different from zero (20th-21st for the sunflower and 24th-25th for sorghum) pointing out the period of the season when statistically water deficit begins to having repercussions on the yield. The weekly values of the PDSI index are weakly or non correlated with the final yield: the *r* is always included between the minimum values of significance, being next to zero in many cases (with the exception of the case Sorghum-Papiano where it catches up the significance limit during the 3rd stage). The CMI for some units shows high correlation values especially in correspondence of 2nd stage. Z and SPI, at last, show similar courses, even if the correlation value for SPI shows off-hand oscillations that can induce errors in the severity evaluation in real time. For the sunflower however it is possible to identify, both for Z and SPI, some weeks when the correlation values are high (27th and 28th).

V – Models based on the drought indices for the predictive assessment of the grain yield

1. Regression analysis

Regression type models based on a single index for predicting grain yield for Sunflower and Sorghum crops in central Italy are developed for each drought index and for each soil-crop-climate unit. For every growth stage i, one variable X_i obtained by the sum of the weekly values of the index, has been determined. The four values (X_1, X_2, X_3, X_4) can be considered to be the significant variables in the prediction/estimation of the grain yield by opportune models of linear multiple regression of the type:

$$\mathrm{Ya} = \lambda_1 \cdot \mathrm{X}_1 + \lambda_2 \cdot \mathrm{X}_2 + \lambda_3 \cdot \mathrm{X}_3 + \lambda_4 \cdot \mathrm{X}_4 + \mathrm{c} \qquad (1)$$

where the coefficients λ_i (i=1…, 4), are like factors of sensibility of the crop to water stress in a given stage i and Ya is the estimated actual crop yield.

The technique of stepwise multiple regression, allows to exclude from the model the variables that do not contribute to meaningful increments of the explained variance. The exclusion of a variable X_i is obtained by setting at zero the corresponding λ_i value. After the application of such technique the characterized model will be able to introduce a reduced number of variables (till to become, eventually, a simple linear regression). For the final models the verification of the hypotheses on the residuals was performed using statistical tests (Shapiro-Wilk for residuals normality, Breusch-Pagan for heteroscedasticity and Ljiung-Box for autocorrelation). The coefficient of determination (R^2) and the Mean Absolute Error (MAE) have been finally used to test the reliability and the performances of the models. The indices adopted in this analysis are: the same of the correlation analysis at weekly time scale and two more indices (anyhow cumulated for every growth stage) that are the simple rain, R, and the deficit ratio ETa/ETm. In this last case the Jensen (1968) model has been adopted:

$$\frac{Ya}{Ym} = \prod_{i=1}^{N} \left(\frac{ETa}{ETm} \right)_i^{\lambda_i} \qquad (2)$$

where Ya and Ym are respectively the actual and the maximum yield, ETa and ETm are respectively the actual and maximum evapotranspiration.

Considering four growth stages eq. (2) can be transformed in the following model:

$$\ln(Ya) = \lambda_1 \cdot \ln\left(\frac{ETa}{ETm}\right)_1 + \lambda_2 \cdot \ln\left(\frac{ETa}{ETm}\right)_2 + \lambda_3 \cdot \ln\left(\frac{ETa}{ETm}\right)_3 + \lambda_4 \cdot \ln\left(\frac{ETa}{ETm}\right)_4 + c \qquad (3)$$

being c=ln(Ym)

Therefore the intercept value, c, represents the crop yield under normal condition for the standardized indices (PDSI, Z, CMI, SPI) derived models, under null water supply for R and under optimal water supply for RS and ETa/ETm.

The λ_i coefficients, the intercept value c, the R^2 and the MAE, are given in the Table 4a for Sunflower and Table 4b for Sorghum.

Table 4. The λi coefficients of the regression models for the different soil-climate units, the intercept value c, the R^2 and the MAE. Highlighted models are not statistically significant (α=0.05). *The regression model adopted for this index is the Jensen equation, eq. (2)

a) Sunflower

	Site	Model					R^2	MAE (t/ha)
		λ_1	λ_2	λ_3	λ_4	c		
PDSI	Papiano	-0.1		0.1		3.5	0.41	0.43
	S.Apoll.		-0.1	0.1		3.6	0.22	0.32
	Osimo	0.1	-0.5	0.4		3.2	0.53	0.39
						Mean	**0.39**	**0.38**
Z index	Papiano	0.1		0.1		3.6	0.41	0.44
	S.Apoll.			0.1	-0.1	3.6	0.36	0.31
	Osimo			0.1		3.1	0.39	0.45
						Mean	**0.39**	**0.40**
CMI	Papiano	0.1		0.1		3.2	0.48	0.39
	S.Apoll.			0.1	-0.1	3.6	0.40	0.28
	Osimo		-0.1	0.1			0.50	0.41
						Mean	**0.46**	**0.36**
Rain	Papiano	0.0	0.0	0.0		2.1	0.48	0.39
	S.Apoll.		0.0	0.0	0.0	3.3	0.41	0.29
	Osimo		0.0	0.0		2.2	0.51	0.42
						Mean	**0.47**	**0.37**
SPI	Papiano	0.1	0.1	0.2	-0.1	3.1	0.54	0.40
	S.Apoll.		0.1	0.1	-0.2	3.7	0.59	0.23
	Osimo		0.1	0.2		2.6	0.50	0.43
						Mean	**0.54**	**0.35**
RS	Papiano			-0.2	-0.1	5.0	0.69	0.32
	S.Apoll.			-0.1		4.4	0.58	0.23
	Osimo			-0.1	-0.1	4.6	0.78	0.24
						Mean	**0.68**	**0.26**
ETa/ETm *	Papiano			0.8		1.5	0.61	0.34
	S.Apoll.			0.7		1.5	0.60	0.24
	Osimo			0.6	0.2	1.5	0.74	0.25
						Mean	**0.65**	**0.28**

b) Sorghum

	Site	Model					R^2	MAE (t/ha)
		λ_1	λ_2	λ_3	λ_4	c		
PDSI	Papiano	-0.3		0.2		6.8	0.57	0.87
	S.Apoll.	-0.5		0.5	-0.3	6.5	0.37	1.11
	Rieti		-0.1		0.1	8.2	0.23	1.06
						Mean	**0.39**	**1.02**
Z index	Papiano		0.1	0.2		6.6	0.62	0.76
	S.Apoll.			0.2	0.2	7.2	0.38	1.34
	Rieti	-0.2	0.1		0.2	8.2	0.42	0.95
						Mean	**0.47**	**1.02**
CMI	Papiano			0.2		7.0	0.64	0.76
	S.Apoll.			0.2		7.4	0.35	1.14
	Rieti	-0.4			0.3	9.2	0.48	0.93
						Mean	**0.49**	**0.95**
Rain	Papiano		0.0	0.0		4.4	0.62	0.73
	S.Apoll.		0.0			6.0	0.19	1.32
	Rieti		0.0		0.0	5.5	0.45	0.94
						Mean	**0.42**	**1.00**
SPI	Papiano		0.5	0.4		5.4	0.57	0.81
	S.Apoll.	0.6	0.7		0.3	5.7	0.54	0.89
	Rieti		0.3		0.3	7.7	0.40	0.85
						Mean	**0.51**	**0.85**
RS	Papiano			-0.4		8.9	0.90	0.42
	S.Apoll.		-0.9	-0.4		9.2	0.92	0.43
	Rieti			-0.3	-0.2	10.5	0.76	0.63
						Mean	**0.86**	**0.50**
ETa/ETm *	Papiano		1.8	0.5		2.1	0.75	0.58
	S.Apoll.		4.1	0.9		2.2	0.93	0.44
	Rieti			0.4	0.3	2.3	0.70	0.76
						Mean	**0.80**	**0.59**

2. Discussion of the results

An examination of the λ_i gives some information about the relative sensitivity of the crop yield to the stress during each of the four growth periods. As the indices PDSI, Z, CMI, R, SPI and ETa/ETm increase with the water supply, a significant positive λ_i suggests that yield may be sensitive to stress during that specific growing period. Conversely, a λ_i with a significant negative value suggests that yield may be enhanced by stress during that specific growth period. For RS an analogous but inverse observation can be made. The best predictive models have been obtained for the RS index that gives results very similar to the reference one ETa/ETm. The performance of the other indices is low and very similar to that obtained adopting the simple precipitation, R, with the exception of the SPI that gives better results. PDSI based models are often not significant and exhibit the lowest performances. In any case the results of this further analysis are in accordance to that obtained with the correlation analysis performed at weekly time scale. For **Sunflower** (Tab. 4a) all the models have the X_3 as significant independent variable (λ_i are positive for PDSI, Z, CMI, R, SPI, ETa/ETm and negative for RS). The X_2 is present always in the models obtained with the indices derived from precipitation (R and SPI), and the X_1 is present only in few cases. For Z, CMI, R, SPI the variable X_4, when significant, presents negative sensitivity coefficients. The results obtained are in accordance with the Sunflower characteristics that is very sensitive to the water stress during the 3rd stage (when flowering takes place) and sometimes penalized from water supply during the 4th one.

For **Sorghum** (Tab. 4b) the models reflect the characteristics of the crop to have an ability to recover rapidly after a period of water stress. Further, the sorghum is able to recover to a certain extent from water deficit in certain period in subsequent periods when the water supply is higher. For this reason a growth stage whose independent variable is always present in the models, is not distinctly present. Anyway the models for RS and ETa/ETm always have the X_3 as significant independent variable.

VI – Conclusions

A comparative analysis of the performances of some drought indices in monitoring and predicting sunflower and sorghum crop yield in Central Italy has been performed. The performances of the various indices have been tested both by an intra-seasonal correlation analysis between the weekly value of the indices and the crop yield and by an evaluation of the ability to predict agricultural drought impact. This ability has been tested by the goodness of crop yield estimation by regression models based on elaboration of the drought indices. In the quantification of such prediction models, several standardized indices (PDSI, Z, CMI, SPI) and not standardized indices (R, RS, ETa/ETm) were considered. The main difference between the selected indices is the effort required in quantifying them in terms of both computational procedure and amount of input data. The analysis shows clearly that for accurate estimate of the crop yield and for the real time monitoring the best predictive indices are those based on the actual evapotranspiration computation (RS, ETa/ETm). The performance of the other indices (PDSI, Z, CMI) has been found to be marginal compared to the effort required in quantifying them, infact the results came out to be similar to that obtained by the simple rain, R. The SPI, can be considered a good compromise between the computational effort and the performance in predicting the crop yield. In the paper the regression models based on the RS index are finally recommended for predicting and monitoring agricultural drought severity for Sunflower and Sorghum in Central Italy. In the case of low availability of data, SPI based model is recommended for prediction even if the correlation presents off-hand oscillations. The weeks when indices are more correlated with the final crop yield in Central Italy come out to be the 28th-29th for Sunflower and around the 30th for Sorghum.

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Analysis of the performances of methods for the evaluation of soil hydraulic parameters and of their application in two hydrological models

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Abstract. Daily measurements of evapotranspiration, mean soil moisture in the root zone and percolation out of the root zone collected in a cropped maize field in Northern Italy (Landriano-PV) were used to test the performances of two models: SWAP, a widely used hydrological model based on Richards equation, and ALHyMUS, a conceptual model based on a reservoir cascade scheme.

Each model was implemented with three different sets of hydraulic parameters values, derived by applying three well-known Pedo-Transfer Functions to the texture and organic matter measurements collected at the experimental site. Simulations were run using meteorological data measured at the site for the time period June - October 2006.

The results confirm the existence of a wide range of variation of the parameter values in the different sets, remarkably in the case of hydraulic conductivity. This is reflected in a high variability of the output variables of each model, which often is larger than the difference between the same outputs for the two models. Finally, the comparison shows that a good agreement of soil moisture patterns may occur even if evapotranspiration and percolation fluxes are significantly different; therefore multiple output variables shall be considered to test the performances of methods and models.

Keywords. Unsaturated zone – Hydrologic model – Pedo-transfer functions.

Analyse de performance des méthodes d'évaluation des paramètres hydrauliques du sol et leur application dans deux modèles hydrologiques

Résumé. *Des mesures journalières de l'évapotranspiration, de l'humidité moyenne du sol dans la zone racinaire et de la percolation, collectées dans un champ de mais au Nord de l'Italie, ont été utilisées pour tester la performance de deux modèles : SWAP, un modèle hydrologique très utilisé basé sur l'équation de Richards, et ALHyMUS, un modèle conceptuel basé sur un réservoir système cascade. Chaque modèle a été exécuté pour trois séries de paramètres hydrauliques à valeurs diverses, dérivées de trois fonctions de pédotransfert bien connues, qui ont été appliquées aux mesures de la texture et de la matière organique du champ expérimental. Les simulations ont été élaborées en utilisant des données météorologiques mesurées sur le site pour la période juin-octobre 2006. Les résultats confirment l'existence d'une grande variabilité des valeurs des paramètres hydrauliques pour les trois séries, en particulier la conductivité hydraulique. Cela entraine une grande variabilité des résultats de chaque modèle, qui est souvent plus grande que la différence entre les résultats des deux modèles obtenus à partir des mêmes paramètres. Enfin, la comparaison montre que les valeurs d'humidité du sol peuvent être en accord, même si les flux d'évapotranspiration et de percolation sont significativement différents; par conséquence plusieurs variables de sortie devraient être prises en compte afin de tester les performances des méthodes et des modèles.*

Mots-Clés. *Zone insaturée – Modèle hydrologique – Fonctions de pédotransfert.*

I – Introduction

Water retention and hydraulic conductivity curves are crucial input parameters in any modelling study on water flow and solute transport. Computed water balance is in fact sensitive to soil hydraulic parameters and therefore their accurate determination is essential to model hydrological processes (Jhorar *et al.*, 2004).

Direct methods for estimating soil hydraulic parameters, either laboratory- or field-based, remain relatively time consuming and costly, especially when data are needed for large areas (Wösten *et al.*, 2001). For these reasons many attempts have been made at estimating soil hydraulic parameters by means of empirical relationships based on readily available soil data, such as textural soil properties and bulk density. These relationships, commonly referred as Pedo-Transfer Functions (PTFs) (Bouma, 1989), are particularly enticing as they are very well suited for large scales applications. In spite of the wide diffusion of these methods, the reliability of the results obtained is still under discussion (see for instance: Tietje and Hennings, 1996; Romano, 1999; Tietje and Tapkenhinrichs, 1993; Bastet *et al.*, 1999; Nemes *et al.*, 2003; Ungaro *et al.*, 2005). These works show that good performances can be obtained also with predictive methods, but in general the evaluations are site specific and therefore it is not possible to draw general conclusions.

To evaluate and compare different methods for the estimation of the soil hydraulic properties, Wösten *et al.* (1986) proposed the use of functional criteria that are directly related to applications, rather then to the direct comparisons of parameters. The basis for the identification of differences in hydraulic properties will therefore be determined by the accuracy with which the functional criteria are predicted and not by the accuracy with which hydraulic properties are characterized (Vereecken *et al.*, 1992).

To further explore this issue, an intensive monitoring activity was conducted in 2006 in a 10 ha maize cropped field located in Northern Italy (Landriano – PV). The information collected has been used in this research: *i)* to compare different methods for deriving the values of the soil hydraulic parameters and *ii)* to evaluate the effect of the uncertainty in the determination of these parameters on the outputs of two hydrological models of different complexity: SWAP (Kroes and van Dam, 2003), a widely used model of soil moisture dynamics in unsaturated soils based on Richards equation, and ALHyMUS (Facchi *et al.*, 2004), a conceptual model of the same dynamics based on a reservoir cascade scheme.

Each model has been implemented with three different set of parameters obtained applying three widely used Pedo-Transfer Functions to the texture and organic matter measurements collected for each horizon of the experimental profile at the monitoring site: *i)* Rawls and Brakensiek (1989); *ii)* HYPRES (Wösten *et al.*, 1999); and *iii)* ROSETTA (Schaap *et al.*, 2001). Simulations have been run with each model and each parameters set using meteorological inputs measured at the site for the time period June - October 2006. The comparison has been focused on three output variables: evapotranspiration, water content in the root zone and outflow at the bottom of the root zone.

II – Materials and methods

1. Experimental field site

The monitoring activities were conducted in 2006 during the cropping season of a 10 ha maize field, located in Northern Italy (Landriano – PV; 45°19’ North, 9°15’ East, 88 m a.s.l.). Instruments for the detailed monitoring of water and energy fluxes have been installed in the experimental field since 2005. A micrometeorological eddy-correlation (EC) based station was located in the centre of the field. A vertical sided trench was opened close to the tower site with the purpose of characterizing the profile and collecting samples from each horizon for standard soil analyses. TDR devices (CS616 Campbell Sci.) and tensiometers (SKYE) were installed in the profile respectively at the depth of 5, 20, 35, 50 and 70 cm and 20, 35 and 70 cm. Due to the presence of a shallow water table (90-120 cm below the topographic surface) a shallow piezometer with a pressure transducer device (STS) was installed as well. Standard meteorological devices and PAR sensors completed the installation. Spatially distributed measures of Leaf Area Index LAI (-), crop height h_c (m) and rooting depth D_r (m) to characterize the crop in the field were conducted periodically. Moreover, saturated hydraulic conductivity K_{sat} (cm h^{-1}) was measured at the different soil depth through a Guelph permeameter.

During the cropping season 2006 there were two irrigation treatments: the first one in date June 8th (Day of the Year, DoY = 159) by sprinkler irrigation to allow the crop emergence, and the second one, in date July 14th (DoY = 195) by surface irrigation. The irrigation depths were estimated through the variation of the measured soil moisture in the profile in the first case and through the measure of the water discharge in the irrigation channel by an electromagnetic flow sensor (Nautilus - OTT) in the second one. The values of the irrigation depths were found to be 20 mm and 140 mm respectively. Due to the field condition (i.e. flat field) the run-off was negligible in the whole monitoring period. A summary of the data collected at the monitoring site is shown in Table 1.

Table 1. Summary of meteo and crop data collected at the monitoring site (3 June – 10 October)

Cumulative rain	**429 mm**
Mean temperature	21 (°C)
Crop	Zea Maize
Emergence	6 June 2006 (DoY = 157)
Harvesting	10 October 2006 (DoY = 283)
LAI_{max}	4.2 (-)
Crop height $_{max}$	3.00 (m)
Rooting depth $_{max}$	0.70 (m)
sprinkler irrigation	8 June 2006 (DoY = 159); 20 mm
surface irrigation	14 July 2006 (DoY = 195); 140 mm

2. SWAP model

The soil–water–atmosphere–plant (SWAP) is a widely applied and well documented model, based on a finite difference solution of the Richards equation (Van Dam *et al.*, 1997). It simulates the vertical soil water flow and solute transport in close interaction with crop growth. Richards equation (Richards, 1931) is applied to compute transient soil water flow:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_a \quad (1)$$

where *C(h)* (cm^{-1}) is the differential soil water capacity $(\partial\theta/\partial h)$, θ (-) is the volumetric water content, *h* (cm) the soil water pressure head, *K(h)* (cm d^{-1}) the hydraulic conductivity, S_a (d^{-1}) the root water extraction rate, and *z* (cm) the vertical coordinate (positive upward). The numerical solution of Eq. (1) (Richards, 1931) is subject to specified initial and boundary conditions, and requires known relationships between the soil hydraulic variables moisture θ, pressure head *h* and hydraulic conductivity *K*. The following relations between these variables have been used (Van Genuchten, 1980; Mualem, 1976):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^m} \tag{2}$$

$$K(\theta) = K_{sat} S_e^L \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{3}$$

where θ_r (-) is the residual water content, θ_s (-) the saturated water content, $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ (-) the relative saturation, α (cm^{-1}) an empirical shape factor, *n* (-) an empirical shape factor, K_{sat} (cm h^{-1}) the saturated hydraulic conductivity, and *L* (-) an empirical coefficient. The value of *m* is fixed as $m = 1-1/n$.

SWAP includes both a simple and detailed crop growth module. In the simple crop module used in this research, crop growth is described by *LAI* (-), crop height h_c (m) and rooting depth D_r (m) as functions of crop development stage. The potential evapotranspiration rate ET_p (mm d^{-1}) is estimated by the Penman–Monteith equation (Monteith, 1965). In field conditions where crops partly cover the soil, the ET_p is partitioned into the potential soil evaporation E_p (mm d^{-1}) and the potential crop transpiration T_p (mm d^{-1}) using the daily pattern of *LAI* (Goudriaan, 1977; Belmans *et al.*, 1983).

3. ALHyMUS model

The unsaturated flow model ALHyMUS (Facchi et al, 2004; Gandolfi *et al.*, 2006) is based on a non-linear reservoir cascade scheme, including two reservoirs in the root-zone and one (or more) additional reservoir(s) extending from the root-zone to the groundwater table. The first reservoir (evaporative) represents the upper part of the soil profile in which infiltration, evaporation and percolation to the subsequent reservoir take place; the second reservoir (transpirative) extends through the root zone having a thickness variable with the phenology of the crop and considers the processes of transpiration and percolation to the reservoir beneath; in the last reservoir(s) only percolation is taken into account. The thickness of the last reservoir(s) varies in time, due to the fluctuations of phreatic levels. Evaporative and transpirative rates are computed using the FAO-56 dual crop coefficient method (Allen *et al.*, 1998). A 1-D mathematical representation of the infiltration and percolation processes is adopted. The potential infiltration rate is estimated by the Green-Ampt equation (Green and Ampt, 1911). Drainage discharges from each reservoir are determined using a simplified scheme, which considers a Darcian-type gravity flow; the relation between the unsaturated hydraulic conductivity and the water content is modelled by Eq. (3). The water balance is computed by an implicit iterative procedure.

Due to the presence of a shallow groundwater table in the study field, for this research the ALHyMUS model was added with the empirical relation of Liu *et al.* (2006), which computes the capillary rise G_c (mm d^{-1}) from groundwater surface to the transpirative reservoir as a function of the moisture in the reservoir θ_v (-), the rate of potential evapotranspiration ET_p (mm d^{-1}) and the shallow groundwater depth *D* (m).

4. Soil hydraulic parameters

Three widely used Pedo-Transfer Functions have been applied to the texture and organic matter measurements collected at the profile of the experimental site (Table 2). The first one is the set of PTFs of Rawls and Braekensiek (1989), based on non-linear multiple regression equations. Calzolari *et al.* (2001) have shown that these PTFs, even if developed using USA soil data, have a good performance also for the soils of the central Padana Plain (Northern Italy). The second set of PTFs used is the so-called HYPRES (Wösten *et al.*, 1999), based on multiple regression equations as well, but developed using an European data-base of soils; it is important to underline that in this data-base no soils from Northern Italy are included. Finally, the last set is the one called ROSETTA (Schaap *et al.*, 2001) developed by the USSL (United States Salinity Laboratory) using a neural network model based on USA soil data. The values of the bulk density ρ_b (g cm^{-3}) necessary for the PTFs has been estimated by the relation proposed by Jeffrey *et al.* (1970), that proved to provide good results for the soil data of the area (ERSAL, 2001).

Table 2. Chemical-physical data for the horizons of the study profile

Depth (cm)	0-10	10-40	40-55	55-90
soil classification (USDA)	Ap1	Ap2	B	2Bt1
Sand (%)	67.0	65.0	56.0	44.5
Silty (%)	30.5	32.0	39.5	31.5
Clay (%)	2.5	3.0	4.5	24.0
Organic matter (%)	2.7	2.3	1.9	0.5

5. Model inputs and parameters

The models have been set up for the period 6 June – 10 October 2006. Measured meteorological and irrigation data have been used for the simulations. Daily pattern of crop height, h_c (m), Leaf Area Index, *LAI* (-) and rooting depth, D_r (m) have been obtained by linear interpolation from the data collected in the field during the cropping season. The daily pattern of K_{cb} (-) (basal crop coefficient, see Allen *et al.*, 1998), used by ALHyMUS to compute the transpiration rate T_p (mm d^{-1}), has been estimated on the basis of literature values (Allen *et al.*, 1998; Huygen *et al.*, 1997; Borgarello *et al.*, 1993) adapted to the cropping stages observed on the field. Table 3 shows the main additional crop parameters necessary for the implementation of the two models: the pressure head values H_{Lim} (cm) for the crop stress condition in SWAP are those proposed in Hupet *et al.* (2004) except for the wet stress condition not taken into account in this research, the canopy resistence r_c (s m^{-1}) for the SWAP Penman–Monteith equation, the interception model parameters *a* (mm d^{-1}) and *k* (-), and the *p* (-) parameter used by ALHyMUS to determine the fraction of Readly Avalilable Water (RAW) form the Total Available Water (TAW) (Allen *et al.*, 1998) are those proposed in literature for maize.

Table 3. Crop parameters values used by SWAP and ALHyMUS models

SWAP						*SWAP – ALHyMUS*		*ALHyMUS*
H_{LIM} 1 (cm)	H_{LIM} 2 (cm)	H_{LIM} 3 (cm)	H_{LIM} 4 (cm)	H_{LIM} 5 (cm)	r_c (s m^{-1})	*a* (mm d^{-1})	*k* (-)	p (-)
-	-	-325	-600	-8000	70	0.25	0.385	0.5

The soil hydraulic parameters have been determined using the three PTFs illustrated above for all the horizons of the study profile. The values of the soil moisture at the field capacity θ_{FC} (-) and at the wilting point θ_{WP} (-) used by ALHyMUS to evaluate the Total Available Water (*TAW*) and the Total Evaporable Water (*TEW*) (Allen at al., 1998) have been computed solving the retention curve equation (Eq. 2) for the pressure head of -100 cm and -8000 cm respectively.

The soil hydraulic parameter values for the ALHyMUS reservoirs have been computed from those determined for each horizon. In particular, for each reservoir, the arithmetic mean of the parameters of the horizons which fall in it, weighted by their thickness, is used for all the soil hydraulic parameters except for the saturated hydraulic conductivity, for which the geometric mean has been adopted.

The initial moisture conditions have been fixed in both models at the measured values and the bottom boundary condition has been prescribed according to the measurements of the groundwater levels, respectively using the daily data as input (Liu *et al.*, 2006) in ALHyMUS and using the data to calibrate the following relationship for estimating the bottom flux Q_{bot} (cm d^{-1}) in SWAP:

$$Q_{bot} = \frac{\phi_{acquif} - \phi_{avg}}{c_{conf}} \tag{4}$$

where ϕ_{acquif} is the hydraulic head in the semi-confined aquifer (cm), ϕ_{avg} is the average groundwater level measured in the field (cm), and c_{conf} is the semi-confining layer resistance (d).

III – Results and discussion

1. Comparison of soil hydraulic parameters

Table 4 shows mean and coefficient of variation (CV) for the parameters determined using the three PTFs for each soil layer. The results confirm the existence of a wide range of variation of the parameters values in the different sets, remarkably in the case of hydraulic conductivity K_{sat} (cm h^{-1}) and of the shape parameter α (cm^{-1}). The parameter *L* (-) also shows a high variability but it is demonstrated that hydrological models are less sensitive to its variations (Jhorar *et al.*, 2004).

Table 4. Statistics for the soil hydraulic parameters determined using the three PTFs.

Depth (cm)		θ_s (-)	θ_{FC} (-)	θ_{WP} (-)	θ_r (-)	n (-)	α (cm^{-1})	K_{sat} (cm h^{-1})	L (-)
0-10	mean	0.49	0.27	0.07	0.03	1.401	0.050	7.7	-0.19
	CV	13%	17%	20%	14%	3%	72%	60%	-341%
10-40	mean	0.47	0.27	0.07	0.03	1.404	0.048	6.2	-0.18
	CV	13%	15%	16%	13%	2%	70%	56%	-360%
40-55	mean	0.45	0.28	0.08	0.03	1.404	0.038	3.4	-0.10
	CV	14%	11%	12%	17%	3%	72%	41%	-521%
55-90	mean	0.38	0.29	0.13	0.05	1.311	0.026	0.3	-0.89
	CV	5%	4%	23%	52%	9%	40%	17%	-166%

2. Performance evaluation

A. *Evapotranspiration*

The actual evapotranspiration rate at the experimental site is generally close to the potential. In this condition the hydraulic parameters don't play an important role and the output of the models obtained with the different sets of values are similar. The performance of both models is different in the first period (3 June - 2 July), when the crop is small and evaporation is the predominant process and in the second period (2 July – 10 October), when the crop grows and reaches the maximum LAI value. Figure 1 shows for example the simulation results obtained with the two models using the set of parameters obtained by the Rawls and Brakensiek PTFs (1989) vs. the EC measurements; the data have been split in the two periods. The results show that in the first period, the performance of both models is poor. This is probably due to processes (such as cracking or soil crusting) not accounted for in the models. In the second period the simulations performance improves, though the estimate values show a systematic overestimation (probably because the agronomic and environmental conditions of the crop are always considered optimal). Similar results have been obtained for the other sets of soil parameters.

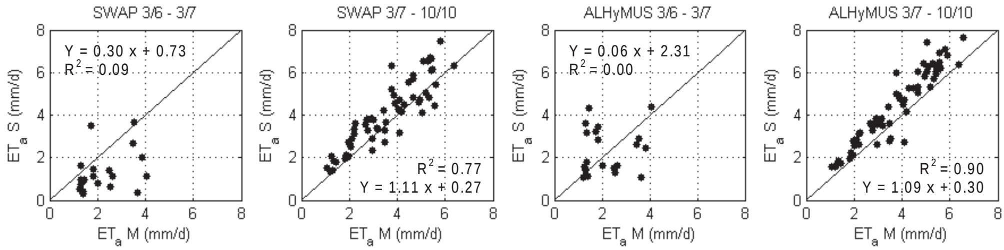

Figure 1. Evapotranspiration: measured values by EC technique (Et_a M) vs. simulated (Et_a S) by the two models using the PTFs of Rawls and Brakensiek (1989); periods 3/6/2006 - 3/7/2006 and 3/7/2006 - 10/10/2006.

B. Soil water content

The pattern of the soil moisture content in the root zone is very sensitive to the different sets of hydraulic parameters for both models. Figure 2 shows the simulated vs. measured values with the three sets. The best fit is very good for either SWAP and ALHyMUS and it is achieved with the set of parameters obtained applying the Rawls and Brakensiek PTFs (1989). On the contrary, the Rosetta set gives the worst performances for both models, but with these soil parameters SWAP systematically over-estimates soil moisture while ALHyMUS does the opposite. The behaviour of the models when the HYPRES set of parameters is adopted is similar, with a rather good performance and a general overestimation of the soil moisture values. These results demonstrate that when the soil water content in the root zone is considered, the choice of the method for deriving the soil hydraulic parameters may be more important than the choice of the model.

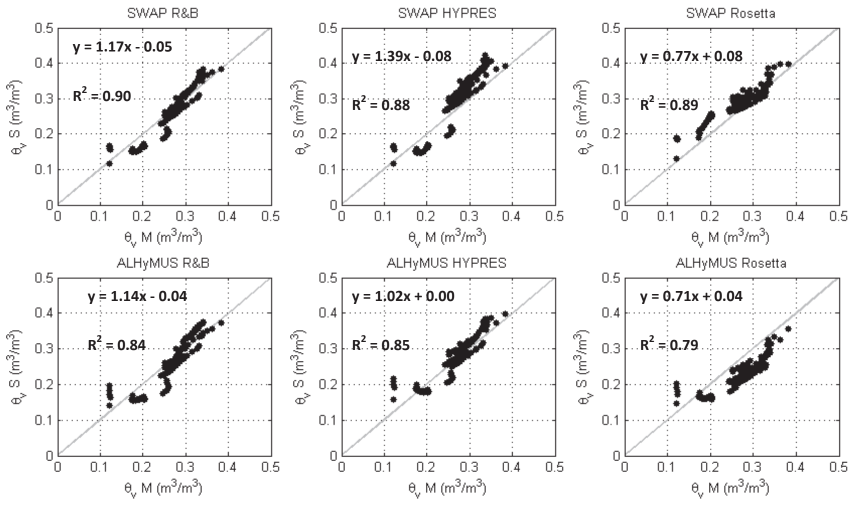

Figure 2. Soil moisture content in the root zone: measured values (θ_v M) vs simulated (θ_v S) by the two models implemented with the different sets of hydraulic parameters.

C. Bottom flux

Figure 3 shows the comparison between the simulated vs. the measured values of the daily flow at the bottom of the root zone which varies from 30 to 70 cm during the growing stages. The values simulated are the outputs of the two models implemented with the different sets of soil parameters. The values measured are obtained as residual terms of the daily hydrological balance by using the available measured values of soil water content and water inputs and outputs (i.e. rainfall, irrigation and evapotranspiration). Flows are significantly influenced by the very shallow water table and thus the monitoring period is characterized by an alternation of deep percolation (negative values in the figure) and capillary rise (positive values). The performance of both models is rather poor: in general the percolation flux is smoothed and delayed compared to the measured values and, especially in days immediately following intense precipitation or irrigation events, this flux are underestimated.

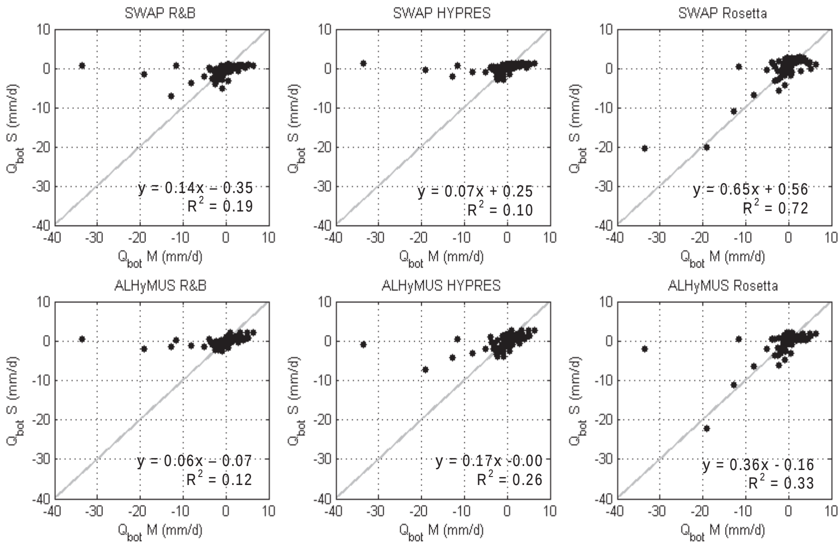

Figure 3. Bottom flux: measured values (Q_{bot} M) and simulated (Q_{bot} S) by the two models implemented with he different set of soil parameters.

IV – Conclusion

The results confirm the existence of a wide range of variation of the hydraulic parameter values obtained applying different PTFs. This is reflected in a high variability of SWAP and ALHyMUS output variables, which often is larger than the difference between the same output simulated by the two models adopting the same soil hydraulic parameters set.

The actual evapotranspiration rate at the experimental site is generally close to the potential. In this condition the hydraulic parameters don't play an important role and the output of the models obtained implementing the different sets of values are similar with a general overestimation of the evapotranspiration fluxes. Both models show a high sensitivity to the different sets of hydraulic parameters when the soil moisture content in the root zone is considered. The best performance is achieved with the PTFs of Rawls and Brakensiek (1989) for both models; these PTFs already proved to provide good results for the soil data of the central Padana plain (Calzolari *et al.*, 2001). When the flux at the bottom of the root zone is considered both models show to capture the influence of the shallow water table in terms of general pattern with each hydraulic parameters set. However, the accuracy of the simulated values is rather poor showing a general underestimation of the process. These general behaviour of overestimation of evapotranspiration and underestimation of the bottom flux suggest that a good agreement of soil moisture patterns may occur even if the performances of the models in the simulation of the fluxes are poor. Therefore multiple output variables shall be always considered to test the performances of methods and models.

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Land surface temperature from remote sensing and from an energy water balance model for irrigation management

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Abstract. Soil Moisture is recognized as the key variable in the hydrologic water balance for operational purpose as for flash flood forecast system as well as for irrigation management. Respect to this role it is most of the time confined to an internal numerical model variable often without any control with measured data. This is mainly due to its intrinsic space and time variability and to the well known difficulties in assessing its value from remote sensing as from in situ measurements. The present paper investigates the possibility to control surface soil moisture trough the detection of land surface temperature from satellite remote sensing due to the simpler information and availability of infrared satellite images respect to the microwave ones. In this context the paper tries to asses soil moisture values and its spatial and temporal dynamic developing an energy water balance model (FEST-EWB) tested at field scale with fluxes measured from an eddy tower. Modelled soil moisture and temperature values are also compared with operative satellite data (MODIS) and in situ ground measurements.

Keywords. Irrigation – Land surface temperature – Energy water balance model – Energy balance closure.

La température de surface résultante de la télédétection et d'un modèle de bilan hydro-énergétique pour la gestion de l'eau

Résumé. *L'humidité du sol est reconnue comme étant la variable clé du bilan hydrologique à fins opérationnelles, comme la prévision des inondations et la gestion de l'irrigation. Vu ce rôle, elle est souvent présentée dans les modèles comme une variable numérique interne qui n'a aucun contrôle sur les données mesurées. Cela est principalement dû à sa variabilité intrinsèque dans l'espace et le temps, et aux difficultés d'évaluer sa valeur à l'aide de la télédétection et des mesures in situ. Cet article étudie la possibilité de contrôler l'humidité du sol à partir de la détection de la température de surface (LST) par télédétection satellitaire, vue la simplicité de l'information et la disponibilité des images satellitaires infrarouges ainsi que celles à micro-ondes. Dans ce contexte, l'article essaie d'évaluer l'humidité du sol et son dynamisme spatio-temporel en développant un modèle de bilan hydrique et énergétique (FEST-EWB) examiné à l'échelle du champ en mesurant les flux à partir d'un circuit de courant. Les valeurs simulées de l'humidité et de la température du sol sont également comparées aux données d'un satellite opératif (MODIS) et aux mesures effectuées in situ.*

Mots-clés. *Irrigation – Température de surface – Bilan hydrique et énergétique – Fermeture du bilan énergétique.*

I – Introduction

The water resources scarce availability in Mediterranean area, which occurs with an increasing frequency in the last years, requires an accurate irrigation water management, due to the fact that agriculture is the main water consumer. It becomes then important to monitor the irrigation performance evaluating the irrigation index, such as the irrigation water needs (IWN) which depends on evapotranspiration and soil moisture content. Soil Moisture is recognized as the key variable in the hydrologic water balance for operational purpose as for flash flood forecast system as well as for irrigation management (Albertson and Kiely, 2001; Montaldo and Albertson, 2003b). Respect to this role, it is most of the time confined to an internal numerical model variable (Dooge, 1986). This is mainly due to its intrinsic space and time variability and to the well known difficulties in assessing its value from remote sensing as from in situ measurements (De Troch *et al.*, 1994; Engman and Chauhan, 1995).

Land surface temperature (LST) is the parameter that links the energy fluxes between the atmosphere and the surface and so it becomes fundamental in the energy balance modeling to estimate the net radiation and the soil, sensible and latent heat fluxes (Noilhan and Planton, 1989; Famiglietti and Wood, 1994; Montaldo e Albertson, 2001). The availability of satellite remote sensing information makes easy to retrieve LST in raster format, mainly suited for the use in conjunction to distributed model. However, some uncertainties have to be addressed, such as the definition of satellite LST over an heterogeneous area that is a function of the surface temperature of each component of the area (bare soil or vegetation), of the occupied percentage by each type of soil and of the scan angle of view of the satellite (Norman *et al.*, 1995; Kustas *et al.*, 2004; Jacob *et al.*, 2004; Soria and Sobrino, 2007).

The potentiality of a “representative surface temperature” in an energy mass balance model as a tool to monitor soil moisture dynamic from operative satellites such as TERRA with on board MODIS sensor is discussed.

At field scale, the paper tries to asses soil moisture values and its spatial and temporal dynamic developing an energy water balance model (FEST-EWB) tested at field scale with fluxes measured from an eddy tower. Modelled soil moisture and temperature values are also compared with operative satellite data (MODIS) and in situ ground measurements to improve irrigation management for the year 2006 in the Landriano agricultural test area.

The goodness of the measured ground data is evaluated testing the energy budget closure considering the additional terms of the energy storage such as the photosynthesis flux, the crop and air enthalpy changes and the soil surface layer heat storage. In fact the traditional energy budget is typically not closed when measuring energy with an eddy correlation station and the available energy is usually bigger than the sum of the turbulent vertical fluxes with a ratio that ranges between 70 and 90% (Jacobs *et al.*, 2008; Meyers and Hollinger, 2004). This is mainly due to instrumental errors, especially those of the eddy covariance technique, to the problem of heterogeneities in the area and to the energy storage.

II – The energy balance model

FEST-EWB is a distributed hydrological energy water balance model and it is developed starting from the FEST-WB and the event based models FEST98 and FEST04 (Mancini, 1990; Rabuffetti *et al.*, 2008). FEST-WB computes the main processes of the hydrological cycle: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamic. In the FEST-EWB the energy balance module is introduced where land surface temperature is the key parameter that links the energy fluxes between the low atmosphere and the ground surface.

At the ground surface, the complete energy balance equation is expressed as:

$$Rn - G - (Hs + Hc) - (LEs + LEc) = \frac{\Delta W}{\Delta t}$$

where: Rn (Wm^{-2}) is the net radiation, G (Wm^{-2}) is the soil heat flux, H_s and H_c (Wm^{-2}) and LE_s and LE_c (Wm^{-2}) are respectively the sensible heat and latent heat fluxes for bare soil (s) and for canopy (c), and $\Delta W/\Delta t$ (Wm^{-2}) assembles the energy storage terms. These terms are often negligible, especially at basin scale with a low spatial resolution; instead at local scale the contribution of these terms could be significant (Jacobs *et al.*, 2008; Meyers and Hollinger, 2004).

All the terms of the energy balance depend on the land surface temperature (LST) and so the energy balance equation can be solved with the well known Newton-Rhapson method:

$$LST_n = LST_{n-1} + \frac{f_t(LST_{n-1})}{f_t'(LST_{n-1})}$$

where LST_n is the actual value, LST_{n-1} is the value at the previous iteration, $f_t(LST_{n-1})$ is the energy balance function and $f_t'(LST_{n-1})$ is its derivative. The solution is acceptable when:

$\left|\frac{f_t(LST)}{f_t'(LST)}\right| < tolerance$ and $f_t(LST) < tolerance$, with tolerance equal to 0.001.

The terms of the energy balance equation are described in the following.

The net radiation is the algebraic sum of the incoming and outgoing short wave and long wave radiation:

$$R_n = R_s(1-r) + \xi_c \sigma (T_a^4) - \xi_s \sigma (LST^4)$$

where R_s is the incoming short wave radiation (Wm^{-2}), while the outgoing short wave radiation (Wm^{-2}) is a fraction of R_s with the albedo (r). ξ_s is the soil emissivity, σ is the Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$) and LST and Ta are respectively the land surface and the air temperature (K). In literature several different equations exist for the description of the atmosphere emissivity, ξ_c, considering clear and cloudy skies with different cloud cover fraction. For this study an average value of the measured atmosphere emissivity is used.

The soil heat flux is the heat changed for conduction with the sub-surface soil and it is evaluated as:

$$G = \left({gterm}/{dz} \right)\left(LST - T_0\right)$$

where T_0 is the temperature below the first layer of soil (K) and dz is the soil thickness (m). gterm is the soil thermal conductivity ($Wm^{-1}K^{-1}$) which depends on the soil water tension valuated with the McCumber – Pielke equation (McCumber and Pielke, 1981; Peters – Lidard *et al.*, 1998).

The sensible heat flux is considered for the situations of bare soil, H_s, and of canopy presence, H_c. The cell of the computational domain is characterized by a vegetation fraction, f_v, to discriminate the percentage of vegetation coverage. The equation of this vertical flux is:

$$Hs + Hc = (1 - fv)\frac{\rho_a c_p}{r_a}(LST - T_a) + fv\frac{\rho_a c_p}{r_a}(LST - T_a)$$

where ρ_a is the air density (Kgm^{-3}), c_p is the specific heat of humid air ($MJkg^{-1}K^{-1}$) and r_a is the aerodynamic resistance (sm^{-1}) which determines the transfer of heat and water vapour from the evapotranspirating surface into the air above the canopy. Correction functions for atmospheric stability or instability are included using the Thom model (Thom, 1975):

$$r_a = \frac{\left[\ln\left(\frac{z_m - d}{z_{om}}\right) - \Psi_m\left(\frac{z_m - d}{L}\right)\right]\left[\ln\left(\frac{z_h - d}{z_{oh}}\right) - \Psi_h\left(\frac{z_h - d}{L}\right)\right]}{k^2 u_z}$$

where z_m is the height of wind measurements (m), z_h is the height of humidity measurements (m), d is the zero plane displacement height (m), z_{om} is the roughness length governing momentum transfer (m), z_{oh} is the roughness length governing transfer of heat and vapour (m), k is the Von Karman's constant, 0.41, and u_z is the wind speed at height z (ms^{-1}). Ψm and Ψh are the correction functions for the heat transfer and the momentum exchange with different equations in case of atmospheric stability (Panofsky and Dutton 1984) and of unstable conditions (Paulson, 1970). L is the Monin-Obukhov length (m).

The latent heat fluxes for bare so\il, LE_s, and of canopy, LE_c. are:

$$LEc + LEs = f_v(\frac{\rho_a c_p}{\gamma (r_a + r_c)})\left(e^* - e_a\right) + (1 - f_v)\frac{\rho_a c_p}{\gamma (r_a + r_s)}\left(e^* - e_a\right)$$

where γ is psychrometric constant (Pa°C^{-1}), e*is the saturation vapour pressure (Pa) computed as function of the LST and e_a is the vapour pressure (Pa).

The canopy resistance, r_c (sm^{-1}), which describes the resistance of vapour flow through the transpiring crop, is expressed as (Jarvis,1976):

$$r_c = \frac{r_{s\,min}}{LAI} \frac{(FC - WP)}{(SM - WP)}$$

considering $r_{s\,min}$ as the minimum stomatal resistance (sm^{-1}), LAI the leaf area index, FC the field capacity, WP the wilting point and SM the soil moisture.

The soil resistance, r_S (sm^{-1}), is the resistance at the evaporating soil surface (Sun,1982):

$$r_s = 3.5(\frac{SM_{sat}}{SM})^{2.3} + 33.5$$

where SM_{sat} is the soil moisture at saturation.

The latent heat of vaporization, λ ($MJKg^{-1}$), and the water density, ρ_w (Kgm^{-3}), link the latent heat flux with the evapotranspiration, ET (ms^{-1}):

$$LE = \lambda\, \rho_w ET$$

The photosynthesis flux (F_CO_2), the crop and air enthalpy changes (S_{canopy} and S_{air}) and the soil surface layer heat flux (S_{soil}) are additional fluxes term (Wm^{-2}) considered in the energy balance:

$$\frac{\Delta W}{\Delta t} = F\_CO_2 + S_{canopy} + S_{air} + S_{soil}$$

The photosynthesis flux, that is the change in the Gibbs free energy, is calculated with the conversion from the measured flux of 1 mg CO_2 m^{-2} s^{-1} to 11 Wm^{-2} (Nobel, 1974).

The air enthalpy is evaluated as:

$$S_{air} = \frac{\Delta T_a \rho_a c_p}{\Delta t} \Delta z_{air}$$

where ΔT_a is the difference of air temperature (°C), Δt is the time step (s) and Δz_{air} is the height of the measurement instrument (m).

The canopy enthalpy is computed only over a fixed vegetation height:

$$S_{canopy} = \frac{\Delta LST\,(m_w c_w + m_b c_b)}{\Delta t}$$

where m_w and m_b (Kgm^{-2}) are respectively the masses of water and biomass, c_w and c_b ($JKg^{-1}K^{-1}$) are the specific heat capacities of water and biomass.

A similar approach is used for the heat flux in the soil surface layer:

$$S_{soil} = \frac{\Delta T_{soil}\,(SMm_w c_w + \rho_s c_s)}{\Delta t}\Delta z_{soil}$$

where T_{soil} is the soil temperature (K) at the soil heat flux plate depth (Δz_{soil}), ρ_s (Kgm^{-3}) is the soil density and c_s ($JKg^{-1}K^{-1}$) is the specific heat of soil capacity.

III – The energy budget measurement

Data used in this analysis were collected during the year 2006 from 13th of March to 11th of October with a micrometeorological station located in an experimental field of maize in Landriano in the Po river plain (Northern Italy) operated by the Politecnico of Milano. The station is equipped with: a 4-component radiometer, a gas analyzer coupled to a 3D sonic anemometer necessary for the eddy correlation technique for the estimation of the latent heat flux, several soil moistures probes, one rain gauge, heat flux plates, soil temperature probes for the soil heat flux, a PAR sensor, an infrared sensor temperature and tensiometers. The station acquires data averaged on half an hour basis, 24 hours a day (Horeschi *et al.*, 2008). The raw data show the closure of the energy balance. Improvement in energy balance closure can be achieved considering additional fluxes such as the photosynthesis flux, the enthalpy changes of crop and air and the soil surface layer heat flux (Meyers and Hollinger, 2004) (Figure 1).

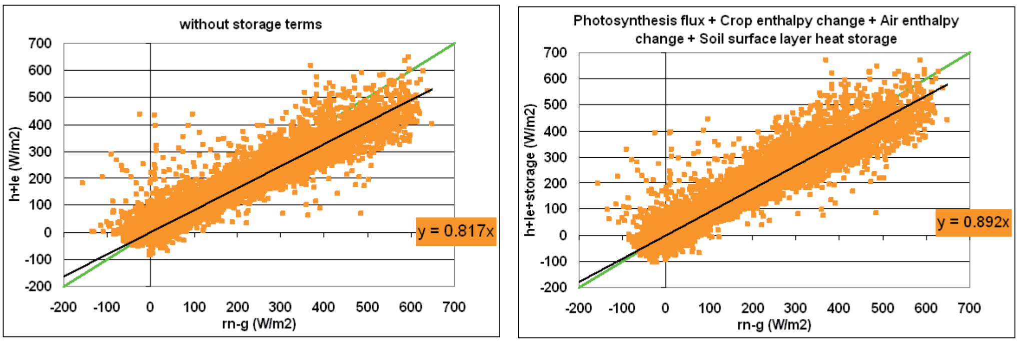

Figure 1. Energy budget closure for measured fluxes (left) and considering the additional flux measurements (right).

IV – Model validation with ground and satellite data

1. Energy fluxes

The measured and simulated principal fluxes of the energy budget, such as the net radiation, the latent and sensible heat fluxes and the soil heat flux, are compared (Figure 2.) and a good accuracy is reached.

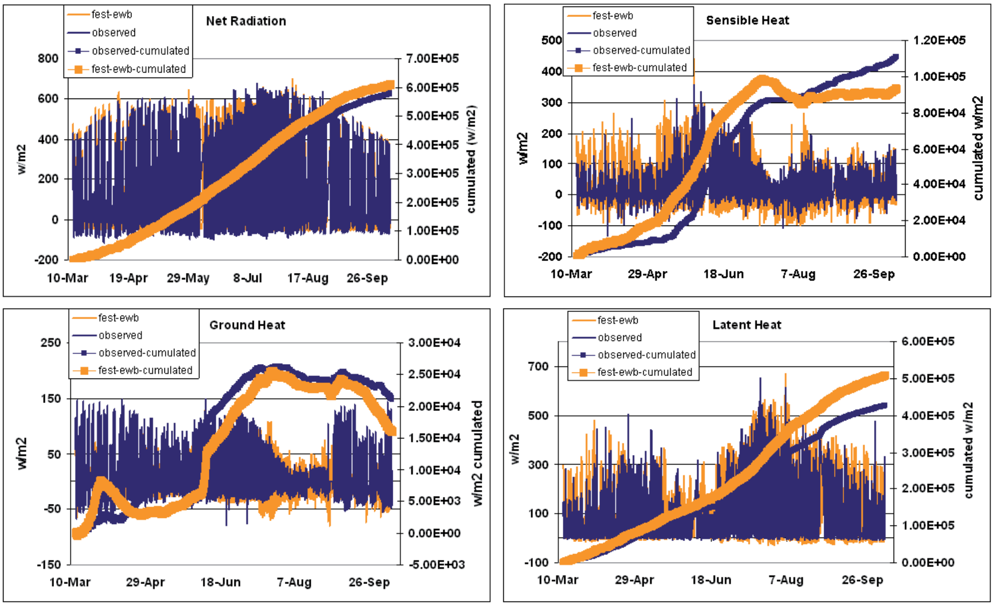

Figure 2. The comparison of the simulated and measured energy fluxes.

These results are confirmed from a statistical analysis looking for the minimization of the root mean square error (RMSE) and the maximization of the efficiency of the Nash and Sutcliffe index (Nash and Sutcliffe, 1970). The RMSE has low values for each flux in regard to its maximum value (Table 1).

Table 1. RMSE and the Nash and Sutcliffe index for the energy fluxes.

	η	RMSE (Wm^{-2})
Net Radiation	0.80	88.83
Latent Heat	0.61	68.88
Sensible Heat	0.35	44.15
Ground Heat	0.51	27.82

2. Land surface temperature

As said before land surface temperature is the key parameter that links the energy fluxes between atmosphere and surface in the energy balance modelling. Satellite images are an important instrument for the use in conjunction to distributed model, even if some uncertainties have to be addressed, such as the definition of satellite LST of an heterogeneous area. For this study we use the LST product from MODIS radiometer (satellite TERRA, http://ladsweb.nascom.nasa.gov/index.html) and in particular 104 daily and nocturne satellite images for the simulation period from 13th of March to 11th of October 2006.

LST from MODIS and LST measured from the radiometer of the eddy station are compared with the land surface temperature simulated from FEST-EWB. From Figure 3, the linear regression forced through the origin for the LST from FEST-EWB against LST form the station is y=0.95x, showing a good behaviour of the model in representing the observed data. When the modelled values are compared with the satellite ones, a slope of 0.89 is reached. Also the rout mean square error (RMSE) and the Nash and Sutcliffe index (η) confirm the results of the modelling simulation according to the ground measured data and to the LST retrieved from MODIS images with high values of the Nash - Sutcliffe index and low values of the RMSE (Table 2).

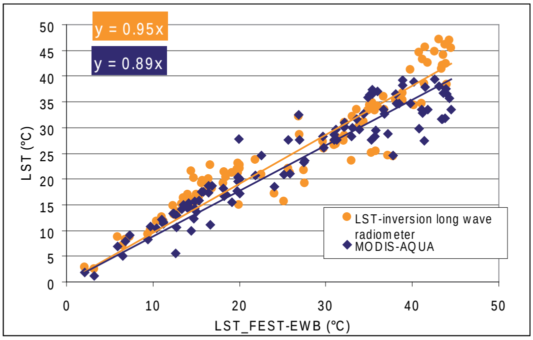

Figure 3. Comparison among land surface temperature simulated and measured from the station and from MODIS (left). RMSE and the Nash and Sutcliffe index for land surface temperature (right).

Table 2. RMSE and the Nash and Sutcliffe index for land surface temperature.

	η	RMSE (°C)
MODIS-AQUA	0.83	4.96
LST-station	0.89	3.99

V – Modelling results and irrigation practice

Soil Moisture from modelling results (FEST-EWB), satellite and in situ data land surface temperature are compared, for the Landriano agricultural field (9 ha) cultivated with maize. Soil moisture field data are acquired using a TDR sensor (5 cm) after each irrigation in 37 points, while local vertical profile is detected continuously in time at the station (Horeschi, 2008). The field is irrigated with farrow irrigation that causes a non homogeneous spatial variability (Figure 4). The FEST-EWB model seems to well reproduce the spatial variability of soil moisture considering both precipitation and irrigation (Figure 4).

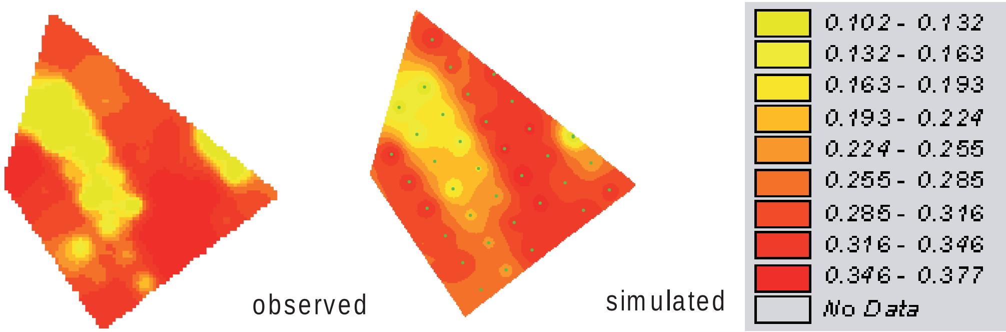

Figure 4. The distributed soil moisture measurement campaign of 6th August 2006 and its simulation.

The soil moisture behaviour of observed and of simulated values is consistent with simulated LST and latent heat flux. As we can observe from the following figure the warmer areas in the middle of the field are the areas with the lower soil moisture content and with the lower change of latent heat flux (Figure 5).

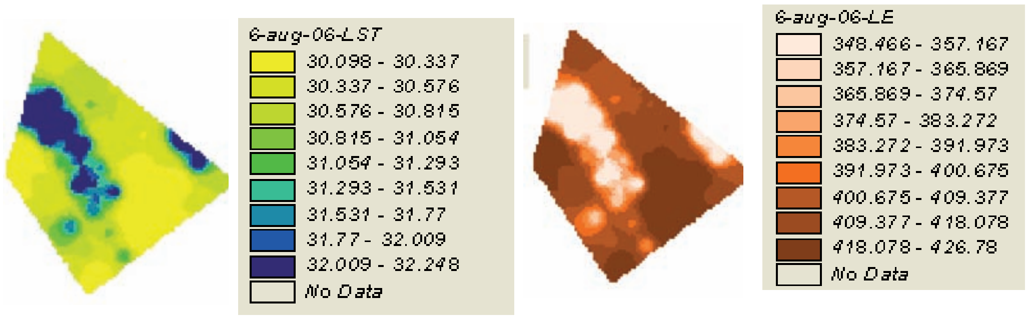

Figure 5. The distributed modeled LST (K) and LE (Wm^{-2}) after the irrigation event of 6th August 2006.

The FEST-EWB model seems to well reproduce also soil moisture temporal dynamic at the station considering both precipitation and irrigation (Figure 6).

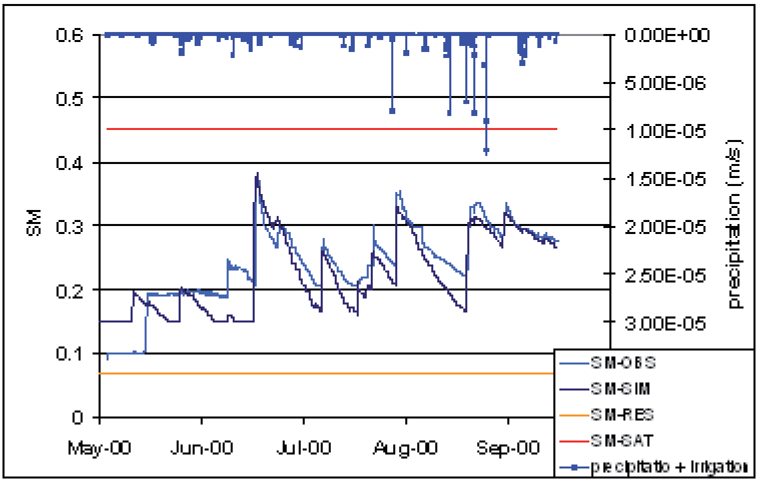

Figure 6. Simulated and observed soil moisture temporal dynamics.

Here in, we present a preliminary result of an agricultural application of the FEST-EWB model oriented to improve and to monitor the irrigation water needs (IWN) for different types of crops. As well known, the IWN (FAO, 1986; D'Antonio *et al.*, 2008) is actually computed as a difference between the potential evapotranspiration (ETP) and the rainfall, as precipitation plus irrigation (Figure 7). So a positive value of the index shows water deficit, while a negative value shows excess of water. In Figure 7, the irrigation water needs index is reported for the entire vegetation period from 29th May to 8th September, as the net rainfall. Negative values of the IWN index are present during two irrigation, respectively 13th -14th July and 20th – 21st July, and also during an heavy precipitation event of 25th August, showing excess of water.

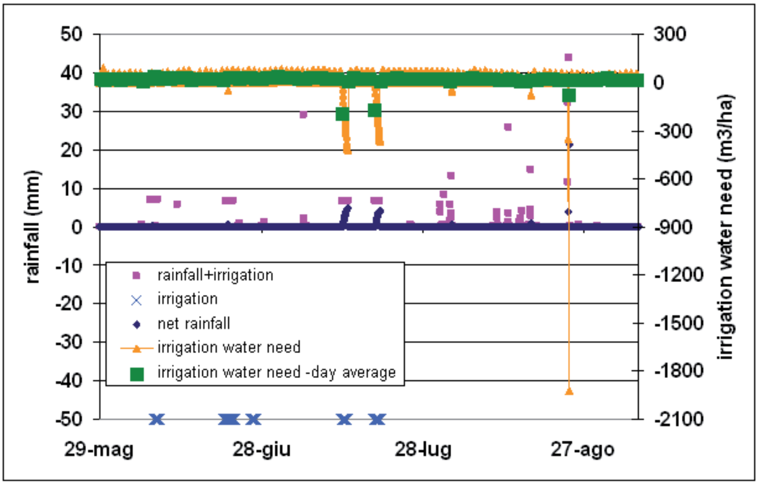

Figure 7. The irrigation water index (FAO, 1986) at hourly and daily time interval plus irrigation an rainfall.

A modified water deficit index is presented as a difference between the potential evapotranspiration and the effective one (Figure 8). The vegetation period can be clearly separated into two sub periods, divided by the irrigation event of 13th -14th July. In the first sub period, the water deficit is very high; while, when the irrigation is performed, this difference becomes very small due to the fact that the maize plant almost reached its transpiration potential. Therefore the two irrigations of 13th -14th July and of 20th – 21st July, even though necessary, seem to have been excessive causing an excess of water.

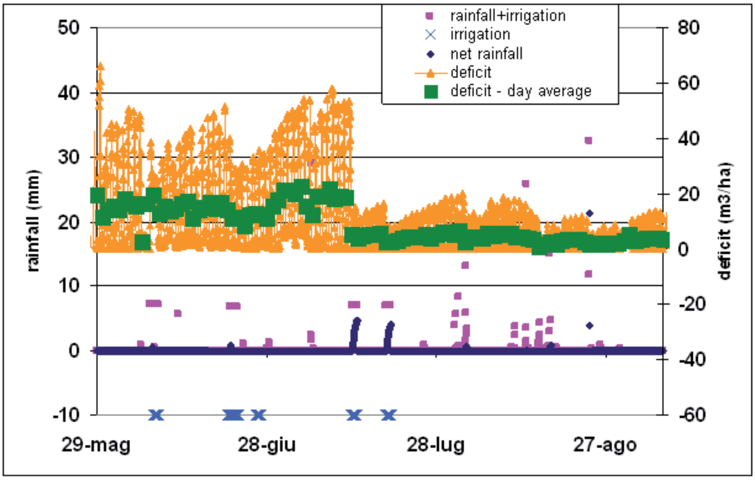

Figure 8. The modified water deficit index at different time scale together wit rainfall and irrigation.

VI – Conclusion

The present paper investigated the possibility to control surface soil moisture into a distributed hydrologic model trough the detection of land surface temperature from satellite remote sensing due to the simpler information and availability of infrared satellite images respect to the microwave ones. The energy water balance model (FEST-EWB) reproduces soil moisture values and its spatial and temporal dynamic in agreement with observed data. Modelled soil moisture and land surface temperature values are also compared with operative satellite data (MODIS) and with in situ ground measurements.

The goodness of the measured ground data has been evaluated testing the energy budget closure considering the additional terms of the energy balance such as the photosynthesis flux, the crop and air enthalpy changes and the soil surface layer heat flux. These terms allow an improvement in the energy budget closure of 7.5 %, that it is not negligible even if the single component gives a low contribution. FEST-EWB is developed considering these additional terms and the energy fluxes from field data and modelling are in good agreement.

A preliminary study is made for the irrigation practice considering the irrigation water need index and the water deficit index, showing possibility of a more parsimonious use of water for maize field.

Acknowledgements

This work was supported by the CAVE Project, funded by Fondazione Cariplo, aiming at the investigation of the potential of water stored in quarries for the maintenance of supplies in times of water scarcity and by the TwoLe/A/B, funded by Fondazione Cariplo, aiming at the realization of a platform of computing tools that implement a Decision Support System for managing water resources at the basin scale (Ticino river basin and Adda river basin). The work is also supported by Italian Ministry of University and Scientific Research (2006), project “Assimilation of remote sensing and ground data for the calibration of distributed hydrologic models and flash flood forecasting” and by European Community in the framework of the ACQWA project (Assessing Climatic change and impacts on the Quantity and quality of Water).

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Soil physical quality in a Sicilian agricultural area

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Abstract. The objective of this study was to determine the soil physical quality for two contiguous agricultural areas under annual crops (A) and vineyard (V), respectively, located at the *Riserva Naturale Integrale Grotta di Santa Ninfa* site, in Sicily. The A and V areas had different textural fractions and organic matter content. Soil water holding parameters did not vary substantially between the two areas whereas field saturated hydraulic conductivity changed appreciably with the area and also with the sampling date, especially in the A soil. Horizontal anisotropy of laboratory determined saturated soil hydraulic conductivity was noticeable especially at the greatest depths. A better quality was detected for the A soil than the V one. However, conditions denoting a generally poor physical quality of the sampled soils were not detected in this investigation. Therefore, agricultural practices were not responsible of substantial soil degradation processes in the sampled areas.

Keywords. Soil physical quality – Agricultural soils – Land use – Soil hydraulic properties.

La qualité physique du sol dans une zone agricole Sicilienne

Résumé. *La qualité physique du sol est un sujet très important, recevant une attention particulière ces dernières années. L'objectif de cette étude est de déterminer la qualité physique du sol dans deux zones agricoles cultivées respectivement en cultures annuelles (A) et en vigne (V) et situées dans la Riserva Naturale Integrale Grotta di Santa Ninfa, en Sicile. Les zones A et V sont caractérisées par des textures et des contenus en matière organique différents. Les paramètres de retention hydrique n'ont pas présenté une variabilité significative entre les deux zones, alors que la conductivité hydraulique a changé remarquablement d'une zone à l'autre et selon la période d'échantillonnage, surtout dans la zone A. La conductivité hydraulique du sol saturé déterminée au laboratoire, a détecté une anisotropie horizontale notable surtout en profondeur. Une meilleure qualité a été détectée pour le sol A en comparaison avec le sol V. Cependant, au cours de l'expérimentation, des conditions dénonçant une mauvaise qualité physique du sol n'ont pas été détectées. Par conséquence, pour les zones étudiées, les pratiques agricoles ne peuvent pas être considérées responsables d'importants processus de dégradation du sol.*

Mots-clés. *Qualité physique du sol – Sols agricoles – Occupation du sol – Propriétés hydraulique du sol.*

I – Introduction

Soil quality, which is a subject receiving increasing attention in recent years, is usually considered to have three main aspects: physical, chemical, and biological (Dexter, 2004). Soil physical quality affects chemical and biological processes in the soil and, therefore, it plays a central role in studies on soil quality (Dexter, 2004). The physical quality of an agricultural soil refers primarily to the soil-strength and fluid transmission and storage characteristics in the crop root zone (Topp *et al.*, 1997; Reynolds *et al.*, 2002). An agricultural soil with a good physical quality maintains a good structure, holds crops upright, resists erosion and compaction, allows unrestricted root growth and proliferation of soil flora and fauna, and permits the correct proportions of water, dissolved nutrients and air for both maximum crop performance and minimum environmental degradation (Topp *et al.*, 1997; Reynolds *et al.*, 2002). Intensive field crop production can cause the physical quality of agricultural soils to decline (Reynolds *et al.*, 2002). Optimal soil physical quality parameter values for maximum field crop production with minimum environmental degradation are still largely unknown, notwithstanding that various empirical guideline parameter values have been proposed (Topp *et al.*, 1997; Reynolds *et al.*, 2002, 2003; Dexter, 2004; Dexter and Czyż, 2007).

Saturated soil hydraulic conductivity, which influences soil physical quality (Reynolds *et al.*, 2003), may vary with both time (Ciollaro and Lamaddalena, 1998) and the considered flow direction (Bagarello and Sgroi, 2008). Therefore, determination of temporal variability and anisotropy of this property should be included in soil physical quality studies.

The site named *Riserva Naturale Integrale Grotta di Santa Ninfa* (GSN), in Sicily, has an important environmental interest due to the presence of a karstic stream. The site includes both agricultural and non-agricultural areas. In particular, two contiguous agricultural areas are under annual crops and vineyard, respectively, that are widely diffused crops at the GSN site. Determining the soil physical quality for these two areas is important to detect a possible occurrence of environmental degradation processes at the GSN site and to evaluate land use effects on soil physical quality parameters.

The objectives of this investigation were to i) compare selected properties of near-surface soil measured in the annual crops and vineyard areas on two sampling dates; ii) determine the near-surface soil physical quality for the two treatments using the existing criteria; and iii) compare the anisotropy of the saturated soil hydraulic conductivity measured in the two experimental areas.

II – Soil physical parameters

The dry soil bulk density, ρ_b (M L^{-3}), i.e. the mass of dry soil solids per unit bulk soil volume, is an index of the soil's mechanical resistance to root growth (Topp *et al.*, 1997). Jones (1983) developed the following empirical relationships to distinguish a lower critical bulk density, ρ_{bL} (g cm^{-3}), below which root growth is effectively unimpeded, and an upper critical bulk density, ρ_{bU} (g cm^{-3}), above which root growth is severely impeded (i.e., ≤ 20% of the root growth at ρ_{bL}) (Reynolds *et al.*, 2002):

$$\rho_{bL} = 1.60 - 0.00468\left(cl + si\right) \quad (1a)$$

$$\rho_{bU} = 1.83 - 0.00429\left(cl + si\right) \quad (1b)$$

where *cl* (%) and *si* (%) are the clay and the silt content of the soil, respectively. Crop root growth becomes progressively more impeded as ρ_b increases above this range due to increasing soil strength, while bulk densities below this range may not provide sufficient root-soil contact and soil water retention for adequate seed germination and seedling growth, nor adequate anchoring to maintain field crops upright when subjected to wind and rain (Reynolds *et al.*, 2003).

The saturated soil hydraulic conductivity, K_s (L T^{-1}), characterizes the ability of soil to imbibe needed water and drain excess water (Topp *et al.*, 1997). Although acceptable K_s for agricultural field soils ranges from about 0.36 to 360 mm h^{-1} (Topp *et al.*, 1997), the narrower range of 18-180 mm h^{-1} is considered to be ideal with respect to promoting rapid infiltration and redistribution of needed crop-available water, reducing surface runoff and soil erosion, and encouraging relatively rapid drainage of excess soil water (Reynolds *et al.*, 2003).

Air capacity of total soil, *AC* (L^{3}L^{-3}), is defined as *SWC-FC*, being *SWC* (L^{3}L^{-3}) the saturated volumetric soil water content and *FC* (L^{3}L^{-3}) the field capacity water content, i.e. the soil water content corresponding to a soil water pressure head, h = -1 m (Reynolds *et al.*, 2002). The *AC* index represents the ability of soil to store and provide essential soil air (Topp *et al.*, 1997). According to Reynolds *et al.* (2002), the near-surface *AC* should be at least 0.10-0.15 m^{3}m^{-3}.

The plant available water capacity, *PAWC* (L^{3}L^{-3}), is equal to *FC-PWP*, being *PWP* (L^{3}L^{-3}) the permanent wilting point water content, i.e. the soil water content corresponding to h = -150 m. The *PAWC* index is used since it is a measure of the ability of the soil to store and provide soil water that is available to crop roots. Reynolds *et al.* (2002) reported that *PAWC* should be > 0.20 m^{3}m^{-3}

or within the range 0.15-0.25 m^3m^{-3}. According to Verdonck *et al.* (1983) and Cockroft and Olsson (1997), 0.20 ≤ *PAWC* ≤ 0.30 m^3m^{-3} is required for optimum root growth/function and minimum droughtiness in fine-textured soils and horticultural substrates.

The *FC/POR* ratio, being *POR* (L^3L^{-3}) the soil porosity, is an index of the balance between soil water holding capacity and aeration. Olness *et al.* (1998) suggested that the optimal value of *FC/POR* is 0.66. The rationale for this criterion is that, in rain-fed agriculture, soils with this ratio are likely to have desirable water and air contents for good microbial production of nitrogen more frequently and for longer time periods than soils that have larger or smaller ratios (Reynolds *et al.*, 2002).

Dexter (2004) proposed the so-called *S* index to evaluate the soil physical quality. This index is defined as the slope value of the soil water retention curve at its inflection point. Dexter and Czyż (2007) provided the following descriptive categories of soil physical quality in terms of the corresponding values of *S*: $S \geq 0.050$, very good; $0.050 > S \geq 0.035$, good; $0.035 > S \geq 0.020$, poor; and $0.020 > S$, very poor.

III – Materials and methods

The study was carried out at the GSN site. The boundaries of this site coincide approximately with the limits of a watershed of 140 ha. Mean annual rainfall is 610 mm and mean annual air temperature is 17 °C. The areas supporting the annual crops (A) and the vineyard (V) are located on the same field at a distance of a few dozen meters. This field has an elevation of approximately 440 m a.s.l., a slope of 15% and a S-E aspect. Information on land use and recent cultivation practices for the A and V areas was summarized in Table 1.

Table 1. Information on land use and recent cultivation practices for the two sampling areas

Area	History	Year 2004/2005	Year 2005/2006
Annual crops (A)	Vineyard until 1998. Temporary grass-land from 1999 to 2004.	Autumn 2004: deep ploughing (depth = 0.8 - 0.9 m) followed by harrowing. December 2004: sowing of Italianrye-grass.	Autumn 2005: ploughing (depth = 0.25 m) followed by sowing of vetch. February 2006: green manure of vetch and harrowing of the surface to prepare the seedbed for wheat.
Vineyard (V)	Vineyard since the 1980s.	No tilling in the months before the sampling date. Harrowing on June.	No tilling in the months before the experiments.

A 100-m^2 sampling area was selected in each area. On May 2005, undisturbed soil cores were collected at nine randomly chosen locations within each sampling area by gently hand-hammering stainless steel cylinders (inside diameter = 0.08 m, height = 0.05 m) into the surface horizon of the soil, after removing the first few centimeters (< 5 cm). A disturbed soil sample was also collected at each sampling point.

The particle size distribution of each soil sample was determined by the hydrometer method for particles having diameters < 74 μm and by sieving for particles between 74 and 2000 μm. The clay (*cl*), silt (*si*) and sand (*sa*) percentages were determined according to the USDA classification scheme (Gee and Bauder, 1986). The organic matter content (*OM*) was estimated to be equal to 1.724 times the organic carbon content determined by the Walkley-Black method. For each soil sample, the soil erodibility factor, K_U (t ha h ha^{-1} MJ^{-1} mm^{-1}), of the Universal Soil Loss Equation (Wischmeier and Smith, 1978) was determined.

Desorption water retention data were determined in the laboratory on each undisturbed soil core using a hanging water column apparatus (Burke *et al.*, 1986) for pressure head values of -0.05, -0.1, -0.2, -0.4, -0.7, and -1.2 m. For each sampling point, sieved soil was packed to the bulk density value of the undisturbed core in rings having an inside diameter of 0.05 m and a height of 0.01 m. These soil samples were used to determine the soil water content corresponding to pressure head values of -3.37, -10.2, -30.6, and -153.0 m by a pressure plate apparatus. For each sampling point, water retention data were described by the van Genuchten (1980) model. The RETC code (van Genuchten *et al.*, 1991) was used to determine the unknown parameters of this model.

Field saturated hydraulic conductivity, K_{fs} ($L\ T^{-1}$), was measured by the SFH technique (Bagarello *et al.*, 2004) in 15 randomly selected points within each sampling area, using stainless steel rings (inner diameter of 0.15 m) that were inserted after removing the first few centimeters of soil. Two undisturbed soil cores (0.05-m diameter by 0.05-m high) were collected near the ring at a depth of 0 to 0.05 m and 0.05 to 0.10 m, respectively, two days before the SFH experiment. These cores were used to determine the bulk density, ρ_b, and the initial volumetric soil water content, θ_i (L^3L^{-3}), that were averaged over the two depths. An α^*-parameter equal to 12 m^{-1} was used to calculate K_{fs} by the SFH equation.

Measurement of K_{fs} was repeated on April 2006 in 15 newly selected points within each sampling area. The second sampling date was characterized by wetter soil conditions (mean of θ_i = 0.270 m^3m^{-3}, sample size, N = 56) than the first one (mean = 0.235 m^3m^{-3}, N = 90). The ρ_b and K_{fs} values obtained on the first and the second sampling dates were denoted by the symbols ρ_{bI} and ρ_{bII}, and K_{fsI} and K_{fsII}, respectively.

On April 2006, undisturbed soil cores (inside diameter = 0.085 m, height = 0.114 m) were also collected in the A and V areas at three depths below the soil surface (0.1, 0.3, and 0.5 m) to evaluate the anisotropy of the laboratory saturated soil hydraulic conductivity, K_s ($L\ T^{-1}$). For a given area and depth combination, two vertically oriented soil cores and two horizontally oriented soil cores were collected at a distance of a few centimeters between replicated cores by gently hand-hammering stainless steel cylinders into the soil (total sample size, N = 24). In the laboratory, the soil cores were saturated from the bottom for 2-4 days, depending on the core, and then K_s was measured by the constant-head permeameter method (Klute and Dirksen, 1986).

For each soil sample, *AC*, *PAWC* and *FC/POR* were calculated using the fitted water retention function, and a value of *S* was obtained according to Dexter (2004). For a given area, the mean and the associated coefficient variation, *CV*, of each considered variable (*cl*, *si*, *sa*, *OM*, K_U, ρ_{bI}, ρ_{bII}, K_{fsI}, K_{fsII}, *AC*, *PAWC*, *FC/POR* and *S*) were calculated. The K_{fs} data were assumed to be ln-distributed, as is common for this variable, and the geometric mean and the associated *CV* were determined (Lee *et al.*, 1985). The other data were assumed to be normally distributed and the arithmetic mean and the associated *CV* value were calculated. For each variable, a comparison between the two areas was carried out using a two-tailed *t* test. A similar comparison was carried out within a given area between the two sampling dates for both ρ_b and K_{fs}. A probability level, $P = 0.05$, was used for all statistical tests. For each considered soil physical quality parameter (ρ_b, K_{fs}, *AC*, *PAWC*, *FC/POR*, *S*), the values measured in the two areas were then compared with the ones suggested to discriminate between various categories of soil physical quality. A comparison between the A and V areas in terms of the anisotropic characteristics of K_s was also carried out. In this case, the geometric mean of the two K_s measurements obtained for given sampling area, depth and orientation was calculated.

IV – Results and discussion

According to the USDA classification scheme, the soil texture of the individual soil samples was silt or silt-loam, and silt was the prevailing textural fraction in both the A and V areas (Table

2). The V area had a significantly higher *si* and *OM* content and a significantly lower *cl* and *sa* content as compared with the A area. The two areas differed by *AC*, with the A area yielding a significantly higher *AC* result than the V one, but not in terms of K_U, *PAWC*, *FC/POR*, and *S*. For ρ_b, significantly higher values were measured in the V area than in the A one on the first sampling date (ρ_{bI}), whereas the results were not significantly different on the second date (ρ_{bII}). The differences between the K_{fs} values measured in the two areas were statistically significant on both sampling dates but the sign of the difference varied with the date. In particular, the K_{fs} values were significantly higher in the A area than in the V one on the first sampling date (K_{fsI}) whereas the opposite result was obtained on the second date (K_{fsII}). However, large or very large *CV* results were obtained for K_{fs}, suggesting that an improved characterization of the sampled areas could be desiderable. For both K_{fs} and ρ_b, the variability between the two sampling dates was more noticeable for the A area (mean values of K_{fs} and ρ_b differing by a factor of 17.0 and 1.14, respectively) than for the V one (K_{fs} and ρ_b differing by a factor of 1.9 and 1.04, respectively), and the differences between the two dates were statistically significant in the A area for both variables and in the V area only for K_{fs}.

Table 2. Soil properties for the A (annual crops) and V (vineyard) areas

Variable	A		V	
	Mean	**CV**	**Mean**	**CV**
cl (%)	17.2a	0.309	7.3b	0.897
si (%)	64.8a	0.071	77.1b	0.103
sa (%)	18.0a	0.076	15.6b	0.141
OM (%)	1.56a	0.191	2.71b	0.093
K_{USLE} (t ha h ha^{-1} MJ^{-1} mm^{-1})	0.057a	0.105	0.065a	0.184
AC (m^3 m^{-3})	0.141a	0.233	0.080b	0.518
PAWC (m^3 m^{-3})	0.180a	0.140	0.187a	0.048
FC/POR	0.748a	0.110	0.832a	0.108
S	0.043a	0.126	0.039a	0.083
ρ_{bI} (g cm^{-3})	1.148a,A	0.110	1.368b,A	0.074
K_{fsI} (mm h^{-1})	3084.4a,A	1.870	453.5b,A	1.860
ρ_{bII} (g cm^{-3})	1.313a,B	0.046	1.317a,A	0.049
K_{fsII} (mm h^{-1})	181.5a,B	5.870	848.1b,B	3.730

Values followed by the same lower case letter in a row are not significantly different (P = 0.05)

For a given variable (e.g. Kfs or ρb), values followed by the same capital letter in a column are not significantly different

Silt particles are known to be particularly erodible because they are more easily detached than clay particles and more easily transported than sand particles (Toy *et al.*, 2002). Therefore, a possible interpretation of the observed differences in terms of textural fractions is that higher soil erosion rates occurred in the A area than in the V one in the past years. The mean values of K_U were in the upper half of the K_U range established by Wischmeier *et al.* (1971). Differences between the two areas were particularly noticeable in terms of soil water transport parameters, but soil water holding parameters did not change significantly with the exception of *AC*. The two areas differed in terms of temporal variability of both ρ_b and K_{fs}, that was more noticeable in the A area than in the V one.

Probably, land use was an important factor, and perhaps the most important one, affecting the comparison between the A and V contiguous areas, differing by crops and cropping practices since 1999 (Table 1). According to this interpretation, soil water holding parameters were less affected than transport parameters by land use and management practices. Temporal variability of both ρ_b and K_{fs} was substantially affected by land use since a different temporal variability of these variables was detected in the two sampled areas.

Eqs. (1) yielded ρ_{bL} = 1.216 g cm^{-3} and ρ_{bU} = 1.478 g cm^{-3} for the A area. The mean value of ρ_{bI} (1.148 g cm^{-3}) was lower than ρ_{bL} whereas the mean value of ρ_{bII} (1.313 g cm^{-3}) was in the range between ρ_{bL} and ρ_{bU} (Table 2). For the V area, the ρ_{bL} and ρ_{bU} values were equal to 1.205 and 1.468 g cm^{-3}, respectively. For this area, the mean values of both ρ_{bI} (1.368 g cm^{-3}) and ρ_{bII} (1.317 g cm^{-3}) were higher than ρ_{bL} but lower than ρ_{bU}. Therefore, density-induced impedance to root growth should not be a factor severely affecting crop production in the two sampled areas. However, other types of problems (e.g. root-soil contact or anchoring) may occur in the A area, given that $\rho_{bI} < \rho_{bL}$ was obtained in this area.

The mean K_{fs} results were at the upper limit of the ideal range of K_s values suggested by Reynolds *et al.* (2003) (18-180 mm h^{-1}) for the second sampling date in the A soil. In the other cases, the K_{fs} results were above the upper limit of the wider ideal range suggested by Topp *et al.* (1997) (0.36-360 mm h^{-1}). Thus, the sampled soils may be susceptible to near-surface droughtiness during dry years, particularly in the V area.

Assuming that an air capacity of 0.10-0.15 m^{3}m^{-3} is the minimum for adequate near-surface root aeration, then the A soil, having AC = 0.141 m^{3}m^{-3}, was well aerated. A probably moderate aeration deficit was detected for the V soil, having a mean value of AC equal to 0.08 m^{3}m^{-3}.

The PAWC of both soils was lower than 0.20 m^{3}m^{-3} but it was in the range 0.15-0.25 m^{3}m^{-3}, that is specifically required for sustained plant growth in constructed urban soils (Crauls, 1999; Reynolds *et al.*, 2002). Therefore, plant available water capacity was probably slightly lower than the optimal one for both areas.

The *FC/POR* ratio calculated for the A area (0.75) was closer to the optimal value of 0.66 than the same ratio obtained for the V area (0.83). According to this criterion, the A soil had a better balance among *FC*, *AC* and *POR* for microbial production of crop-available nitrogen as compared with the V soil (Reynolds *et al.*, 2002).

The mean values of the *S* index (0.043 for the A soil and 0.039 for the V soil) were in the range of the *S* values defining a good soil physical quality according to Dexter and Czyż (2007). Therefore, a good soil physical quality in terms of *S* results was associated with bulk density values lower than the ones denoting substantial impedance to root growth, optimal or near-optimal aeration conditions, slightly lower than optimal plant available water capacity, higher *FC/POR* ratios than the optimal one, and high to excessively high saturated soil hydraulic conductivities measured in the field.

The A soil had a better physical quality in the near-surface zone than the V soil in terms of density-induced impedance to root growth, near-surface root aeration, and balance among *FC*, *AC* and *POR*. The two areas had a similar, and probably slightly lower than optimal, quality in terms of ability to store and provide soil water that is available to crop roots. The physical quality in terms of K_{fs} was better for the A soil (near-optimal values on a sampling date) than the V one (excessively high values on both sampling dates). Therefore, the general conclusion was that a better quality was detected in the A soil than in the V one. However, conditions denoting a generally poor physical quality of the sampled soils were not detected in this investigation, although some individual parameters suggested a lower than optimal quality. Therefore, this analysis suggested that agricultural practices were not responsible of substantial soil degradation processes within the field. This result is particularly important given the particular environmental interest of the experimental area.

Both horizontal, K_{sH}, and vertical, K_{sV}, saturated hydraulic conductivity decreased with depth in the V area whereas they increased in the A area (Fig.1). The K_{sH} and K_{sV} values of the surface layer were higher in the V area than in the A one. The A area yielded higher K_{sH} and K_{sV} results than the V area at greater depths. For the V area, a relatively low vertical anisotropy (K_{sV}/K_{sH} =1.5) was detected in the surface layer. At greater depths, a more appreciable horizontal anisotropy was observed, especially at the greatest depth (K_{sH}/K_{sV} equal to 3.3 at 0.3 m and to 10.2 at 0.5 m). For the A area, only horizontal anisotropy was detected with K_{sH}/K_{sV} ratios varying between 1.7 and 3.7. Therefore, horizontal anisotropy prevailed in the sampled field and it was particularly noticeable at the greatest depth in both areas. The soil profile was less disturbed in the V area than in the A one (Table 1). Therefore, this investigation suggested that the quasi-natural tendency was that the soil hydraulic conductivity decreased appreciably with depth, developing a remarkable horizontal anisotropy at the greatest depths. Tillage and earthworm activity, that was observed only in the A area at depths ≥ 0.3 m, homogenized the soil conductivity along the profile and reduced the anisotropic character of this hydraulic property.

The percentage of the individual K_s measurements falling within the ideal range of K_s values was 42% for the narrow ideal range (18-180 mm h^{-1}) and 83% for the wide ideal range (0.36-360 mm h^{-1}). Therefore, comparison between laboratory K_s results and the wide ideal range suggested that the two soils had a near optimal soil physical quality in terms of saturated conductivity. Generally, lower conductivity results were obtained in the laboratory than in the field. This discrepancy may depend on different factors including compaction of undisturbed soil cores or swelling phenomena of laboratory saturated soil. However, the effect of the measurement procedure on the conductivity results should be investigated for the sampled field.

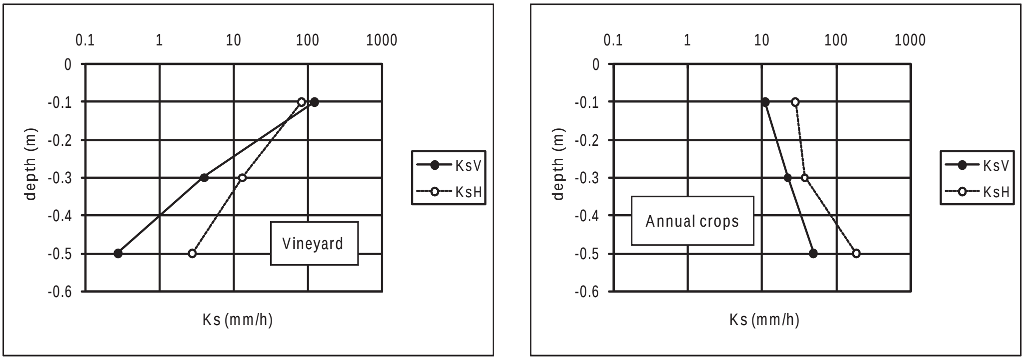

Figure 1. Saturated hydraulic conductivity measured in verticaly (K_{sV}) and horizontaly (K_{sH}) soil cores collected in the annual crops (A) and vineyard (V) areas at three depths below the soil surface.

V – Conclusions

Intensive field crop production can cause the physical quality of agricultural soils to decline. The site named *Riserva Naturale Integrale Grotta di Santa Ninfa* (GSN), in Sicily, has an important environmental interest due to the presence of a karstic stream. The main objective of this investigation was to determine soil physical quality for two contiguous, cropped areas supporting annual crops (A) and a vineyard (V), respectively, located within the GSN boundaries.

Based on available criteria, the A soil was found to have a better physical quality in the near-surface than the V soil in terms of density-induced impedance to root growth, near-surface root aeration, and balance between soil water holding capacity and aeration for microbial production of crop-available nitrogen. The two areas had a similar, and probably slightly lower than optimal, quality in terms of ability to store and provide soil water that is available to crop roots. The physical quality in terms of field saturated soil hydraulic conductivity was better for the A soil than the V one since near-optimal results were obtained in the A soil on one of the two sampling dates whereas excessively high values were obtained for the V soil on both sampling dates. In quasi-natural conditions, saturated soil hydraulic conductivity measured in the laboratory decreased appreciably with depth, developing a remarkable horizontal anisotropy at the greatest depths. Tillage and earthworm activity homogenized the soil conductivity along the profile and reduced the anisotropic character of this hydraulic property.

Conditions denoting a generally poor physical quality of the sampled soils were not detected. Therefore, the conclusion of this investigation was that agricultural practices were not responsible of substantial soil degradation processes within the field.

The ideal ranges established in the literature may not be optimal for any particular soil or field site because they are only guidelines based on broad soil types. Therefore, more relevant estimates of optimal indicator ranges may be required to improve soil physical quality evaluation.

Acknowledgements

V. Bagarello wishes to thank dr. Carmine Albero, dr. Giulia Casamento, Prof. Lucio Gristina and Prof. Ignazio Poma for their experimental, financial or logistical support to this investigation.

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Predicting the water retention characteristic of Sicilian soils by pedotransfer functions

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Abstract. The accuracy in predicting the water retention characteristics of some widely used pedotransfer functions (PTFs) was tested using a database of 149 soil samples collected in three Sicilian areas. The PTFs performance was assessed in terms of maximum error (*ME*), average error (*AE*) and root mean square error (*RMSE*) between predicted and measured water content data. The influence of pressure head and input soil attributes on the predictions was also evaluated. The PTF-VE by Vereecken *et al.* (1989) yielded the best result, even if it tended to underestimate the water contents in the considered pressure head range. Good results were also obtained with the PTF-HY by Wosten *et al.* (1999) and the PTF-S2 by Saxton and Rawls (2006). In particular, the PTF-HY was the less biased PTF among the five considered. The PTF-S1 by Saxton *et al.* (1986) had a little worse performance, but this result should be considered with particular interest given that only texture is required as input. Prediction obtained by the PTF-RB by Rawls and Brakensiek (1989) was affected by the highest mean *RMSE* value. Most of the considered PTFs tended to overestimate the water content at high pressure heads and to underestimate it at low pressure heads. The estimated water contents were affected by soil sample attributes like bulk density, clay and silt content whereas no substantial influence of organic matter and sand content was detected. Practically, the use of the PTF-VE or PTF-HY may be recommended when adequate on soil information is available. Alternatively, the use of the PFT-S1 is suggested if only soil texture is known.

Keywords. Soil water retention – PTF.

Titre : Prédiction de la retention hydrique des sols Siciliens à partir des fonctions de pédotransfert

Résumé. La précision de la prédiction des caractéristiques de la retention hydrique du sol à partir de quelques fonctions de pédotransfert (PTFs), largement utilisées, a été testée en utilisant une base de données de 149 échantillons de sol prélevés dans trois zones Siciliennes. . La performance des PTFs a été évaluée en termes d'erreur maximale (ME), erreur moyenne (AE) et racine de l'erreur moyenne quadratique (RMSE) entre les valeurs de la teneur en eau mesurées et estimées. L'influence de la pression et des variables d'entrée du sol sur les prédictions, ont été également évaluées. La PTF-VE proposée par Vereecken et al. (1989) a donné le meilleur résultat, même si elle tend à sous-estimer la teneur en eau dans l'intervalle des pressions considérées. De bons résultats ont aussi été obtenus avec la PTF-HY proposée par Wosten et al. (1999) et la PTF-S2 proposée par Saxton et Rawls (2006). En particulier, la PTF-HY a produit moins d'erreurs parmi les cinq PTF considérées. La PTF-S1 proposée par Saxton et al. (1986) a montré un résultat médiocre, qui devrait être interprété considérant que cette fonction n'exige que la texture comme donnée d'entrée. Les estimations obtenues par la PTF-RB proposée par Rawls et Brakensiek (1989) ont été caractérisées par les valeurs les plus élevées de la RMSE. . La plupart des PTFs considérées ont montré une tendance à surestimer la teneur en eau pour les hautes valeurs de pression et à la sous-estimer pour les valeurs inférieures. Les estimations de la teneur en eau ont été affectées par les propriétés du sol comme la densité apparente, le contenu en argile et limon, cependant, aucune influence n'a été attribuée à la teneur en matière organique et sable. En pratique, le recours à la PTF-VE ou à la PTF-HY peut être recommandé quand les informations sur les caractéristiques du sol sont disponibles. Alternativement, le recours à la PTF-S1 est recommandé dans les conditions où seulement la texture est connue.

Mots-clés. Retention hydrique du sol – Fonction de pédotransfert (PTF).

I – Introduction

Application of simulation models to predict transport of water and chemicals in unsaturated soils is often limited by the lack of representative data for soil hydraulic properties, i.e. the relationships between soil water pressure head, *h*, water content, θ, and hydraulic conductivity, *K*. Because of soil spatial variability, direct measurements of soil hydraulic properties are time consuming and require complex measurement devices and skilled operators which make them practically unfeasible at the scale of irrigation district. As a result, there is a great interest in developing pedotransfer functions (PTFs) that predict the soil hydraulic properties from more easily measured and/or routinely surveyed soil data such as particle size distribution, organic carbon content and bulk density.

The saturated and near-saturated soil hydraulic conductivity is greatly controlled by soil structural features (e.g. macropores) and its prediction from bulk soil properties has met with limited success (Tietje and Tapkenhinrichs, 1993; Wosten *et al.*, 2001; Jarvis *et al.*, 2002). On the other hand, empirically or theoretically derived PTFs often proved to be good predictors of the soil water retention characteristic (e.g. Tietje and Tapkenhinrichs, 1993). A field strategy to facilitate determination of both the water retention curve, $\theta(h)$, and the hydraulic conductivity function, $K(\theta)$, may rely on the measurement of simple soil physical/chemical attributes and the saturated soil hydraulic conductivity by an infiltrometric technique. The $\theta(h)$ curve is estimated using existing or specifically developed PTFs. The $K(\theta)$ function can be obtained using the estimated water retention curve and a "matching *K* value" measured at saturation (e.g. Lassabatère *et al.*, 2006).

The first step in this strategy is the selection of appropriate PTFs for estimating the water retention curve. As most of available PTFs were developed empirically, their applicability may be limited to the data used to define them and their use for other soils may yield unreliable predictions (Wosten *et al.*, 2001). The accuracy of PTFs can only be evaluated using independent data sets (Schaap, 2004). This means that users should preliminarily obtain a data set and test several PTFs in order to decide whether or not a particular PTF is suitable for a particular application. However, the lack of truly representative information on soil hydraulic characteristics is the main drawback to PTFs validation in certain areas. In particular, soil databases contains mainly results for soils in Northern Europe and Northern America, whereas validation for soils in the Mediterranean region is very limited (Goncalves *et al.*, 1997).

With the aim to evaluate the accuracy in predicting the water retention characteristics for Sicily, some widely used PTFs (Saxton *et al.*, 1986; Rawls and Brakensiek, 1989; Vereecken *et al.*, 1989; Wosten *et al.*, 1999; Saxton and Rawls, 2006) were tested using a data set specifically collected in three areas characterized by different pedology and land use.

II – Materials and methods

1. Description of the pedotransfer functions

A PTF is a function that has as arguments basic data describing the soil (e.g., particle size distribution, bulk density and organic carbon content) and yields as a result the water retention function and/or the unsaturated hydraulic conductivity function (including saturated hydraulic conductivity) (Tietje and Tapkenhinrichs, 1993). The soil water retention function may be determined by estimating discrete water content values, θ_i, at specific pressure heads, h_i, or by estimating the parameters of selected closed-form analytical functions $\theta(h)$ (Romano and Santini, 1997). The former method is referred to as the Point Regression Method and the latter one as the Functional Parameter Regression Method (Tietje and Tapkenhinrichs, 1993). The Point Regression Method may result in non-monotonic retention functions mainly when water contents are calculated from different regressor variables at different pressure head values or when prediction is carried out for soils differing from those included in the calibration database. The PTFs that estimate the retention function parameters are easy to use for modeling purposes (Tietje and Tapkenhinrichs, 1993).

Five PTFs were chosen in this investigation. Selection of PTFs was conducted according to their reliability as well as to previous validations under different conditions (Tietje and Tapkenhinrichs, 1993; Romano and Santini, 1997). All selected PTFs were characterized by input data that are easily gathered by common soil survey (i.e. soil texture, organic matter content and bulk density).

The PTFs by Saxton *et al.* (1986) (PTF-S1) and Saxton and Rawls (2006) (PTF-S2) describe the water retention function with three equations for different pressure head subranges, and strictly speaking cannot be considered as Functional Parameter Regression Methods. In particular, the following relationships were considered: i) a constant water content equal to the saturated water content, θ_s, for pressure head ranging from zero to the air entry pressure head, h_b, that is itself estimated from soil physical attributes; ii) a linear relationship from h_b to an intermediate pressure head fixed to -102 cm (PTF-S1) or -336.6 cm (PTF-S2); iii) an exponential function for h values lower than -102 cm (or -336.6 cm). The database of soil attributes used to develop the PTF-S1 (Saxton *et al.*, 1986) included a very extensive set of 2541 soil horizons (Rawls *et al.*, 1982). The derived expressions are applicable to soils with the following ranges of clay, *Cl*, and sand, *Sa*, contents: $5\% \le Sa \le 30\%$ if $8\% \le Cl \le 58\%$ and $30\% \le Sa \le 95\%$ if $5\% \le Cl \le 60\%$. As compared to PTF-S1, a wider dataset of approximately 2000 soil water characteristics from A-horizons and 2000 soil water characteristics from B- and C-horizons was used to derive the PTF-S2 (Saxton and Rawls, 2006) which is applicable for $Cl < 60\%$ and organic matter content, *OM*, lower than 8%.

The PTF from Rawls and Brakensiek (1989) (PTF-RB) estimates the parameters (residual water content, θ_r, saturated water content, θ_s, air-entry pressure head, h_b, and pore size index, λ) of the Brooks and Corey (1964) retention function:

$$\theta = \theta_s \qquad \text{for } h_b \le h \le 0 \tag{1a}$$

$$\theta = \theta_r + (\theta_s - \theta_r)(h_b / h)^{\lambda} \qquad \text{for } h < h_b \tag{1b}$$

The regression equations, were based on the same database from Rawls *et al.* (1982) and are valid for $5 \le Sa \le 70\%$ and $5 \le Cl \le 60\%$.

The European soil database HYPRES was used by Wosten *et al.* (1999) to develop a PTF (PTF-HY) giving the parameters of the van Genuchten's water retention function (van Genuchten, 1980):

$$\theta = \theta_r + (\theta_s - \theta_r)\left(1 + |\alpha h|^n\right)^{-m} \tag{2}$$

in which α (cm^{-1}), n and m are empirical parameters with $m = 1 - 1/n$. Note that eq. (2) is structurally similar to eq. (1b) with $\alpha = h_b–1$, $n = \lambda + 1$ and $m = \lambda/(\lambda + 1)$ (Romano and Santini, 1997).

A modified form of the van Genuchten function was used by Vereckeen *et al.* (1989), who reduced the number of parameters to be estimated with the simplifying assumption $m = 1$ (PTF-VE). Expressions for parameters α, n, θ_s and θ_r, were derived for 182 horizons in Belgium, with $Cl < 54.5\ \%$, $Si < 80.7\%$, $5.6 < Sa < 97.8\%$, organic carbon content, $OC < 6.6\%$ and bulk density, $1.04 < \rho_b < 1.23$ Mg m^{-3}. It should be noted that the modified form of eq. (2) results in different values for α and n, so that they cannot be compared with the corresponding values of the original van Genuchten equation.

Figure 1. Locations of the three sampling areas.

The five PTFs chosen for this comparison are characterized by an increasing level of soil attributes needed for estimation: two textural fractions for PTF-S1; two textural fractions plus soil porosity or organic matter content for PTF-S2 and PTF-RB; two textural fractions plus bulk density and organic matter content for PTF-HY and PTF-VE.

2. Sampled areas and laboratory measurements

Application of the selected PTFs was conducted on a data set made up by soil properties collected in three areas in Sicily (Figure 1). The first data sampling was conducted in the wine-specialized area of *Menfi*. Soil samples were collected in the upper horizon of 84 sampling points located in an area of approximately 850 ha. The second data sampling was conducted in the lower valley of *Dirillo*, in a 3000 ha area characterized by different pedology and land use with prevailing horticultural and herbaceous crops. The data set consists of data for 61 sampling points located in both the upper (A horizon) and the lower (B and/or C horizons) parts of 29 soil profiles. The third data sampling was conducted in an environmental protection area of 140 ha named *Riserva Naturale Integrale Grotta di Santa Ninfa* including both extensive crops and non-agricultural crops. A total of 54 sampling points were established in six plots characterized by a different land use (Bagarello *et al.*, 2008). Additional information on the data set is given in Table 1.

For each sampling point, the clay, *Cl*, silt, *Si*, and sand, *Sa*, percentages were determined according to the USDA classification (Gee and Or, 2002). The organic carbon, *OC*, content was determined by the Walkley-Black method (Nelson and Sommers, 1996). Where required, the organic matter, *OM*, content was estimated to be 1.724 times *OC*.

Water retention data were determined on undisturbed soil core (inside diameter = 0.08 m, height = 0.05 m) by a hanging water column apparatus (Burke *et al.*, 1986) for *h* values ranging from –0.05 to –1.5 m.

At the end of experiment, the undisturbed soil cores were used to determine the dry bulk density, ρ_b (Mg m^{-3}). Soil porosity, Φ (m^3 m^{-3}) was calculated from ρ_b assuming a particle density of 2.6 Mg m^{-3}. For each sampling point, sieved soil was packed to the ρ_b value of the undisturbed core in rings having an inside diameter of 0.05 m and a height of 0.01 m. These soil samples were used to determine the soil water content corresponding to *h* = –3.37, –10.2, –30.6, and –153.0 m by a pressure plate apparatus (Dane and Hopmans, 2002). For a small number of the undisturbed soil cores collected in the *Menfi* area (*N* = 22), two additional points of the water retention curve were determined by the pressure plate apparatus (*h* = –3 and –6 m) on the same sample used in the hanging water columns apparatus.

3. Method of evaluation

The considered PTFs were calibrated within different ranges of soil physical variables, depending on the PTF. Even if PTFs were sometimes applied to soils with properties differing from those of the calibration data set (Tietje and Tapkenhinrichs, 1993), they should not be used to make predictions for soils that are outside the range of soils used to derive them (Wosten *et al.*, 2001). Therefore, we considered only the soils for which all the selected PTFs could be applied. This resulted in a reduced data set of 149 soil data covering a broad range of textures (Figure 2). Information on the ranges of the variables used for PTF evaluation is given in Table 2.

Three out of the selected PTFs (PTF-RB, PTF-HY and PTF-VE) predict the parameters of the closed form functions used to describe the water retention curve, whereas PTF-S1 and PTF-S2 give the water content at fixed pressure head values. In order to make the comparison of the selected PTFs homogeneous, we decided to use the parameters estimated by PTF-RB, PFT-HY and PTF-VE with the appropriate water retention function (i.e. Brooks and Corey or van Genuchten) to estimate the water content at the experimentally imposed pressure heads. In this way, five estimated θ values (one for each selected PTF) were obtained for each soil of the validation data set and for each measured θ value.

The water content estimates were evaluated using the following statistics (Wosten *et al.*, 2001):

Maximum Error, $$ME = max\left|P_i - O_i\right| \quad (3)$$

Table 1. Description of the data set used to evaluate the pedotransfer functions

	Menfi	Dirillo	Santa Ninfa
N. of soil samples	84	61	54
N. of soil units	8	28	n.a.
Date of sampling	Jan. – Feb. 2002	March 2006	May 2006
Pressure heads for water retention measurements (m)	-0.05, - 0.1, -0.2, -0.4, -0.7, -1, -1.2, -1.5, -3, -3.37, -6, -10.2, - 30.6, -153	-0.05, - 0.1, -0.2, -0.4, -0.7, -1, -3.37, -10.2, - 30.6, -153	-0.05, - 0.1, -0.2, -0.4, -0.7, -1.2, -3.37, -10.2, - 30.6, -153

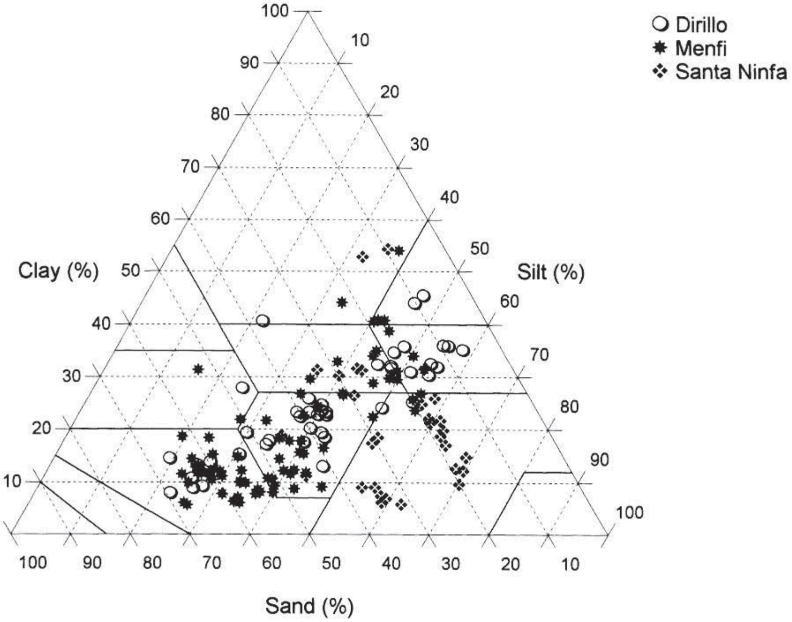

Figure 2. Texture classification, according to USDA, of the experimental data set.

Average Error,
$$AE = \frac{\sum_{i=1}^{N}(P_i - O_i)}{N} \quad (4)$$

Root Mean Square Error
$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (5)$$

where *N* is the number of observations, O_i is the measured value of θ and P_i is the predicted value of θ. The *ME* value can be considered as a local indicator of the goodness of the estimate provided by a certain PTF. The *AE* value reveals the presence of a systematic over- or under-estimation. The *RMSE* is a measure of the dispersion between measured and estimated values (Romano and Santini, 1997). Three statistical indices were used for PTFs evaluation given that each index serves different purposes and it is not possible to define a single statistic that adequately describe the PTFs performance (Donatelli *et al.*, 2004).

Table 2. Value ranges and statistics of the 149 soil samples considered for PTF comparison

	Cl (%)	Si (%)	Sa (%)	OC (%)	ρ_b (Mg m^{-3})	Φ (m^3 m^{-3})
min	5.7	15.8	6.5	0.10	0.830	0.332
max	54.3	70.3	69.2	3.70	1.769	0.687
mean	21.0	41.3	37.7	1.01	1.271	0.515
st. dev.	11.0	11.9	17.6	0.67	0.172	0.062

The statistics were calculated separately for each soil sample thus obtaining 149 values of *ME*, *AE* and *RMSE*, respectively. This approach is somewhat similar to that of Tietje and Tapkenhinrichs (1993) who defined the mean error and the root mean square error of a single water retention curve by integration over a certain pressure head range. In our case, from a minimum of 10 to a maximum of 14 water content data were obtained for a given soil sample (Table 1). Therefore, the *ME*, *AE* and *RMSE* statistics were calculated for each soil sample using a relatively similar, but not identical, *N* value. For comparative purposes, *RMSE* was also calculated for a given PTF by considering simultaneously all available predicted vs. measured data points. In this case, the statistic was denoted as total *RMSE*.

The influence of the pressure head value on the estimated θ values was evaluated by calculating the *ME*, *AE* and *RMSE* statistics at selected *h* values ranging from ˜0.1 to ˜153 m. To better investigate the PTFs performances, an analysis of the patterns of the errors was also conducted (Ungaro and Calzolari, 2001; Donatelli *et al.*, 2004). The *RMSE* values calculated for each soil sample were correlated to the input variables (*Cl*, *Si*, *Sa*, *OM* and ρ_b) and an F-test was conducted to evaluate the statistical significance of the calculated correlation coefficients ($P = 0.05$).

III – Results and discussion

The tested PTFs produced mean *ME* values ranging from 0.084 to 0.116 $m^3\ m^{-3}$ (Table 3) but, for a few soil samples, *ME* raised up to 0.23 – 0.28 $m^3\ m^{-3}$ showing that, for a given pressure head value, application of PTFs may yield a large error in predicted water content.

The mean *AE* values ranged from –0.0087 to 0.0082 $m^3\ m^{-3}$. In absolute terms, the lowest mean *AE* value (*AE* = –0.0052 $m^3\ m^{-3}$) was obtained for the PTF-HY that was the less biased PTF among the five considered. The second best result was obtained with the PTF-S1 (mean *AE* = 0.0062 $m^3\ m^{-3}$), whereas the PTF-RB, PTF-S2 and PTF-VE yielded worse results (Table 3). Negative values of the mean *AE* were obtained with the PTFs by Wosten *et al.* (1999) (PTF-HY) and Vereecken *et al.* (1989) (PFT-VE), indicating that, generally, an underestimation of soil water content should be expected with these PTFs. Conversely, PTF-S1, PTF-S2 and PTF-RB yielded positive mean *AE* values.

Table 3. Minimum, maximun and mean values of the statistics ME, AE and RMSE resulting from application of the selected PTFs to the samples of the data set. Total AE and RMSE are also reported

		PTF-S1	PTF-S2	PTF-RB	PTF-HY	PTF-VE
	min	0.0442	0.0283	0.0266	0.0214	0.0244
ME	max	0.2409	0.2315	0.2768	0.2689	0.2508
	mean	0.1064	0.0962	0.1158	0.0920	0.0835
	min	-0.1347	-0.1460	-0.1065	-0.1182	-0.1566
AE	max	0.1091	0.0955	0.1338	0.1744	0.1078
	mean	0.0062	0.0082	0.0080	-0.0052	-0.0087
	min	0.0279	0.0174	0.0150	0.0091	0.0141
RMSE	max	0.1455	0.1561	0.1682	0.2003	0.1586
	mean	0.0629	0.0579	0.0684	0.0566	0.0517
Total RMSE		0.0667	0.0617	0.0975	0.0637	0.0576

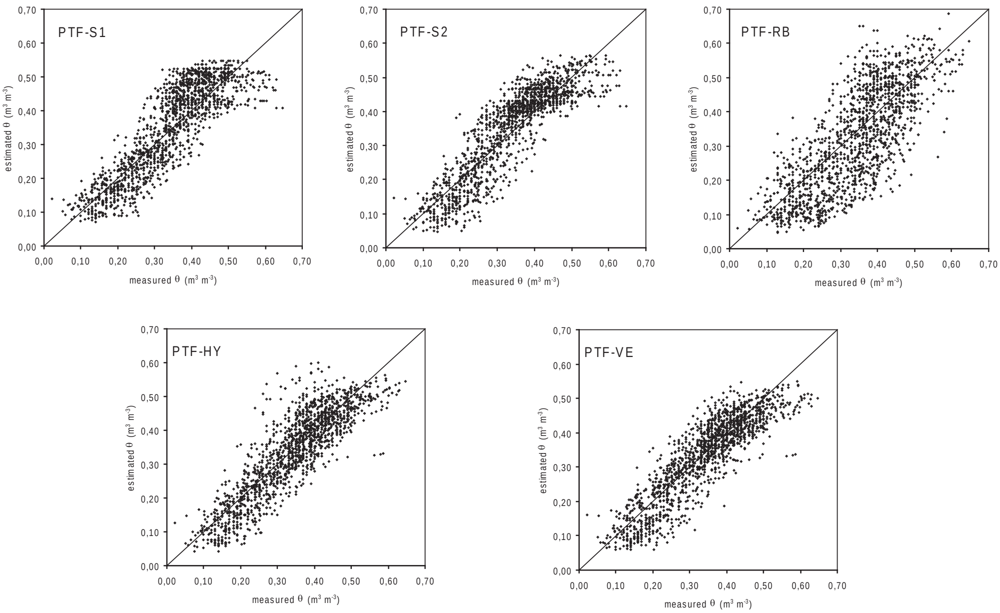

Figure 3. Estimated vs. measured water content, θ, values for the tested PTFs.

The *RMSE* values calculated for each soil sample and for each PTF ranged from 0.009 to 0.200 $m^3\ m^{-3}$. The best result in terms of mean *RMSE* was achieved by the PTF-VE, followed by the PTF-HY and PTF-S2 (Table 3). A higher mean *RMSE* value was obtained with the PTF-S1 whereas PTF-RB produced the worst mean *RMSE* value. The total *RMSE* values did not coincide with the corresponding mean *RMSE* values and a slightly different ranking of the considered PTFs was obtained with the two procedures for *RMSE* calculation (Table 3). However, the best (PTF-VE) and the worst (PTF-RB) PTF did not change between the two sets of *RMSE* values (Figure 3). A difference between total and mean *RMSE* was not surprising since the number of θ data was not exactly constant (i.e., it varied between 10 and 14) among samples.

Donatelli *et al.* (2004) suggested that *RMSE* normally takes precedence over the other statistics in the evaluation procedure of different PTFs. According to this criterion, PTF-VE yielded the most reliable results among the tested PTFs for the considered data set. However, the best *AE* result was obtained with the PTF-HY that also yielded the second best results in terms of both (mean) *RMSE* and *ME*. Moreover, both visual inspection of the estimated vs. measured plot (Figure 3) and examination of the calculated statistics (Table 3) suggested that using the PTF-S1 and PTF-S2 did not introduce substantial additional errors as compared to the PTF-VE and PTF-HY. This last result is important because the PTF-S1 uses only soil textural fractions to predict θ.

For a broad range of soils in Germany, Tietje and Tapkenhinrichs (1993) also found an overall better performance of the PTF-VE with a mean *RMSE* value of 0.0531 $m^3\ m^{-3}$ very close to the one obtained in this evaluation. In their case, the PTF-VE also resulted in a general underestimation of the water content ($AE = -0.0145\ m^3\ m^{-3}$). A comparison of the PTF-RB and PTF-VE conducted by Romano and Santini (1997) showed that the water retention curves were better described using the PTF proposed by Vereecken *et al.* (1989). Moreover, these authors detected that the largest deviations between the measured and the estimated water content were chiefly associated to those samples having low sand content and/or low values of bulk density. Ungaro and Calzolari (2001) reported a better performance of the PTF-S1 as compared to the PTF-RB and PTF-VE (mean *RMSE* equal to 0.0698, 0.0882 and 0.0915 m^3 m^{-3}, respectively). However, the different behavior could be attributed to differences in texture of the soils considered for comparison. In this investigation also, the PTF-S1, using two textural fractions, performed better than the PTF-RB, using two textural fractions plus porosity.

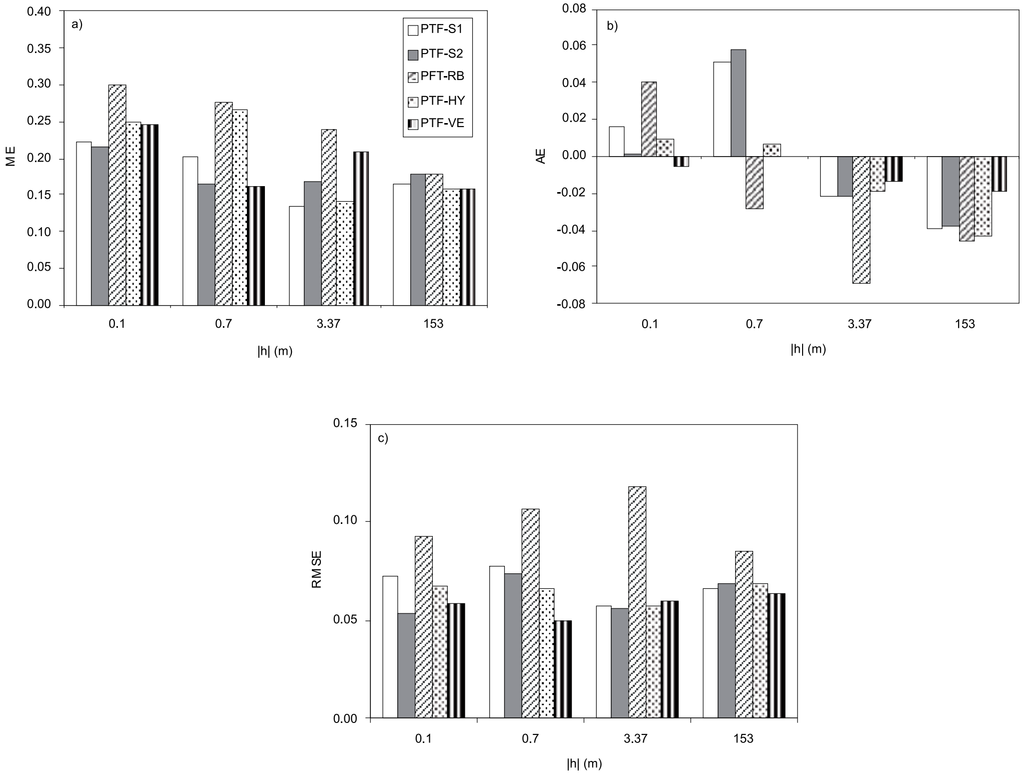

Figure 4. Statistics ME, AE and RMSE for the tested PTFs at specific pressure head, h, values.

The influence of the selected pressure head value on the water content estimates was assessed by calculating the *ME*, *AE* and *RMSE* statistics corresponding to four *h* values (*h* = –0.1, –0.7, –3.37 and –153 m) to explore a wide range of pressure heads. These *h* values were chosen because the maximum number of θ measurements (*N* = 149) were performed for each of them. Therefore, the comparison of *AE* and *RMSE* results was not distorted by *N*.

A general decrease of *ME* was detected as *h* decreased from –0.1 to –3.37 m, even if a moderate increase of *ME* was observed at *h* = –153 m (Figure 4a). Therefore, prediction of water content at high *h* values (i.e. less negative) is expected to be more prone to the occurrence of particularly high absolute deviations between measured and estimated θ values. Most of the considered PTFs showed a tendency to overestimate θ at high *h* values and to underestimate θ at low *h* values (Figure 4b). The only exception was for the PTF-VE that always underestimated θ, thus explaining the negatively biased estimation of water retention (Table 3). For the PTF-HY, a result similar to the one obtained in this investigation was reported by Ungaro e Calzolari (2001) who observed that the most significant discrepancies between measured and estimated θ values were localised at the wet and the dry end of the water retention curve. Influence of pressure head on *RMSE* was less pronounced and a common trend with *h* was not observed (Figure 4c). In most cases, *RMSE* decreased as *h* decreased from –0.1 to –3.37 m and then increased slightly at *h* = –153 m. A similar influence of the pressure head on the performances of the PTF-VE and PTF-RB was also observed by Wosten *et al.* (2001).

Plot of errors allows detecting if the goodness of the prediction changes according to the input value (Donatelli *et al.*, 2004). The error indices *RMSE* calculated for each soil sample with the five selected PFTs were therefore plotted vs. texture, organic matter content and bulk density and correlations analyses were performed. Only the *RMSE* was considered for this analysis due to the following reasons: i) interpretation of regression between *AE* and a selected soil attribute may be complicated by the sign of *AE* given, for example, that a significant negative correlation could be indicative of both a reducing positive bias or an increasing negative bias; ii) in absolute terms, a low bias in the estimation of θ, suggesting a good performance of the tested PTF, could be associated with large maximum errors and highly scattered data; and iii) a highly significant linear correlation ($P = 0.05$) was detected between *ME* and *RMSE* ($r^2 > 0.824$, $N = 149$) suggesting that the patterns for *ME* could be explained by the analysis of *RMSE* correlations.

RMSE was generally independent of *Sa*, given that a significant negative correlation with *Sa* was detected only for the PTF-S1 (Table 4). All the selected PTFs tended to yield less accurate estimations of θ for high *Si* values. However, it should be considered that, for the PTF-S2, PTF-RB, PTF-HY and PTF-VE, *RMSE* was also negatively correlated with *Cl*. Therefore, in fine textured soils high in both clay and silt content, the increase in the estimation error due to positive correlation with *Si* may be partly compensated by the negative correlation with *Cl*. When considered separately, the estimation accuracy will improve at increasing *Cl* and decline at increasing *Si*. The *RMSE* values exhibited a low but significant negative correlation with *OM* only for the PTF-VE. For the remaining cases, no correlation was found between *RMSE* and *OM*. It could be concluded that organic matter content did not influence appreciably the accuracy of water content estimates for the selected PTFs. In all cases but one (PTF-S1), the *RMSE* values were negatively correlated with bulk density (Table 4), denoting that more accurate estimates of θ could be obtained at high ρ_b values. As an example, Figure 5 shows the mean *RMSE* vs. bulk density plot for the PTF-RB. In this case, the bulk density explained up to 47% of the variability of *RMSE*. A marked influence of ρ_b on the water content predicted by the PTF-S1, PTF-RB and PTF-VE was also reported by Ungaro and Calzolari (2001) for 139 soil horizons in the Pianura Padano-Veneta (Italy). Tietje and Tapkenhinrichs (1993) also reported a similar trend for the PTF-VE with errors that were higher for soils with low bulk density values.

Table 4. Regression coefficients for *RMSE* correlations with *Cl, Si, Sa, OM* and ρ_b

	Cl	*Si*	*Sa*	*OM*	ρ_b
PTF-S1	0.0357	**0.4510**	**-0.3274**	0.0557	-0.1434
PTF-S2	**-0.2359**	**0.3948**	-0.1185	0.1197	**-0.3584**
PTF-RB	**-0.2366**	**0.2476**	-0.0186	0.0080	**-0.4652**
PTF-HY	**-0.2133**	**0.1814**	0.0115	0.0076	**-0.3465**
PTF-VE	**-0.1688**	**0.3311**	-0.1177	**0.2022**	**-0.3091**

Correlation coefficients in bold are statistically significant at P = 0.05 level according to an F-test.

Overall, it may be concluded that the performance of the selected PFTs was generally independent of organic matter content but depended on bulk density. Regarding the influence of texture, where significant correlations were found, the clay and silt content influenced the *RMSE* value in an opposite way. Therefore, their effects could partly compensate for fine textured soils with high clay and silt content. However, the risk that water retention predictions could be less accurate for soil with high *Cl* is real for all the considered PTFs.

IV – Conclusions

The performance of five PTFs was compared for a database of 149 water retention characteristics of Sicilian soils covering a broad range of texture. Evaluated PTFs included three of the most widely applied and recommended PTFs (i.e. PTF from Saxton *et al.* (1986), Rawls and Brakensiek (1989) and Vereecken *et al.* (1989)) as well as the two more recently developed PTFs from Wosten *et al.* (1999) and Saxton and Rawls (2006). The procedure applied to calculate the error indices influenced the ranking of the evaluated PTFs, but the best result in terms of *RMSE* was undoubtedly obtained by the PTF-VE. A similar result was found by Tietje and Tapkenhinrichs (1993) and Romano and Santini (1997). Comparison of the PTF-S2 and PTF-HY with other PTFs is lacking in literature. In our case, they behaved almost as well as the PTF-VE, with the PTF-HY showing the best results in terms of unbiased predictions. Comparatively reliable results were obtained with the PFT-S1 that requires only texture as input. This result is of outmost practical interest given that soil particle size distribution is generally determined in routinely conducted soil survey, whereas bulk density measurements are often neglected.

Pressure head generally affected the PTFs performances as four out of the considered PTFs tended to overestimate θ at high *h* values and to underestimate θ at low h values. The only exception was for the PFT-VE that underestimated the predicted water contents in the entire range of considered pressure head values.

A similar level of accuracy can be obtained for the entire range of the organic matter values explored. Conversely, the soil bulk density significantly influenced the accuracy of water content estimates given that, in all cases but one (PTF-S1), more accurate estimates of θ were obtained at high ρ_b values. In general, the sand content did not influence the performances of the considered PTFs whereas the clay and silt contents had an opposite influence on the *RMSE* statistic. In fine textured soils with both *Cl* and *Si* content, these effects may partly compensate each other but poor water content estimates should be expected for soil with low clay content and high silt content.

The evaluation performed is the first conducted in Sicily on a large soil database. Its results confirmed that most of the considered PTFs allow reliable estimations of soil water retention characteristics and, if coupled with field measured hydraulic conductivity values, are potentially capable to yield soil hydraulic properties sufficiently accurate for large scale simulation of the soil water balance.

Acknowledgements

Funding for this research was provided by Ministero dell'Istruzione, Università e Ricerca (PRIN 2006) and of Assessorato Agricoltura e Foreste della Regione Siciliana (projects MONIDS e DIFA). The authors wish to thank Mr. Cosimo Vivona for his help in conducting laboratory experiments.

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Water resource management at district level. First results of AQUATER research project

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Abstract. An efficient management of water resources is a crucial point for Italy and in particular for southern areas characterized by Mediterranean climate in order to improve the economical and environmental sustainability of the agricultural activity.

AQUATER is a research project funded by the Italian Ministry of Agriculture, Food and Forestry Policies (2005-2009). It has the aim to develop a decision support system to integrate remote sensing information and crop simulation model to allow a best management of irrigation water at district scale. It is focused on the remote sensing, the plant and the climate and, for interdisciplinary relationships, the project working group consists of agronomists, engineers and physicists.

The Project is structured in four workpackages with specific objectives, high degree of interaction and information exchange: 1) Remote sensing and image analysis; 2) Cropping systems; 3) Modelling and softwares development; 4) Stakeholders.

In the paper the main results of the first two years of the Project are reported and briefly commented.

Keywords. Remote sensing – Evapotranspiration – Simulation model – Soil – Weather – DSS.

Gestion de l'eau au niveau du pèrimètre irrigué. Résultats préliminaires du projet de recherche AQUATER

Résumé. *Une gestion efficiente de la ressource en eau est cruciale pour l'Italie et en particulier pour les régions du sud, à climat méditerranéen, pour améliorer la durabilité des activités économiques et environnementales. AQUATER est un projet de recherche financé par le Ministère Italien de l'Agriculture (2005-2009). Il a comme objectif de développer un système pour intégrer les informations de la télédétection avec celles des modèles de simulation des cultures pour permettre une gestion de l'irrigation plus efficace au niveau du périmètre. Le projet met le point sur la télédétection, la plante, le climat et les relations interdisciplinaires, ainsi le groupe de travail du projet comprend agronomes, ingénieurs et physiciens. Quatre groupes de travail avec objectifs spécifiques et un haut degrée d'interaction s'échangent l'information qui couvre: 1) la télédétection et l'analyse de l'image; 2) l'assolement; 3) le développement des modèles et des logiciels; 4) stakeholders. Dans cet article sont présentés en bref les résultats principaux des deux premières années du projet.*

Mots-clés. *Télédétection – Évapotranspiration – Modèles de simulation – Sol – Climat – DSS.*

I – Introduction

Earth observation is reported as a tool in order to obtain information about land use, vegetation status, soil moisture, surface roughness and, in general, to estimate crop and soil information. Different methods have been developed to estimate evapotranspiration from remote sensing data, using energy balance equation and thermal infrared information. Basic and applied knowledge about crop water requirement are well documented, but the water distribution authorities need to have tools and support to best manage water at district level. Crop simulation models are mathematical representations of the soil-plant-atmosphere system, involving interactions between biological factors and environment. Spatially distributed models can be used also in simulation of basin, watershed or region.

A tool combining the above reported technologies could be very valuable for forecasting crop yield, water use, drought risk and to support irrigation authorities on decision about water management.

The AQUATER project, supported by Italian Ministry of Agriculture, Food and Forestry Policies (Rinaldi *et al.*, 2005) started in 2005 to develop and test methods for interpreting remote sensing data that could lead to a better evaluation of soil and vegetation functioning. The proposed approach is based on the assimilation of remote sensing data into soil and vegetation simulation models.

In the framework of the AQUATER project, the three largest plains of Southern Italy were monitored: Capitanata Plain, Sele river Plain and Ionic coastal Plain (Fig. 1).

The Project is structured in four workpackages:

A - Remote sensing and image analysis;

B - Cropping systems;

C - Modelling and software development;

D - Stakeholders.

The Working Units participating to the Project are:

- Agricultural Research Council – Research Unit for cropping systems in dry environments of Bari, with 5 sub-units and coordinating the Project;
- University of Napoli, Department of Hydraulic Engineering;
- National Research Council, Institute of Intelligent Systems for Automation, Bari;
- University of Milano, Department of Agriculture Production.

In this paper the preliminary results obtained during the first two years of the Project are summarized and reported according the four workpackages.

II – Results

1. Remote sensing and image analysis

Various earth observation techniques have been widely used in recent years to monitor the temporal and spatial variability of land use, plant canopy (LAI) and soil moisture (SWC), in order to estimate crop water requirements and assess drought risk. Optical sensors with different spatial and spectral resolutions have been extensively exploited to provide an estimation of LAI with satisfactory accuracy for most applications. However, cloud coverage may represent a strong limitation in using optical sensors for all the applications which require a frequent revisiting coverage. Active and passive microwave sensors have proven their potentiality for detecting SWC in several recent studies; in particular, space-borne active microwave imaging techniques are of special attractiveness thanks to their fine spatial resolution and the repetitiveness of measurements. In the AQUATER Project images obtained by both sensors have been acquired during crop growth cycle, processed and used: MERIS (resolution 300 m), LANDSAT TM (30 m), SPOT (20 m), IKONOS (4 m), in the optical, ASAR (30 m) and PALSAR (30) in the microwave region.

Firstly, to use remote sensed data for monitoring land cover it is very important to develop methodologies to obtain reliable maps. In order to achieve this objective a possible approach is to combine both “spectral” and “spatial” features characterizing each ground class. Fiorentino *et al.* (2006) and Castrignanò *et al.* (2008) proposed the integration of a spectral classifier for remote sensed data at medium resolution, based on a traditional statistical supervised classifier as "Maximum Likelihood", with the spatial information provided by a geostatistical tool, as "Indicator Kriging" algorithm. Using this combined approach, better results in land cover class discrimination have been obtained and the resulting maps look more homogenous than in the case with the spectral information only (Fig. 2).

Satalino *et al.* (2007, 2008) used a physically based method for mapping winter wheat using ASAR AP data, acquired at HH and VV polarization and at high incidence angles. The study analysed two temporal series of ASAR AP images, acquired in 2006 and 2007, over an agricultural area located in the Capitanata plain.

The wheat classification was obtained by applying an optimal threshold to the co-polarized backscatter ratio of ASAR AP data acquired during the peak growing stage. Classification accuracies on test data ranging between 75% and 80%, depending on the amount of spatial and temporal filtering performed, were obtained.

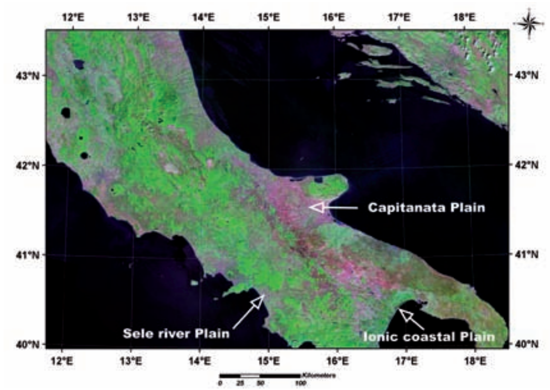

Figure 1. LANDSAT TM image with the indication of the three test areas of AQUATER Project.

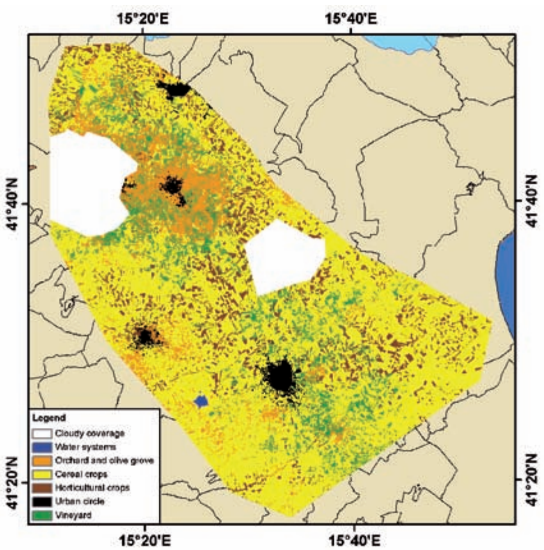

Figure 2. Land use maps in Capitanata plain, using the combined approach.

The obtained accuracies were not critically sensitive to the adopted threshold or to the specific acquisition date in the peak growing stage. In this respect, although optical data can provide higher level of classification accuracies, the proposed method appears robust and of particular interest for sites where the acquisition of cloud-free optical data is critical (Fig. 3).

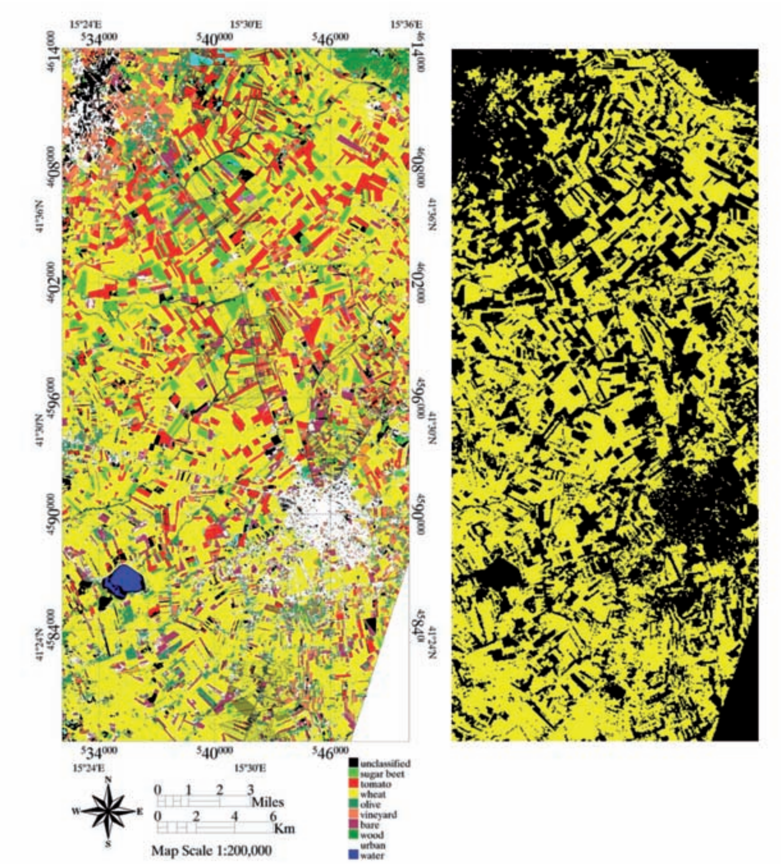

Figure 3. Classified image obtained from SPOT data (left). Wheat crop mapping obtained from ASAR data (right).

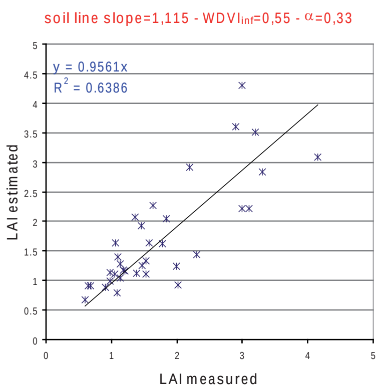

Figure 4. Relationship of estimated LAI from WDVI index and measured LAI of maize crop.

In the Sele river plain, the combined use of multi-temporal images LANDSAT and SPOT (June-August 2006) allowed to obtain land use, albedo and crop coefficients maps, in order to estimate seasonal crop water requirements. The relationship between Vegetation Index (VI) and LAI has been verified with good accordance using WDVI (Weighted Difference Vegetation Index) (estimated LAI vs. measured LAI: R2 = 0.64) (Fig. 4) (D'Urso *et al.*, 2008). Using other data-set the possibility to estimate from L-band SAR data, LAI and soil moisture in the upper soil layer has been positively evaluated (D'Urso *et al.*, 2007).

An algorithm transforming temporal series of ALOS-PALSAR SAR data into SWC by using a constrained minimization technique, integrating a priori information on soil parameters, has been developed (Satalino *et al.*, 2007). The algorithm has been applied to winter wheat and has been assessed on simulated and experimental data acquired during the 2006 and 2007 growing seasons over the site of Foggia. Two SWC maps referring to April 2 and May 18, 2007, are shown in Fig. 5. Preliminary results indicate the feasibility of retrieving volumetric soil moisture content with an accuracy of 5%.

2. Cropping systems

Systematic measurement campaigns at satellite overpassing have been carried out in 2006 and 2007 in the three experimental areas. To capture the main processes controlling soil-atmosphere exchanges, the local climate, soil and land use were fully characterized; surface energy fluxes, vegetation biomass and structure, soil moisture profiles, surface soil moisture and soil temperature were monitored. Additional spectral plant measurements and a full characterization of physical soil parameters were also carried out. The examined crops have been: durum wheat, tomato and sugar beet in Capitanata; water melon in Metaponto and maize in Sele river plain.

Continuous measurements of water status vegetation of crop let possible to schedule irrigation with the highest precision. Mainly in the Mediterranean regions the precision is required to use efficiently the water resources at field and regional levels. The first results support the hypothesis of identifying the vegetation water status based upon the relationship based on NDVI data. The existing data-set demonstrates that NDVI is also a function of the crop water status. The relationship between NDVI and pre-dawn leaf water potential (Ψ) is linear: $\Psi = 1.67NDVI-1.59$; $r^2 = 0.95$ (Fig. 6). From this relationship it seems possible to predict the crop water status starting from completely automatic measurements and, above all, from those ones that can be acquired through remote sensing techniques. Vice versa, the measurements of radiative temperature used to estimate the tomato water status proved to be unsatisfactory. The temperature of the vegetation, besides the soil water regime, is more dependent by meteorological conditions at the time of measurement (Mastrorilli *et al.*, 2008). A large database of climatic and pedological data have been acquired, also from previous projects, and quality control, georefentiation and harmonization have been carried out.

Delineation of broad soil zones within the study areas has been attempted using different soil and subsoil physical/chemical attributes. The multivariate data sets were submitted to an original combined approach of clustering, based on multivariate geostatistics linked to a nonparametric density function algorithm (Castrignanò *et al.*, 2008).

The proposed approach provided quite suitable to identify spatially contiguous zones, which are more homogeneous in soil properties than the whole area for both Capitanata and Ionic coastal plain (Fig. 7). Moreover, a 3D visualisation of the density function allowed to have an additional description of the residual within-cluster variation and then to judge the compactness of cluster.

Daily weather information has been recorded with automatic weather station. Eddy covariance method was used to measure actual crop evapotranspiration; the results showed how this latter measurement is well correlated to the evapotranspiration estimated with Penman-Monteith formula, but with less expensive equipment (Katerji and Rana, 2008; Ferrara *et al.*, 2008).

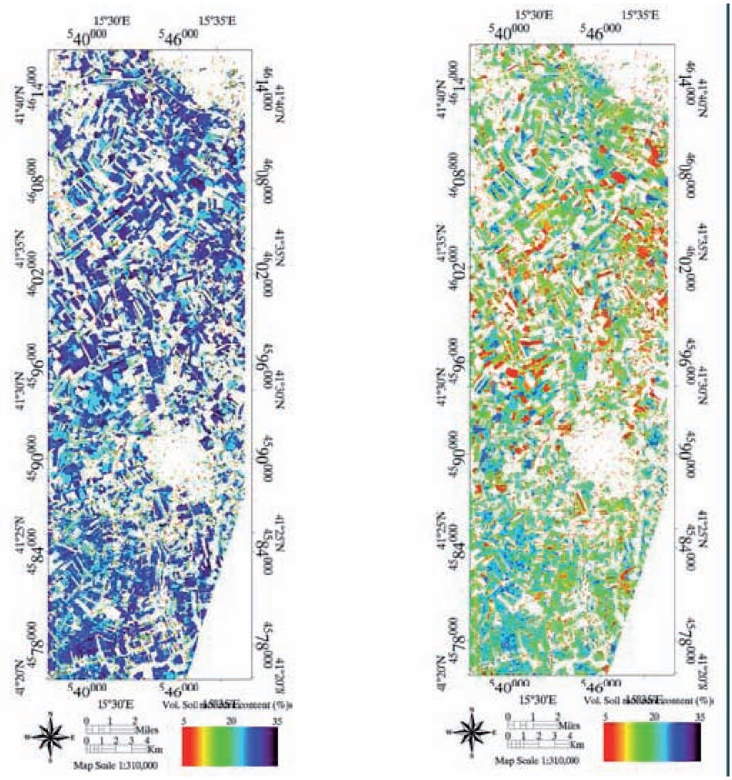

Figure 5. Soil moisture maps retrieved from PALSAR data over the Foggia site. The maps on the left and on the right refer to April 2 and May 18, 2007, respectively.

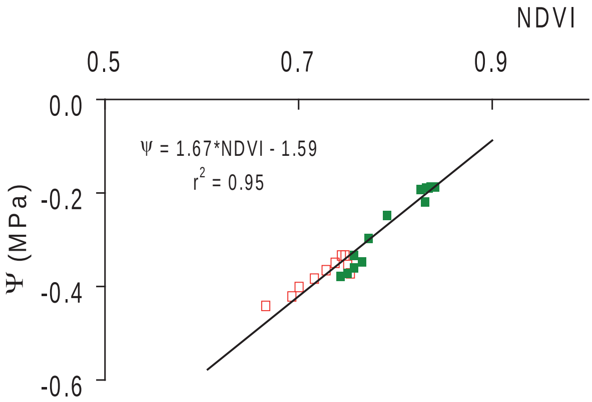

Figure 6. Pre-dawn leaf water-potential (Ψ) vs daily values of NDVI. Values derive from the full-irrigation (solid symbols) and the stressed (unfilled symbols) treatments.

Figure 7. Clustering of soil attributes in Ionian coastal plain.

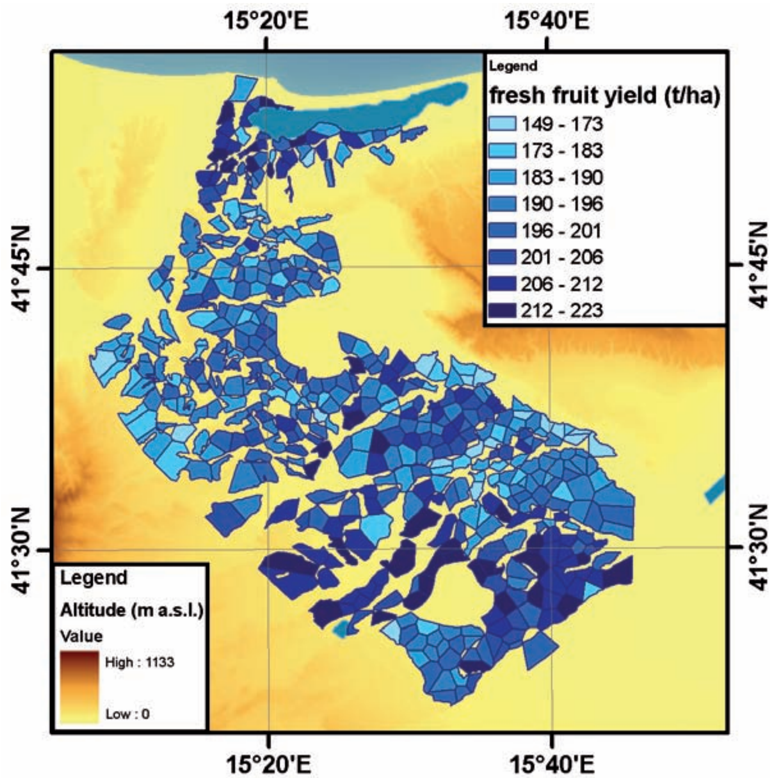

Figure 8. Distribution map of DSSAT simulated values of tomato fresh fruit yield irrigated at 45% of crop soil water in Capitanata plain.

3. Modelling and software development

Crop simulation models can appreciate "soil-climate-crop" interaction, offering stakeholders suggestions for better water allocation and advising farmers on the best irrigation scheduling from an economic point of view. In the AQUATER project several models have been used.

CropSyst model has been calibrated and validated for durum wheat and horse bean. The following application has been carried out simulating three cropping systems (durum wheat continuous cropping, 2-year and 3-year rotations with horse bean); a positive effect of leguminous crop on following wheat in rotation has been shown (higher soil water content at wheat sowing) (Garofalo *et al.*, 2007).

DSSAT crop simulation package and its GIS interface were used in some case-studies in Capitanata. Durum wheat and processing tomato have been simulated punctual-based using soil and long-term weather data (45 years). The two crops have been compared in the following management scenarios: rainfed and three automatic irrigation levels based on soil water content thresholds. GIS allowed visualising the output variables in the soil polygons. The wheat productivity was increased by irrigation of 19% and no difference occurred among automatic irrigation thresholds. In tomato the irrigation increased the yield by 3 times with respect to rainfed, with no difference among irrigation scenarios. The "soil x climate" interaction influenced the spatial response at regional level, allowing us to identify the area more productive for wheat and tomato (Fig. 8) (Rinaldi *et al.*, 2007;2008).

In Sele river and Metaponto coastal plains the physically-based model SIMODIS (SImulation and Management of On-Demand Irrigation Systems) has been applied on a data-base from another research project (SIGRIA, Inea), allowing to estimate seasonal irrigation volumes on maize and water melon at different spatial and temporal scales. This result, allowed to calculate some indicators of irrigation efficiency for the different soil classes, useful to save wastes in irrigation management at district scale (D'Urso *et al.*, 2008; Ventrella *et al.*, 2008). In Metaponto coastal plain SIMODIS has been also used to simulate the water melon crop. In particular, this approach was successful in estimating the main components of soil water balance. Analyzing the spatial distribution of these indicators it was possible to individuate the areas characterized by higher irrigation requirements and low water use efficiency due to water losses by deep percolation (Fig. 9). In general, the irrigation strategy of melon based on plant water status, allows to use water in a lightly more efficient way than the irrigation based on soil water status. However, with sand soil, characterized by very large value of saturated hydraulic conductivity, the best way to save water is to schedule the irrigation by monitoring the soil water content or adopting the evapotranspirometric method (Ventrella *et al.*, 2008).

Dente *et al*. (2006) developed a method to assimilate LAI maps retrieved from ASAR and MERIS remote sensing data into CERES-Wheat crop growth model in order to improve the accuracy of the wheat yield estimates at catchment scale. The assimilation leads to have information on the spatial variability of the yield in the area, which otherwise would have not been available. The assimilation method described in this work is a promising technique to apply crop growth models, such as CERES-Wheat, at catchment scale when no accurate in-situ information to run the model is available.

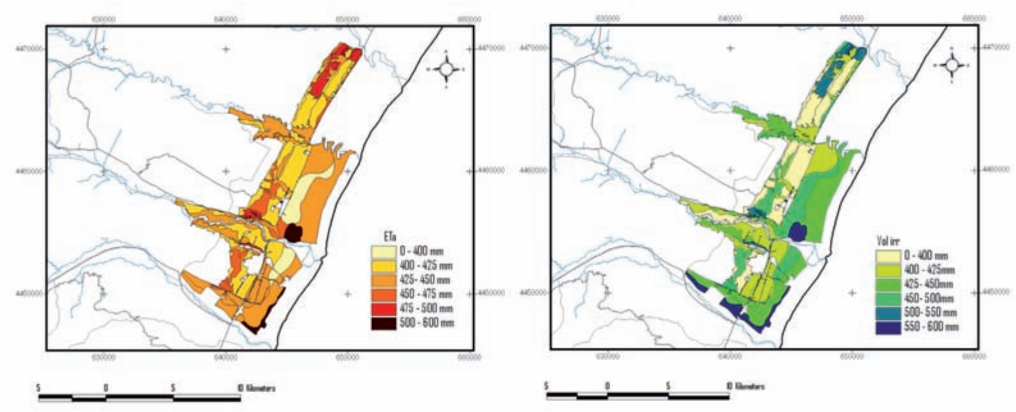

Figure 9. Spatial distributions of actual evapotranspiration (left) and irrigation depths (right) for Metaponto coastal plain.

A prototype of a Decision System Support (DSS) has been developed in order to schedule irrigation at district level in a Mediterranean area. The DSS uses the Unified modelling language and it integrates the information deriving from soil and climatic georeferenced database with a crop simulation model (STAMINA model), based on gross assimilation of CO_2 and on maintenance and growth respiration to get the final net carbon assimilation.

The software frame derives from the integration of interchangeable and extensible components and it has been developed for "Net" environment using VBNet and C# programming languages. Crop growth, water stress and water balance are simulated to estimate the water requirement and irrigation needs at regional level for different crops (until now only for sugar beet and maize). A set of input for the DSS, like crops and sowing dates, can be derived by remote sensing images. The LAI and plant biomass derived from remote sensing, can be further assimilated into the simulation model, to force the model to fit the values and to obtain an improvement of the simulation results. The DSS is at first prototype phase, but it is already provided of a GIS visualization tool. The first results obtained show the capabilities of the model that in the following research, will be further calibrated and validated with plant and soil experimental data. It will be improved also for the user interface, more friendly and easy to use (Acutis *et al.*, 2007; 2008).

4. Stakeholders

They represent the interface between "researchers" and "farmers" and, consequently, the exploiters of Project's results. They could give useful indications to the researchers about examined areas, and criteria for irrigation water management.

In the 2008 a 2-week training course about "Irrigation at new spatial scale" has been held in Foggia, at "Consorzio per la Bonifica della Capitanata" in Foggia, with 30 participants (technicians, graduate and Ph-students). The course has been structured in five main modules: 1) Soil-water relationships; 2) Crop water requirements; 3) New irrigation systems; 4) Modeling of the water balance processes; 5) Upscaling of the water balance processes.

III – Conclusion

The first results of the project have been shown and the real possibility to use the new technologies to efficiently manage water at district level resulted clear. In the ending part of the Project the third measurement campaign, the corroboration of relationships between vegetation indexes and bio-physical variables and the application of DSS, will be carried out.

Efforts could be done to improve the integration of different authorities – researchers, farmers, policy makers, and environmental agents - to share information and working together for a sustainable use of water in agriculture.

Acknowledgements

This work was supported by the Italian Ministry of Agriculture, Food and Forestry Policies (AQUATER project, contract nr. 209/7303/05).

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A comparison between a traditional and a geometrical supervised classifier to produce land cover Maps from SPOT5 images

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Abstract. The new high-resolution images from the satellites as IKONOS, SPOT5, Quickbird2 give us the opportunity to map ground features, which were not detectable in the past, by using medium resolution remote sensed data (LANDSAT). More accurate and reliable maps of land cover can then be produced. However, classification procedure with these images is more complex than with the medium resolution remote sensing data for two main reasons: firstly, because of their exiguous number of spectral bands, secondly, owing to high spatial resolution, the assumption of pixel independence does not generally hold. It is then necessary to use new spectral classifiers taking into account also proximal information. In this view, it is necessary to combine both "spectral" and "spatial" features to optimise land use classification. Standard supervised classification techniques, so-called "per-pixel" classifiers, use only spectral information of remote sensing image, whereas neglecting the relationships between neighbouring pixels. The objective of this work is the comparison between a conventional supervised classifier, as "Maximum Likelihood" algorithm, and a spatial classifier based on a searching algorithm of a given geometrical pattern.

The data in this study were a remote sensing image taken by SPOT5 satellite in July 2007 and used to discriminate the water melon cover class. Applying the object recognition tecnique the overall accuracy increased of about 12%.

Keywords: High resolution satellite images – Maximum Likelihood – Object-oriented.

Comparaison entre classificateurs traditionel et géométrique pour la production de cartes de couverture du sol à partir d'images SPOT5

Résumé. *Les nouvelles images à haute résolution des satellites comme IKONOS, SPOT5, Quickbird2 nous donnent la possibilité de dresser des cartes caractéristiques du terrain, qu'on ne pouvait pas relever, par la télédétection d'images de moyenne résolution (LANDSAT). Des cartes plus précises et fiables, de couverture du sol peuvent alors être produites. Toutefois, la procédure de classement de ces images est plus complexe que la classement des données de télédétection à résolution moyenne pour deux raisons principales: tout d'abord, en raison de leur nombre exigu de bandes spectrales, d'autre part, en raison de la haute résolution spatiale, l'hypothèse de l'indépendance de pixels ne peut plus être acceptée. Il est alors nécessaire de recourir à de nouveaux classements spectraux en tenant compte également de l'information proximale. De ce point de vue, il est nécessaire de combiner l'information «spectrale» et «spatiale» afin d'optimiser la classification des sols. Les techniques de classification supervisée standard, soi-disant «per-pixel», utilisent uniquement l'information spectrale de la télédétection image, négligeant les relations entre les pixels voisins. L'objectif de ce travail est la comparaison entre un classificateur conventionel supervisé, en tant que «Maximum Likelihood» algorithme, et un classificateur spatial sur la base d'un algorithme de recherche d'un modèle géométrique. Les données de cette étude sont une image de télédétection par satellite SPOT5 prise en Juillet 2007 et utilisée pour l'individuation des champs de pastèque pour identifier sa classe de couverture. L'application de la technique de «object-recognition» a augmenté la précision globale du classement d'environ 12%.*

Mots-clés. *Haute résolution des images satellite – Maximum Likelihood – Object-oriented.*

I – Introduction

Traditional methods of remote sensing analysis, as aerial-photo interpretation, have taken advantage from the overlapping of adjacent photographs to assess size and structure. This method has produced successful results, but it has also been problematic and expensive for various reasons; for example, the acquisition of aerial photographs may be difficult, owing to the bad weather conditions. Since at present there is a number of high resolution satellites in orbit, acquisition of satellite imagery is now much easier and more readily available than photography. Moreover, once aerial photographs are obtained, interpretation must be made on individual photographs, often numbering in hundreds or thousands.

In early 2002, two new high resolution satellites were launched, bringing to three the total number of satellite sensors capable of delivering imagery with resolution under 5 meters. These satellites will continue to proliferate and, as a new satellite is added, the price of this type of imagery will continue to drop. Moreover, some of these new satellites have larger footprints (cover larger areas) without any loss of spatial resolution. Although features can always be extracted from high resolution imagery through visual means with hand delineation procedures (Lillesand *et al.*, 2004), this approach is very time consuming and subjected to human error. As high resolution imagery is collected in digital format and is multispectral, this makes it a good candidate for an automated approach of feature extraction. To date the standard automated mapping approach has been to use unsupervised or supervised classification techniques. Higher spatial resolution improves the ability to differentiate features, but, in complex environments, different classes can have identical spectral reflectance and, reversely, the same class can have different spectral reflectance values. To improve classifications, size, shape, texture, context, and pattern can be incorporated into classification methods. New algorithms, such as nearest neighbour analysis, neural networks, decision trees and the mixing of spectral and textural data, can be applied (Donnay *et al.*, 2001, Herold *et al.*, 2003).

This improves the results, but further increases the skill level required for use (Herold *et al.*, 2003).

Object-oriented approaches classify objects rather than individual pixels (Geneletti and Gorte 2003). The traditional methods rely entirely upon the spectral information in an image, while neglecting the spatial arrangement of the pixels. Pixel-based classification methods frequently group dissimilar pixels with the larger, surrounding class. The Feature Analyst approach to object-recognition and feature extraction overcomes these shortcomings by using inductive learning algorithms and techniques to model the feature-recognition process. The user gives the system a sample of extracted features from the image and the system then automatically develops a model that correlates known data (such as spectral or spatial signatures) with targeted outputs (i.e., the features or objects of interest). The learned model then automatically classifies and extracts the remaining targets or objects. This approach leverages the natural ability of humans to recognize objects in complex scenes.

Object-oriented classification allows relevant objects to be of any size. Object-oriented classification is not without drawbacks. Classifications are difficult in areas, where complex obstacles and shadows may lead to misclassification. Moreover, advanced user expertise in processing techniques is frequently needed to develop classification algorithms (Mitri *et al.*, 2004).

II – Methodology

Maximum Likelihood algorithm is a conventional statistical classification technique that allocates each pixel of an image to the class with which it has the highest likelihood or 'a posterior' probability of membership. Let the spectral classes for an image be represented by the categorical variable ω_i, i=1,…..,M with M mutually exclusive categories and let $\mathbf{X}=\mathbf{X}(\mathbf{u}_\alpha)$ be B-variate random vectors

(B = number of spectral bands of the image), the pattern observations describing a point at the position **u** $_\alpha$.

In remote sensing the measurement vector **X,** referred to the pixel of spatial coordinates **u**$_\alpha$ (α=1,….,n), is a column of brightness values for the image and the training data for ground cover type are associated to the sample points **u**$_\alpha$.

To determine the class or category (Duda, 1973) to which a generic pixel vector **X**(**u)** belongs, it is strictly the conditional probabilities:

$P(\omega_i \,|\, \mathbf{X}(\mathbf{u}))$ i =1,……..,M

that are of interest. This probability gives the likelihood that the class ω_i prevails for the pixel at the position **u.**

Maximum Likelihood algorithm assigns each pixel to the class whose 'a posterior' probability is maximised:

*assign the position **u** at the class* ω_i ☐ $P(\omega_i \,|\, \mathbf{X}(\mathbf{u})) = \max_\omega P(\omega \,|\, \mathbf{X}(\mathbf{u}))$

$P(\omega_{i|}\, \mathbf{X}(\mathbf{u}))$ are unknown, but suppose we have sufficient training data for each class that can be used to estimate a "spectral" probability density function $P(X(u)\,|\,\omega_i)$ for a cover type, i.e. the chance of finding a pixel from class ω_i , say, at the position **X**(**u).** $P(\omega_{i|}\, \mathbf{X}(\mathbf{u}))$ is then obtained by applying the Bayes rule:

$$P(\omega_i \mid \mathbf{X}(\mathbf{u})) = \frac{P(\mathbf{X}(\mathbf{u}) | \omega_i) P(\omega_i)}{P(\mathbf{X}(\mathbf{u}))}$$

where $P(\omega_i | \mathbf{X}(\mathbf{u}))$ represents the posterior probability of a pixel with data vector **X**(**u)** to belong to class i, $P(\mathbf{X}(\mathbf{u}))$ is the unconditional probability that the pixel **u** occurs in the image, $P(\omega_i)$ is the 'a priori' probability of the class ω_i. It is assumed that spectral probability density function is of the form of multivariate normal model.

Feature Analyst uses an inductive learning based approach to object-recognition and feature extraction. The Feature Analyst workflow (VLS, 2004) includes the following steps:

1. User digitalizes several examples of the feature to collect (training data set). Feature Analyst is an approach similar to traditional supervised classifier, because the user needs to supply ground truth sites of each feature of interest. However, the main difference is that it uses these sites to find areas in the image that are similar, not only on the basis of spectral signature but also of geometrical shape parameters. Typically, to start only a few examples are required.

2. User selects the feature type, which automatically sets all of the learning parameters behind the scene. The contextual classifier can be adjusted based on the feature to be extracted. It is possible to define the spatial context for the feature of interest and it is important to use an input pattern that captures the essence of the feature you are trying to extract. In our case study the geometrical pattern applied is represented in figure 1 because it would work well for extracting land cover features on 10 meter imagery (VLS, 2004). The input representation describes the pattern of pixels considered around a target pixel to classify it.

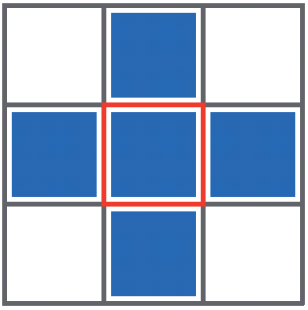


Figure 1. Pattern recognition in supervised classification of water melon field.

The key is to use an input representation that captures the essential spatial structure of the feature of interest. In general, the more complex the pattern is (this relates also to image resolution) the more input pixels are required.

The algorithm was used by the following supplementary settings:

- the imagery had four available bands and all of them were used;
- objects with less than 5 pixels were automatically aggregated with the most appropriate neighbouring object;
- rotated instances were included so that classification of similar objects oriented differently was allowed.

3. User extracts feature.

4. Results analysis and, if required, the user provides "positive" and "negative" examples to remove clutter and improve classification. This tool allows the user to define new examples of "correct," "incorrect," and "missed" areas so to produce a new output more refined than the previous one. This process can be repeated as many times as necessary. Clutter is the most common form of error in feature extraction. The objective of clutter mitigation is to remove false positives. Thus, the learning task is to distinguish between false positives and correctly identified positives. The user generates a training set by labelling the positive features from the previous classification as either positive or false positive. The trained learner then classifies only the positive instances from the previous pass. The false positives from the previous pass are considered correct in clutter mitigation and are thus masked out.

The classification is improved in successive passes, where each new pass is designed to remove one form of error from the results of the previous pass.

III – The case study

The study site is located along the coast of the Ionian Sea (south Italy), in an area widely cropped with water-melon. An image, dated July 2007, from SPOT5, with a spatial resolution of ten meters and four bands in visible and near/medium infrared spectrum, has been used.

Firstly, a data set of ground truths was collected on the scene, that was, then, split into a training data set, to recognise pattern on the study area, and a test data set, to validate the land cover maps.

Two supervised classifiers were compared: standard "Maximum Likelihood" (ML) and Feature Analyst (FA), both implemented in ERDAS software, using the same training and validation data sets.

IV – Results and discussion

Figure 2 shows the SPOT5 image of the investigated scene obtained by relating the bands 3, 2, 1 to the red green and blue channel (RGB) respectively. The data set of ground truths was obtained through a visual inspection of the fields by an expert and was split into the training data set and the validation data set. The validation data, within the target cover class, were selected by randomly drawing a given proportion (0.3) of the overall class occurrence. The same data sets, training and validation, have been used to produce and validate the land cover maps, obtained by applying the two classification techniques: traditional 'Maximum Likelihood' and combined approach performed by Feature Analyst.

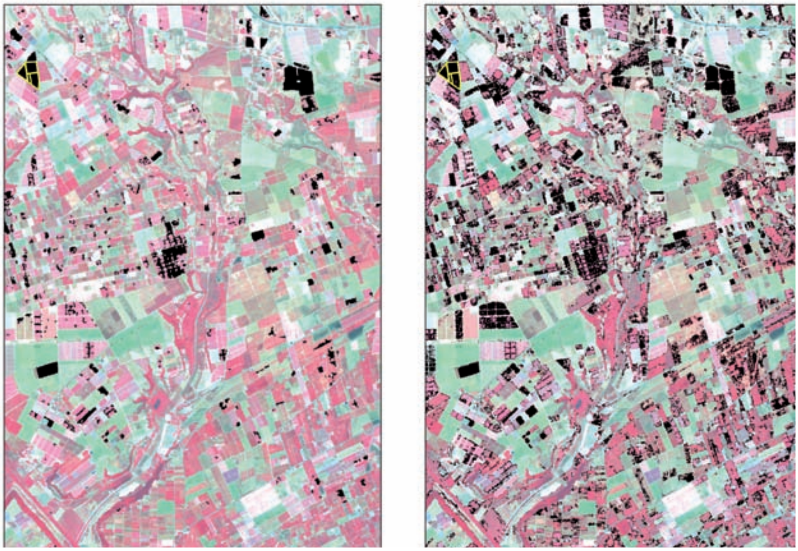
Figure 2. Image from SPOT5 satellite in combination of colours 321RGB.

Figure 3 and 4 show two sub-areas of the whole classified map that are of particular interest because including the two experimental farms (highlighted in yellow) in the AQUATER research project coordinated by CRA-SCA. In figures 3a and 3b there are shown the localizations of the water melon fields (black coloured), obtained by applying the object recognition tecnique and the traditional Maximum Likelihood classifier, respectively, overposed on the original SPOT5 image (fig.2). In the ML classifier the map was obtained by setting a probability threshold equal to 50% value, which allows to determine those pixels that are most likely to be incorrectly classified, so that they can be masked. However, ML has no possibility to improve classification by successive steps of a hierarchical feature extraction. The quality of the classification might be improved by applying a "majority" filter which substitutes the mode value within a moving window.

On the contrary in the FA only two post processing steps were necessary to improve classification, in order to distinguish between false positive and correctly identify positives on the basis of expert knowledge. For example, the area near the studied farm (highlighted with a blue circle in fig.4) used to orchard, was incorrectly identified as water melon also by FA at the first step. But after application of the "remove clutter" tool, it was correctly classified already at the second step. Using ML classifier it wasn't possible to correct this error (even by applying the threshold), because this area has a spectral signature very similar to water melon.

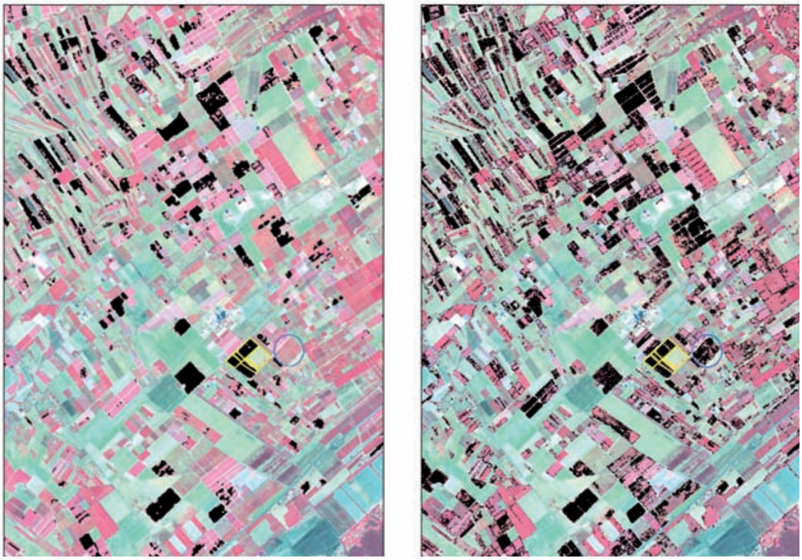
In order to compare the overall behaviour of the two classifiers, we calculated the overall accuracy obtaining 78% and 90% for ML and FA, respectively.

The better results in land cover class discrimination by FA were partly expected because FA approach utilises both (spectral and spatial) types of information. Differently, ML tecnique, using only spectral information per pixel, produces a map with several isolated and misclassified pixels and then a quite noisy land cover map. Therefore, the land discrimination by ML looks quite confused, whereas the FA classification map extracts more compact and homogeneous patterns corresponding to the fields cropped with water melon.



(a) (b)

Figure 3. Zoom details of the maps of water melon land cover (represented in black) obtained by applying the ERDAS Feature Analyst algorithm (a) and the traditional Maximum Likelihood classifier (b).



(a) (b)

Figure 4. Zoom details of the maps of water melon land cover (represented in black) obtained by applying the ERDAS Feature Analyst algorithm (a) and the traditional Maximum Likelihood classifier (b).

The ML map was deemed to overestimate the target class according to the judgement of an expert. The better performance of FA classifier compared with the ML one was evaluated not only on the basis of an objective statistical test, but also of the expert knowledge of the study area. This stresses the role of the expert knowledge in improving the classification by manually adding new polygons to initial training data set. However, this can also be assumed as a drawback of FA classifier, revealing the mostly heuristic character of the approach.

V – Conclusion

The resulting maps, obtained by applying the two classification methodologies, traditional Maximum Likelihood and object oriented tecnique, have been validated and the goodness of classification, evaluated by calculating overall accuracy, showed an increasing of 12%. The statistical comparison between the two approaches then shows Feature Analyst to be more accurate in water-melon pattern recognition, even if testing the method in more and different spatial contexts is needed, before declaring its better performance.

However, also other researchers, using object-oriented classification, have obtained similar results, such as Wang *et al.* (2004) that used IKONOS imagery to classify seven land cover types and obtained an overall accuracy of 89% for pixel level spectral classification and of 91% for spectral and object oriented classification.

The FA classifier has several advantages which proves it to be very promising in high resolution image classification. Those include:

- FA uses a spatial component of imagery which is the key when extracting features from high resolution imagery. In this way it is possible to extract more detailed vegetation information from high resolution imagery than what has been possible by using traditional classifiers working per pixel.

- The hierarchical learning of FA makes it easier to reach better results in classification, because it allows the user to select "correct", "uncorrect" and "missed" areas in multiple steps.

Nevertheless, we think that the main drawback of this approach is the difficulty in defining the input pattern which captures most spatial structure of the feature being classified. This representation may be relatively easy for an isolated object, but may be more complex for a cropped field. Quite likely, there are other approaches, more efficient in homogeneous crop fields recognition, that integrate spatial and spectral information to classify high resolution imagery, such as the methodology that combines geostatistics with bayesian spectral approach (Goovaerts 2002, Fiorentino et al 2006).

Another disadvantage of FA relies on the ability of the user to introduce additional information into the initial training data set and then on the empirical nature of this approach.

To classify medium resolution imagery as Landsat TM, quite likely per pixel approach remains the better, whereas FA may perform better when we need more detailed information as individual plants and trees.

Acknowledgments

This work was supported by the Italian Ministry of Agriculture, Food and Forestry Policies (AQUATER project, contract nr. 209/7303/05).

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Assessing agro-hydrological models to schedule irrigation for crops of Mediterranean environment

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Abstract. Despite in Mediterranean environment water resources for irrigation are limited, water management for agriculture is often practiced ignoring principles of environmental sustainability.
Objective of the paper is to asses the possibility of using agro-hydrological models for irrigation scheduling, in order to optimize the water use efficiency.
The results of a comparison between the numerical SWAP model and the functional model proposed by FAO to estimate water requirements in two typical arboreal Mediterranean Crops (grapevine and olive) are showed.
In the initial phase of the research, involving both irrigation seasons 2005 and 2006, after a preliminary analysis of soil hydraulic and biophysical plant parameters, two intensive field measurements campaigns were carried out to measure the soil water content at different depths, to proceed to the validation of both the models.
Validation of the model was carried out by means of the comparison between measured and predicted soil water content.
Finally different irrigation scheduling options were examined, in order to compare the scheduled irrigation times with those planned by the farmers.
The results of investigations evidenced that FAO model simulates reliably the values of average water content of the soil profile, even if a certain overestimation of evapotranspiration fluxes can be observed with the FAO 56 model compared with SWAP. Consequently, the FAO model anticipates the starting date for irrigation obtained with SWAP, but, in terms of seasonal water requirements, the estimates determined by the two modes did not result significantly different.

Keywords. SWAP – FAO – Scheduling irrigation.

Evaluation de modèles agro-hydrologiques pour la programmation de l'irrigation des cultures en environnement méditerranéen

Résumé. *Malgré la rareté des ressources hydriques pour l'irrigation dans la zone méditerranéenne, la gestion de l'eau dans l'agriculture est souvent pratiquée tout en ignorant les principes de durabilité de l'environnement. L'objectif de cet article est d'évaluer la possibilité d'utiliser des modèles agro-hydrologiques pour la programmation de l'irrigation, afin d'optimiser l'efficience de l'utilisation de l'eau. Les résultats de la comparaison du modèle SWAP avec le modèle proposé par la FAO pour évaluer les besoins en eau, sont présentés pour deux cultures arboricoles (vigne et olive) typiques de la Méditerranée. En phase initiale de la recherche où les deux saisons d'irrigation 2005 et 2006 ont été considérées, deux sessions intensives de mesure de l'humidité du sol à différentes profondeurs ont été effectuées, tenant compte d'une analyse préliminaire des paramètres hydrauliques du sol et biophysiques de la plante, afin de valider les deux modèles. La validation des modèles a été effectuée en comparant la teneur en eau eau du sol mesurée et prédite. Enfin, différentes options pour la programmation de l'irrigation ont été examinées, afin de comparer les dates d'irrigation conseillées par le modèle avec celles envisagées par les agriculteurs. Les résultats ont montré que le modèle de la FAO simule bien les valeurs de la teneur moyenne d'eau du profil du sol, même si une certaine surestimation des flux d'évapotranspiration a été observée par rapport à SWAP. Par conséquent, le modèle de la FAO 56 a anticipé la date de partance de l'irrigation par rapport à SWAP, mais, du point de vue des besoins saisonniers d'eau, les estimations déterminées par les deux modèles ne diffèrent pas significativement.*

Mots clés. *SWAP – FAO – Programmation de l'irrigation.*

I – Introduction

The question related to the efficient water use in irrigated areas has a fundamental importance in Mediterranean regions, where the water scarcity and the semi-arid climate often cause fragility and severe damages in the agro-ecosystems. In the last two decades, this evidence has induced the development of several models to simulate the mass and energy exchange processes in the Soil-Plant-Atmosphere system (SPA) (Feddes *et al.*, 1978; Bastiaanssen *et al.*, 2007). Some of these models are physically based and allow to simulate in great detail all the components of the water and energy balance, including crop growth, irrigation and solute transport (van Dam *et al.*, 1997; Vanclooster *et al.*, 1994; Ragab, 2002). Others models using simplified schematizations, focusing on the possibility to simulate only the main terms of soil water balance allowing to schedule irrigations, have also been proposed.

Objective of the work is to assess the suitability of two different agro-hydrological models for irrigation scheduling. In particular a comparison between the physically based SWAP model (Soil-Water-Plant-Atmosphere, van Dam *et al.*, 1997) and the simplified FAO procedure (Allen *et al.*, 1998) to estimate water requirements for two typical arboreal Mediterranean crops (grapevine and olive) is showed.

For the study area, located in the south-western cost of Sicily, agro-hydrological and micro–climatic parameters, were monitored during two irrigation seasons. A temporal series of measured soil water content at different depth and observed irrigation volumes were used to validate both the models.

II – Study area description

Investigation was carried out during irrigation seasons 2005 and 2006 in an experimental farm (Figure 1) near Castelvetrano (TP), where land use is characterized by arboreal crops (mainly olives, grapes and citrus) and soil textural class, according to USDA classification, is silty clay loam.

During the considered years the most important micro–climatic parameters, such us precipitation, wind speed and direction, global radiation and air humidity were monitored. Furthermore agro–hydrological and physiological parameters were observed in two experimental plots (a vineyard and an olive grove).

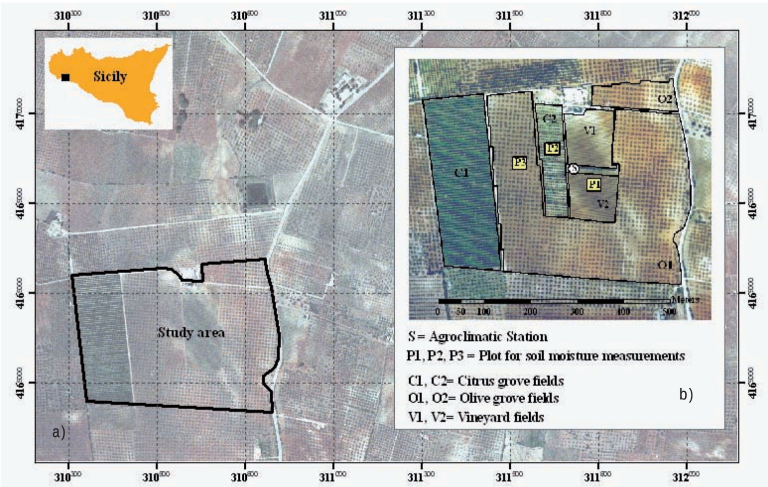

Figure 1. Geografic location with a) subset of study area and b) the description of landuse and field facilities.

III – Materials and methods

1. Soil hydraulic characterization

Traditional laboratory methods were used to evaluate soil hydraulic properties of undisturbed soil cores representative of four different depths of a soil profile. Soil texture, bulk density, hydraulic conductivity of saturated and near saturated soil conditions, as well as some points of the water retention curve in the potential range between –5 and -15300 cm were deduced for each depth. The van Genuchten-Mualem parameters of soil hydraulic characteristics, showed in Table 1, were then deduced by using the RETC code (van Genuchten *et al.* 1991) to the experimental values θ_i-h_i and k_i-h_i, being θ_i-h_i the volumetric soil water content and the matric potential at the generic depth, and k_i the soil hydraulic conductivity measured at the same depth.

Table 1. van Genuchten-Mualem parameters for the investigated soil layers (θ_r=residual water content, θ_s= saturated water content, K_0=saturated hydraulic conductivity; α, n and λ= fitting parameters)

Parameters	Layers			
	1	2	3	4
	0-20 cm	20-40 cm	40-60 cm	60-80 cm
θ_r	0.030	0.139	0.103	0.119
θ_s	0.400	0.444	0.400	0.410
K_0 [cm/day]	10.00	3.00	30.00	0.24
α	0.0104	0.0118	0.0159	0.046
n	1.838	2.128	1.548	1.487
λ	0.5	0.5	0.5	0.5

2. Soil moisture content measurements

Temporal variability of soil water contents in two different plots were measured, at several depths, using Diviner 2000 Sentek capacitance sensor. The probe containing the sensor can measure the soil water content at different depth, when inserted in an preliminarily installed access tube. In the vineyard three access tubes were installed at 10, 30 and 50 cm from the source point where the emitter was located, with an axis-symmetric scheme, as shown in Figure 2. In the olive plot, where irrigation water is supplied with a micro-sprinkler system, a single access tube was installed at the border of wetted zone.

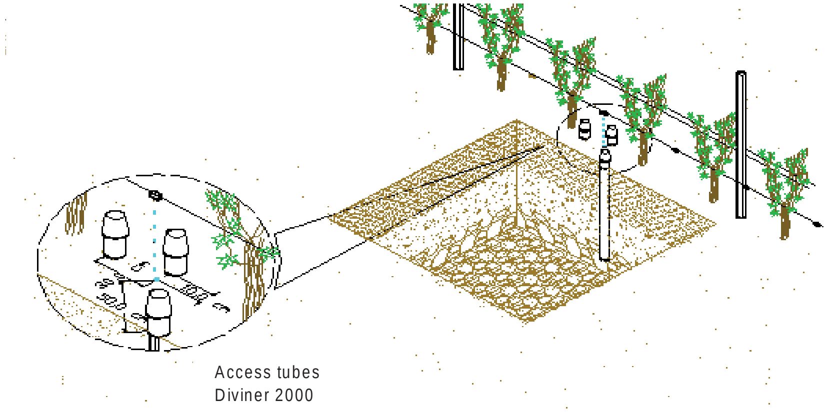

Figure 2. Set-up of DIVINER access tubes in the vineyard.

IV – Agro-hydrological models

SWAP model aims to simulate all the water processes in the soil-plant-atmosphere continuum. The model includes detailed sub-models for soil water flow, soil evaporation, crop growth, irrigation practice and can operate on fixed temporal interval from daily to seasonal cycle.

The Bucket model "FAO 56" solves the water balance equation in terms of soil water depletion. The actual water fluxes terms are obtained from the potential fluxes, using the approach based on a "dual crop K_c coefficients" taking into account the crop water stress by means of a transpiration reduction coefficient, K_s, and a evaporation reduction coefficient, K_e.

1. SWAP Basic equations

SWAP (Soil-Water-Atmosphere-Plant) is a one-dimensional physically based model for water flow in saturated and unsaturated soil (Kroes *et al.*, 2000) and simulates the vertical soil water flow and solute transport in close interaction with crop growth. Richards' equation (Richards, 1931), including root water extraction, is applied to compute transient soil water flow:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]+S(h) \tag{1}$$

under specified upper and lower boundary conditions. In eq. (1), z (cm) is the vertical coordinate, assumed positive upwards, t (d) is time, C (cm^{-1}) is the differential moisture capacity, K(h) (cm d^{-1}) is the soil hydraulic conductivity function and S (d^{-1}) is the root uptake term that, for uniform root distribution, is defined by the following equations:

$$S(h) = \alpha_w(h)\frac{T_p}{|z_r|} \tag{2}$$

$$T_p = K_c \times ET_0\left[1-\exp(-K_{gr}LAI)\right] \tag{3}$$

in which T_p (cm d^{-1}) is the potential transpiration, z_r (cm) the rooting depth, α_w (-) is a h-dependant reduction factor which accounts for water deficit and oxygen stress (Feddes *et al.*, 1978), K_c (-) is the crop coefficient, ET_0 (cm d^{-1}) is the reference evapotranspiration, K_{gr} (-) is an extinction coefficient for global solar radiation and finally LAI (-) is the leaf area index.

The numerical solution of eqs. (1), (2) and (3) is possible when initial, upper and lower boundary conditions and the soil hydraulic properties, i.e. the soil water retention curve, $\theta(h)$, and the soil hydraulic conductivity function, K(h), are specified; detailed field and/or laboratory investigations are therefore needed.

Different options are available in SWAP to schedule irrigation (i.e. determining irrigation times and water requirements); for the purpose of this study, only the irrigation time parameter, defined as an allowable depletion fraction, f, of readily available water in the root zone, was defined:

$$f = \frac{\sum_{i=1}^{n} \left(\theta_{fc_i} - \theta_{lim_i}\right)_i}{\sum_{i=1}^{n} \left(\theta_{fc_i} - \theta_{wp_i}\right)_i} \qquad (4)$$

in which θ_{lim} is the soil water content below which it is necessary to irrigate, θ_{fc} and θ_{wp} are the soil water content at field capacity and at wilting point respectively, and n is the number of layers of homogeneous soil, as defined in the model.

2. The FAO 56 procedure

In the FAO 56 procedure the root zone depletion is calculated daily, with a water balance model based on a simple tipping Bucket approach:

$$D_{r,i} = D_{r,i-1} - P_i + ET_i + DP_i \qquad (5)$$

where $D_{r,i}$ (mm) and $D_{r,i-1}$ (mm) are the root zone depletion at the end of day i and i-1 respectively, P_i (mm) is the precipitation, ET_i (mm) is the actual evapotranspiration and DP_i (mm) is the deep percolation of water moving out of the root zone.

In absence of water stress (potential condition), the actual evapotranspiration ET is obtained multiplying the crop coefficient K_c (-) to the Penman-Monteith reference evapotranspiration rate, ET_0, (Allen *et al.*, 1998). FAO 56 paper proposed a new “dual crop coefficients approach” that splits the K_c factor in two separate coefficients, a basal crop coefficient, K_{cb}, for transpiration and a soil evaporation coefficient, K_e. The actual evapotranspiration ET can therefore be evaluated as:

$$ET = (K_{cb} + K_e)\ ET_0 \qquad (6)$$

When water represents a limiting conditions, the coefficients of Eq. (6) are multiplied by a reduction factors, K_s, that can be variable between 0 and 1; the last value have to be used when soil water storage in the root zone has been depleted under a threshold value (mm), RAW, corresponding to the readily available water.

The reduction coefficients, K_s, is expressed by:

$$K_s = \frac{TAW - D_{r,i}}{TAW - RAW} \qquad (7)$$

where TAW (mm) is the total available water (i.e. water stored in the root zone between field capacity and permanent wilting point), $D_{r,i}$ (mm) the root zone depletion, and RAW (mm) is the readily available water. RAW values can be obtained multiplying the TAW values by a depletion coefficient, p, taking into account the crop water stress resistance.

A completed description to calculate TAW, RAW and p, for numerous crops, can be found in FAO 56 paper (Allen *et al.*, 1998).

The irrigation times in the FAO 56 procedure is based on the management allowed depletion, MAD, of the available water that can be stored in the root zone, obtained as

$$MAD = \frac{\left(\theta_{fc} - \theta_{lim}\right)}{\left(\theta_{fc} - \theta_{wp}\right)} \qquad (8)$$

in which θ_{lim} is the average soil water content below which it is time to irrigate.

When irrigation is scheduled in absence of crop water stress, the MAD parameter can be assumed equal to the p coefficient.

V – Results and discussions

In order to evaluate the values of the irrigation scheduling parameters, a preliminary simulation was carried out on both vineyard and olive grove plots, by using, as input, the observed irrigation times and water volumes. Table 2a,b, summarizes the values of the main measured parameters used in the simulations. The values of other parameters necessary to run the simulations have been estimated according to the procedures suggested by the FAO 56 paper (Allen *et al.*, 1998). Since SWAP uses the "single K_c" schematization, the values of crop coefficients, showed in Table 2.b as deduced from FAO 56 paper, differs respect to the "dual approach" values indicated in Table 2.a. The values of soil moisture at field capacity, θ_{fc}, and at wilting point, $\theta_{wp,}$ used in the FAO 56 simulations are obtained averaging the correspondent values measured in the four different soil layers, as considered in the SWAP simulations. For both the irrigation seasons, the initial soil water content assumed in the simulations was fixed according to the corresponding values measured in the soil profile.

Table 2a. Main parameters used in the FAO 56 simulations (in parenthesis are indicated the values used for 2006).

PARAMETERS		Grapevine	Olive
θ_{fc}, Soil moisture at field capacity [cm^3/cm^3]		0.42	0.42
$\theta_{wp,}$ Soil moisture at wilting point [cm^3/cm^3]		0.13	0.13
TAW, Total Available Water [mm/m]		187.6	187.6
Development stage and main crop parameters	$DOY_{plant.}$ K_{cb}	105 (116), 0.15	105 (95), 0.65
	$DOY_{dev.}$ K_{cb}	110 (120), 0.15	105 (95), 0.65
	$DOY_{mid.}$ K_{cb}	160 (162), 0.65	105 (95), 0.65
	$DOY_{late.}$ K_{cb}	247 (249), 0.65	258 (258), 0.65
	$DOY_{harv.}$ K_{cb}	258 (258), 0.40	258(258), 0.65

Table 2b. Main parameters used in the SWAP simulations (in parenthesis are indicated the values used for 2006).

PARAMETERS		Grapevine	Olive
Critical pressure heads (cm)			
h_2 (h below which optimum water uptake starts in the root zone)		-25	-25
h_{3h} (h below which optimum water uptake reduction starts in the root zone in case of high atmospheric demand)		-750	-1500
h_{3l} (h below which optimum water uptake reduction starts in the root zone in case of low atmospheric demand)		-1500	-1500
h_4 (wilting point, no water uptake at lower pressure heads)		-10000	-16000
k_{gr} (extinction coefficient) (-)		0.45	0.50
Development stage and main crop parameters	$DOY_{plant.}$ K_c	105 (116), 0.30	105 (95), 0.7
	$DOY_{dev.}$ K_c	110 (120), 0.30	105 (95), 0.7
	$DOY_{mid.}$ K_c	160 (162), 0.75	105 (95), 0.7
	$DOY_{late.}$ K_c	247 (249), 0.75	258 (258), 0.7
	$DOY_{harv.}$ K_c	258 (258), 0.60	258(258), 0.7

1. Models validation and assessment of scheduling parameters

For the considered irrigation seasons Figure 3 a,b shows the simulated daily average soil water content in the root zone, obtained for the vineyard field, and the volumes of each water supply. The average water contents measured in the soil profile (white dots) as well as the rainfalls and irrigation amounts are also plotted.

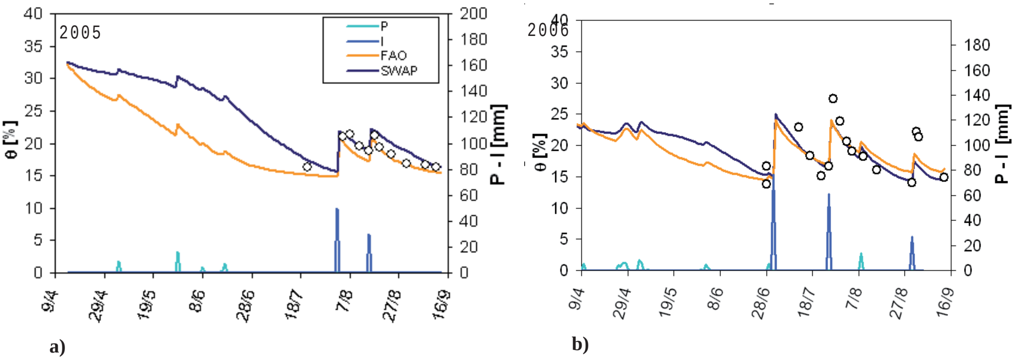

Figure 3. a,b. Measured (white dots) and simulated (continuous lines) average soil water content in the root zone for grapevine. In the secondary axes the irrigation volumes and the rainfall amounts for the two considered irrigation seasons are plotted.

As can be observed in the figure both the model are able to predict quite well the values of average soil water contents. Differences between the two models can be observed mainly at the beginning of the 2005 simulation period, during which the simulated values of soil water content obtained with the FAO 56 model are lower than those obtained with the SWAP model. This behavior can be justified by higher evapotranspiration rates simulated from the FAO 56 model (Agnese *et al.*, 2008). Unfortunately, the absence of measured water content values during the initial phase of simulation, does not allow to verify which model performs better.

Similar results are obtained for the olive crop, as illustrated in figure 4 a,b for both the simulation years.

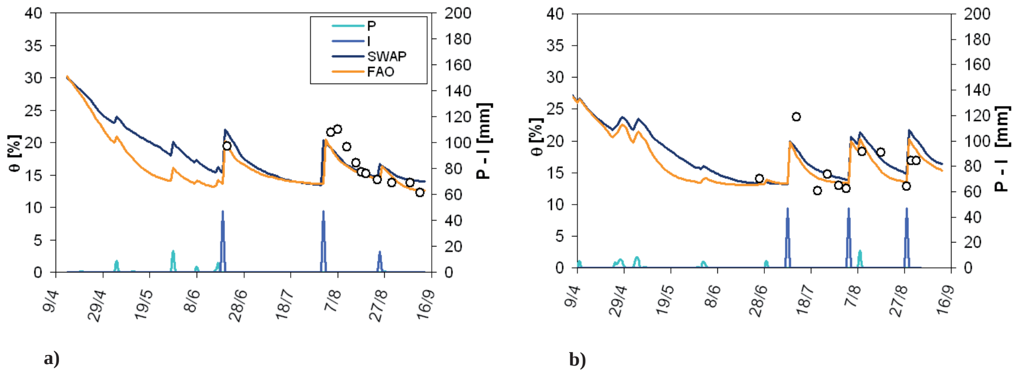

Figure 4. a,b. Measured (white dots) and simulated (continuous lines) average soil water content in the root zone for olive crops. In the secondary axes the irrigation volumes and the rainfall amounts for the two considered irrigation seasons are showed.

The outputs of the two models allowed to assess the farmer strategy for irrigation. Ordinary scheduling parameters f and MAD were therefore calculated as the average values obtained during the two years. In particular the values of f and MAD parameters corresponding to each irrigation practiced by the farmer were evaluated according to equations (4) and (6), as results of the simulations carried out by using SWAP and FAO 56 model respectively. Table 3 shows the values of f and MAD obtained for both the considered crops and irrigation seasons as well as the calculated average values. Lately the average values indicated in Table 3 have been used as input parameters in further simulations, in order to evaluate the simulated irrigation times, that were then compared to the observed ones.

Table 3. Values of f and MAD obtained for both vineyard and olive grove for each irrigation practised by the farmer (average values in bold characters).

Date	Irrig.	Date	DOY	*f*	*MAD*
vinegrape	1	03-08-05	215	0.48	0.90
	2	16-08-05	228	0.34	0.72
	3	02-07-06	183	0.50	0.92
	4	29-07-06	207	0.47	0.79
	5	31-08-06	243	0.59	0.85
		average		**0.48**	**0.83**
Olive crops	1	20-06-05	171	0.45	0.96
	2	02-08-05	213	0.54	0.96
	3	26-08-05	237	0.50	0.92
	4	09-07-06	190	0.55	0.98
	5	04-08-06	216	0.53	0.98
	6	29-08-06	241	0.50	0.97
		average		**0.51**	**0.96**

2. Results of model application for irrigation scheduling

The models were run in order to obtain the irrigation time, whereas the water supply was fixed to 50 mm, corresponding approximately to the average depth provided by the farmer. The scheduling MAD and f parameters were fixed equal to the average values of table 3.

Figure 5 a,b shows the evolution of soil water content during the irrigation seasons for the vineyeard, obtained by FAO 56 and SWAP models. As can be observed in figure 5 a,b, for both the seasons, FAO 56 model generally anticipates the irrigation times respect to SWAP. The observed circumstance, as described in the previous paragraph, is essentially due to the higher evapotranspiration fluxes simulated by the FAO 56 model during the initial phase of simulations. Similar results were obtained for the Olive grove, as can be observed in figure 5 c,d.

Table 4 shows, for both the considered crops the amount of the water supplied according with the farmer strategy as well as those obtained with the simulations. Despite some differences between the simulated irrigation time and in terms of seasonal water requirements, the corresponding values obtained with the two models are not significantly different.

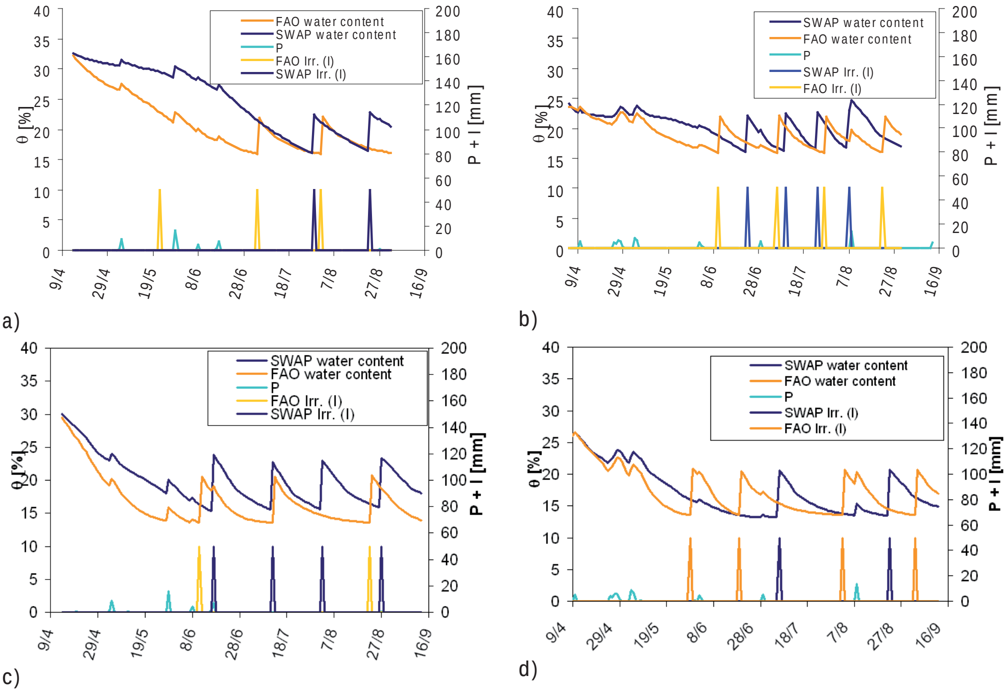

Figure 5. Comparison between simulated SWAP and FAO 56 daily soil water contents in the root zone and irrigation volumes during irrigation season 2005 and 2006 for the vineyard (a,b) and olive grove (c,d).

IV – Conclusion

First of all the time scheduling parameters f and MAD were evaluated as result of models' validation, considering fixed irrigations actually observed in the field.

Then the FAO 56 and SWAP soil water balance outputs i.e. the scheduling time and seasonal water requirements are compared.

FAO 56 model simulates reliable values of average water content of soil profile when a modification of stress function K_s is used, even if, compared with SWAP, a certain overestimation of evapotranspiration fluxes is observed.

Consequently the FAO 56 model anticipated the starting irrigation time evaluated with SWAP even if, in terms of seasonal water requirements, the estimates obtained by the two modes does not evidence significant differences.

Table 4. Observed irrigation volumes and times for vineyard and olive grove in both the irrigation seasons and scheduled values obtained with SWAP and FAO 56.

			Season 2005					Season 2006				
		Irrig.	**I**	**II**	**III**	**IV**	**TOT**	**I**	**II**	**III**	**IV**	**TOT**
Vineyard	**Ordinary Irrigation**	**DOY**	215	228				183	207	243		
		Irrig. depth [mm]	50	30			80	77	61	27		165
	SWAP Scheduled Irrigation	**DOY**	211	236				175	192	206	220	
		Irrig. depth [mm]	50	50			100	50	50	50	50	200
	FAO 56 Scheduled Irrigation	**DOY**	186	214				162	188	209	235	
		Irrig. depth [mm]	50	50			100	50	50	50	50	200
Olive grove	**Ordinary Irrigation**	**DOY**	171	215				190	216	241		
		Irrig. depth [mm]	47	50			97	47	47	47		141
	SWAP Scheduled Irrigation	**DOY**	169	194	215	240		188	235			
		Irrig. depth [mm]	50	50	50	50	200	50	50			100
	FAO 56 Scheduled Irrigation	**DOY**	163	194	235			150	171	215	246	
		Irrig. depth [mm]	50	50	50		150	50	50	50	50	200

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Field and laboratory studies towards better use of saline irrigation water in NW China

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Abstract. The Shiyang River basin is located in the northwest China and suffers from water scarcity, drought and salinity. The objective of this paper is to evaluate the impact of saline water on crop yield and on the soil water retention capacity under different irrigation treatments and climate conditions. A soil water and solute flow model was calibrated at low salinity level (Tds= 0.8 g l^{-1} identified as C_{08}) and at a moderate salinity level (Tds =5 g l^{-1} identified as C_5). Numerical experiments were carried out on a dry and wet year

The water retention capacity (WRC) was larger for the C_5 treatment for all depths: 121.09 mm for the C_{08} and 249.53 mm for the C_5 , both for the 0 – 100 cm soil layer. The lower WRC for the C_{08} treatment can be explained by higher percentage of macropores and by a partial redistribution for the C_5 treatment of the porosity in smaller and more retentive micropores. Model calibration gave RMSE = 0.06 cm^3 cm^{-3} for the C_{08} and 0.045 cm^3 cm^{-3} for the C_5 For the C_{08} treatment available soil water, AW, in the 0 - 60 cm root zone was lower than WRC for 84 days in 2005 (dry year) and 71 in 2002 (wet year). For the C_5 treatment, instead, AW < WRC for the entire irrigation season of 93 days in all years. The numerical experiments gave higher WUE on the C_{08} treatment than the C_5 treatment for all years considered.

Keywords. Soil salinity – Model simulation – Saline water management.

Etudes de laboratoire et sur le terrain pour une irrigation par eau saline dans la Chine du nord-ouest

Résumé. *Le fleuve Shiyang du Nord-Ouest de la Chine présente une pénurie d'eau ; il est souvent à sec et ses eaux sont salines. Le but de cette étude est d'évaluer l'impact de l'eau saline sur le rendement des cultures et la capacité du sol de retenir l'eau dans de différentes conditions climatiques et stratégies d'irrigation. Un modèle de flux d'eau et d'un soluté a été calibré à un faible niveau de salinité (Tds= 0.8 g l^{-1} identifié par C_{08}) et à un niveau modéré de salinité (Tds =5 g l^{-1} identifié par C_5). Des expérimentations numériques ont été exécutées au cours d'une année sèche et d'une année pluvieuse.*

La capacité du sol de retenir l'eau (WRC) s'est démontrée plus grande sous le traitement C_5 à toutes les profondeurs : 121.09 mm pour le C_{08} et 249.53 mm pour le $C_{5'}$, toutes les deux pour une couche de 0 – 100 cm. Les valeurs plus basses de WRC pour le traitement C_{08} peuvent être expliquées par un pourcentage plus élevé de macropores et pour le traitement C_5 par une redistribution partiele de la porosité dans des micropores plus petits et plus rétenteurs. La calibration du modèle a donné RMSE = 0.06 cm^3 cm^{-3} pour le C_{08} et 0.045 cm^3 cm^{-3} pour le C_5. Pour le traitement C_{08} l'eau disponible dans le sol, AW, dans la zone racinaire 0 - 60 cm était plus basse que la WRC pour 84 jours en 2005 (année sèche) et 71 en 2002 (année pluvieuse). Pour le traitement C_5, par contre, AW < WRC pour toute la saison d'irrigation de 93 jours dans toutes les années. Dans toutes les années étudiées, les expérimentations numériques ont montré que WUE est plus élevé pour le traitement C_{08} que pour le C_5.

Mots-clés. *Salinité du sol – Modèle de simulation – Gestion de l'eau saline.*

I – Introduction

Human water consumption effectively exacerbates the impact of drought. A combination of drought and human activity (such as overcultivation, overgrazing, deforestation and salinity) may lead to desertification of vulnerable areas, causing soil and bioproductive resources to become degraded. In this situation drought and salinity can be considered as related phenomena and represent two of the most important environmental stresses influencing the productivity of agricultural systems around the world.

Salinity increases in extensive portions of irrigated lands and the area becomes degraded by salinization and waterlogging resulting from over-irrigation and other forms of poor agricultural management (Ghassemi, *et al*., 1995). Saline and sodic water is used in different parts of the world, especially in arid and semi-arid regions. In these areas, scarce water often is of poor quality. Appropriate management of saline-sodic soils in arid and semi-arid regions is one of the key factors to maintain or improve their agricultural productivity and/or avoid soil and environmental degradation.

The inner drainage basins of Northwest of China, such as the Shiyang River basin, are progressively becoming salt affected, mainly because of irrigation with saline groundwater.

The irrigation with saline waters can lead to negative effects on the soil related to the relationship between the concentration of sodium ion, calcium and magnesium ions. The saturation level of sodium and the saline concentration of the soil solution have adverse effects on the physical state of the soil rather than directly on toxicity conditions for crops or interference with the absorption of other ions. They affect the dispersion of clay particles, the soil hydraulic conductivity (Shainberg and Letey, 1983) and aggregate stability in water and the formation of crusts on the soil's surface (Varallyay, 1977a, b; Postiglione et al, 1995).This may led to clogging of soil pores, so that a considerable reduction in soil permeability, soil porosity and soil hydraulic conductivity occurs (Felhendler *et al.*, 1974; Frenkel *et al.*, 1978; Pupisky and Shainberg, 1979; Shainberg *et al.*, 1981a,b; Shainberg and Levy, 1992; Amézketa, 1999). Somani (1991) found that these changes were clearly reflected by changes in a water retention curve (see also Tedeschi *et al.*, 2007). The curve indicated a close relationship between the degree of Na saturation and the water retention of the soil, especially in the pF 2.0-3.0 range. A similar tendency was also observed even when swelling was limited. Water retention increased over the entire range of soil water content. By contrast macropore space decreased. The same author found that the available moisture content increased with ESP, which conflicts with the classical explanation of the water supply of plants in alkali soils and confirmed the findings of Varallyay (1977).

Under saline condition, a reduction in growth is a consequence of several physiological responses, including modifications of ion balance, water status, mineral nutrition, stomatal behaviour, photosynthetic efficiency, and carbon allocation and utilization (Greenway and Munns 1980; Mass, 1986). Photosynthesis is generally reduced in plants growing in saline condition.

Notwithstanding the known negative effects described above, the reduction of good quality water for agricultural use has determined in the Northwest of China an increase in the use of water with high salt concentration. Such waters are traditionally rated as unsuitable for irrigation due to the negative effects on the soil physical and chemical characteristics.

In the NW of China the salinization of the groundwater in the last 20 years has increased with consequences on the crop production and on the soil physical characteristics.

The objective of this paper is to evaluate the impact of the saline water on crop yield and soil properties under different irrigation treatments. The work described includes model calibration, followed by numerical experiments to evaluate irrigation schedules for two different soil conditions, at low salinity level (Tds= 0.8 g l^{-1} identified as C_{08}) and at a moderate salinity level (Tds =5 g l^{-1}

idefitied as C_5). SWAP model has been used. The research was carried out on a silt-loam soil; a melon crop was furrow irrigated with water at concentration of 0.8, and 5 g l^{-1}.

The observed differences in soil hydrological properties for the low respectively moderate salinity conditions may have a significant impact on the temporal variability of soil water content, e.g. on the frequency and duration of soil water content lower than a pre-defined critical threshold. To this end the soil water balance calculations will be performed for a range of different meteorological conditions, in particular when a dry, wet and normal climatic year occurs. The water balance calculations will be used to evaluate the water storage in the profile through the year.

II – Description of the experimental areas

The Shiyang River basin is located in the Hexi Corridor, central-west Gansu province, northwest China. Two sub-basins can be distinguished in the Shiyang River, namely the Wu Wei basin in the south and the Min Qin basin in the north. The Min Qin basin where the research was carried out, borders WuWei basin to the south, Tegger desert to the east and north. The Shiyang River basin has features of arid to semiarid areas, and is a typical region of arid continental inland climate, characterized by low and irregular rainfall, high evaporation and severe drought periods. In fact in the Min Qin Basin, the mean annual precipitation is less than 150mm, but the mean annual evaporation can reach 2650 mm. Since 1940s, the rapid increase of population in Shi Yang River led to an increase of irrigation farmlands, and much grassland has been reclaimed and became farmlands. In the Min Qin Basin, 50% water supply comes mainly from groundwater. Along the Min Qin basin the groundwater salinity is between 2 g l^{-1} and 12 g l^{-1}. In the Min Qin basin two plots with groundwater at two different saline concentrations were selected, i.e. 0.8 g l^{-1} (C_{08}); and 5 g l^{-1} (C_5), to evaluate the effects that the saline water had on soil properties and on crop production. The irrigation system is furrow irrigation and usually the farmers apply an irrigation before sowing to leach the salt from the soil profile using canal water that has a TDS value of 0.8 g l^{-1}. This high quality resource is very scarce and lower quality groundwater must be used throughout the season. The crops grown in the area are horticultural crops, wheat and crops typical for the Chinese habits. Irrigation water gifts are determined by local practice and it was not possible to determine any objective estimation procedure. The irrigation volume is neither calculated on the ET0 basis nor to restore the soil root zone to field capacity.

III – Materials and methods

At the Minqin experimental farm (province of Gansu) in a arid environment an experiment on a melon crop was carried out in 2007. The soil characteristics of the two soils are reported in Table 1. The ions composition of groundwater was for C_{08}: Cl 120 (mg l^{-1}); SO_4 225 (mg l^{-1}); HCO_3 196 (mg l^{-1}); CO_3 absent; Ca 87 (mg l^{-1}); Mg 44 (mg l^{-1}); K 5 (mg l^{-1}); Na 52 (mg l^{-1}); pH 8 and ECw (dS m^{-1}) 1.0. For C_5 the groundwater composition was: Cl 781(mg l^{-1}); SO_4 1334(mg l^{-1}); HCO_3 346 (mg l^{-1}); CO_3 5(mg l^{-1}); Ca 205 (mg l^{-1}); Mg 136 (mg l^{-1}); K 34 (mg l^{-1}); Na 704 (mg l^{-1}); pH 7.5 and ECw (dS m^{-1}) 7.03.

Two local melon varieties were used, they were irrigated by furrow irrigation with a frequency of around 15 days. Local regulations aim at limiting water use, particularly groundwater, by prescribing rather long irrigation intervals. Farmers may determine irrigation water gifts, albeit within limits. Table 2 reports the water volume applied on melon in the 2007.

Table 1. Soil properties for the C_{08} and C_5 soil.

Soil site	Organic matter %	Bulk density g cm^{-3}	Silt %	Clay %	Sand %
C_{08} (0-40 cm)	0.45	1.56	43.08	11.02	45.90
C_{08} (40-60 cm)	0.44	1.52	64.14	17.98	17.89
C_{08} (60-100 cm)	0.39	1.54	54.10	15.19	30.71
C_5 (0-40 cm)	0.70	1.55	53.86	15.81	30.32
C_5 (40-60 cm)	0.54	1.46	69.63	16.72	13.65
C_5 (60-100 cm)	0.46	1.48	58.00	21.47	20.53

An ex-post comparison of water gifts with ET0 (see Table 2) shows that the ratio of irrigation water gift to ET0 changed throughout the season, leading to a variable water stress. This is confirmed by the comparison of water gifts with the actual soil water deficit, evaluated by measuring the soil water content the day before the irrigation and by calculating the water needed to restore a soil layer of 60 cm to field capacity. Table 3 shows that the irrigation water gifts were different from actual soil water deficit.

Undisturbed soil samples were taken to determine the hydrological properties of two soils that have been irrigated by saline water for a long time .

The undisturbed soil samples were taken at 0-20; 45-60 and 80-100 cm depth, in two repetitions to determine the h(θ) and K(h) characteristics in the laboratory according to the procedure suggested by Tamari *et al.*, (1993). The soil water retention characteristics have been parameterized using the relationship proposed by van Genuchten (1980) and by the one proposed by Ross & Smettem (1993). The parameters of the retention functions were obtained by a least squares optimization technique and were used to calculate available water retention capacity at prescribed pressure head values.

Additional disturbed soil samples were taken at 0-20; 20-40; 40-60; 60-80 and 80-100 cm depth to determine the texture, and the organic matter, moreover undisturbed soil samples were taken to determine the bulk density, as reported in Table 1. Moreover on these disturbed soil samples at the depths indicated, the aggregates stability indexes (IASW and IC) were determined on aggregates with diameter between 1 and 2 mm. The results were expressed as reported in Pagliai, 1997.

Table 2. Water volume applied throughout the season. Water volume calculated to recover a layer of 0-60 cm at field capacity by the water content measurements taken throughout the irrigation season.

Treatment								
	θ field measurements (cm^3 cm^{-3}) at 0-60 cm		Irrigation volume calculated to restore root zone to field capacity m^3 ha^{-1}		Irrigation water applied		ET0 Penman Monteith	Ratio of irrigation to ET0
Doy	C_{08}	C_5	C_{08}	C_5	Doy	m^{3}ha^{-1}	m^3 ha^{-1}	%
164	0.265	0.223	177	245	165	510	1068.4	48
179	0.117	0.221	1063	297	180	390	534.3	73
191	0.220	0.221	445	295	192	390	635.2	61
208	0.200	0.203	567	401	209	337.5	805.1	42
225	0.160	0.186	797	507	226	337.5	625.1	54

The Van Genuchten parameters were estimated by using the Hypres pedotransfer procedure (Wösten *et al.*, 1998) implemented in the SWAP model.

After each irrigation disturbed soil samples from the treatments C_{08} and C_5 were taken at depth 0-20; 20-40; 40-60; 60-80 and 80-100 cm to determine the ECe . Before and after each irrigation the soil water content by gravimetric methods was determined at depth 0-20; 20-40; 40-60; 60-80 and 80-100 cm.

The meteorological station gave daily observations of precipitation, temperature relative humidity, net radiation an wind speed. Every two weeks values of leaf area index (LAI) were measured as well as the root depth.

- Model simulations.

The SWAP Model (van Dam *et al.*, 1997) was used. Soil water actual transport extended (SWAP) is a one-dimensional, deterministic model based on the Richard's equation. It was developed by Feddes *et al.* (1978) and later modified by Belmans *et al.* (1983).

To solve the differential equation describing water and solute flow, either boundary conditions at both the top and bottom of the system or one initial condition (e.g. water content) and one boundary condition (e.g. at the bottom) have to be specified. Therefore from the available data at beginning of the crop season, the initial soil conditions were described. We assumed that the soil profile was at saturation after the first irrigation applied on the 27/4/2007 by 1500 m^3 (150mm), such quantity was programmed to leach the salt from the soil profile, therefore the assumption that was at saturation was not so far from the reality. At the bottom of the domain a free drainage boundary condition was prescribed. On both C_{08} and C_5 the crop was melon, sown on 1/5/2007 and harvested on 20/8/2007. Though the irrigation calendar, frequency, quantity and salt concentration of each irrigation, it was possible to reproduce the experimental conditions in the model simulation.

Code	Year	h(θ), K(h)
207_C_{08}	2007	C_{08}
207_C_5	2007	C_5
205_ C_{08}	2005	C_{08}
205_ C_5	2005	C_5
202_ C_{08}	2002	C_{08}
202_ C_5	2002	C_5

After the calibration, numerical experiments were performed. The analysis was conducted for a dry and a wet year, selected on the basis of the value of ET0 between March and September (irrigation season) and the annual rainfall R. The highest value of (ET0-R) identifies the dry year, the lowest value of (ET0-R) the wet year. During the period 2000 – 2007 the wet year was 2002 and the dry year was 2005. For easy reference the numerical experiments described in this paper were coded as above reported in the table.

IV – Results

1. Effects of sodic water on soil physical properties

The data in Table 1 were used to estimate the h(θ) using the Hypres pedotransfer procedure implemented in SWAP (Fig. 1). The same soil properties were also determined in the laboratory on undisturbed soil samples (Fig. 2).

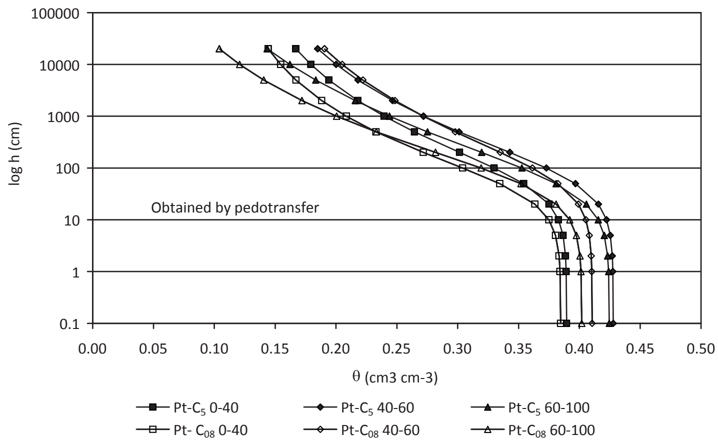

Figure 1. h(θ) for the 2 soil type and different depths estimated by the Hypres pedotransfer implemented in SWAP

Fig 1 shows curves with a very similar trend for the C_{08} and C_5 cases, although the θ value at 100 cm of pressure head is always higher for the C_5 treatment than the C_{08} at each depth. Different is the case of the laboratory analyses (Fig. 2).

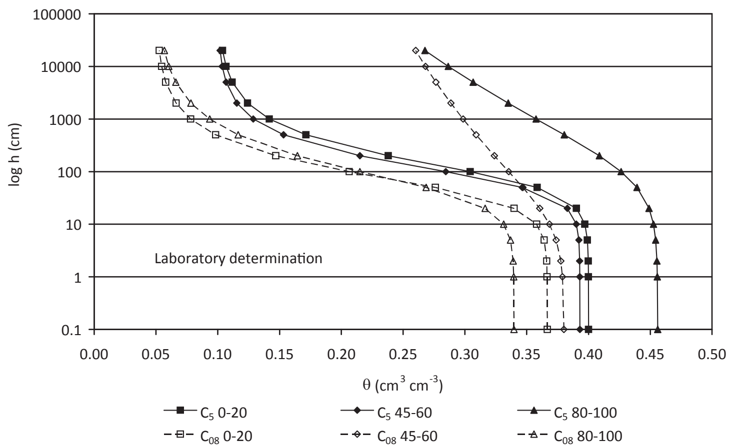

Figure 2. h(θ) for the 2 soil type and different depths estimated by the laboratory analysis on undisturbed soil samples.

Except the depth 45-60 cm of C_{08}, the C_5 has higher value of θ at the pressure head of 100 cm than the C_{08}. The different behaviour of the C_{08} at depth 45-60 cm could depend by a compaction of the layer due to the depth of ploughing, that usually it is around 45-50 cm. Moreover the total porosity for the C_5 is always higher at any layer considered, even for the layer 45-60 cm, that is (0.39) in the case of C_5 and (0.38) for the C_{08}. To evaluate if a change in soil structure, in particular compaction occurred on both soils, at the same depth at which the hydrological parameters were determined, disturbed soil samples were taken through the soil profile to determine the index of aggregates stability in water (IASW %) (Tedeschi *et al.*, 2005) as well as the IC index. The latter differs from IASW because of a correction factor that considers the sand fraction. Figure 3 shows the aggregates stability index (IASW and IC). Both IASW and IC are significantly lower for C_5 at all depths, while at the depth 45-60 cm both IC and IASW are lower for the C_{08}.

This depth it is the same at which the C_{08} h(θ) curve has an anomalous behaviour, with a consequence on the available water in the soil profile. This effect can only be captured by using the laboratory experiments on undisturbed soil cores. The observed differences in the h(θ) curves agree with the results of Somani (1991) and Tedeschi *et al.*, (2007), although smaller because of the lower clay content in the Minqin soil. Quirk and Schofield (1955) suggested: that swelling of clay particles, which increase in clay sodicity, could result in blocking or partial blocking of the conducting pores.

To evaluate the impact of differences in the h(θ), the water retention capacity, WRC, defined as [θ(h=100 cm) - θ(h=10000 cm)] and calculated for a 100 cm deep soil layer and for the C_{08} and C_5 cases. The WRC was larger for the C_5 treatment for all the depths considered, except the 80-100 cm. Overall WRC was 121.09 mm for the C_{08} and 249.53 mm for the C_5 case. The lower WRC for the C_{08} treatment can be explained by higher percentage of macropores and by a partial redistribution for the C_5 treatment of porosity in smaller and more retentive micropores. For the layer 45-60 cm WRC is even lower and it depends on a strong reduction in porosity due to the plough layer, as confirmed by the IASW values.

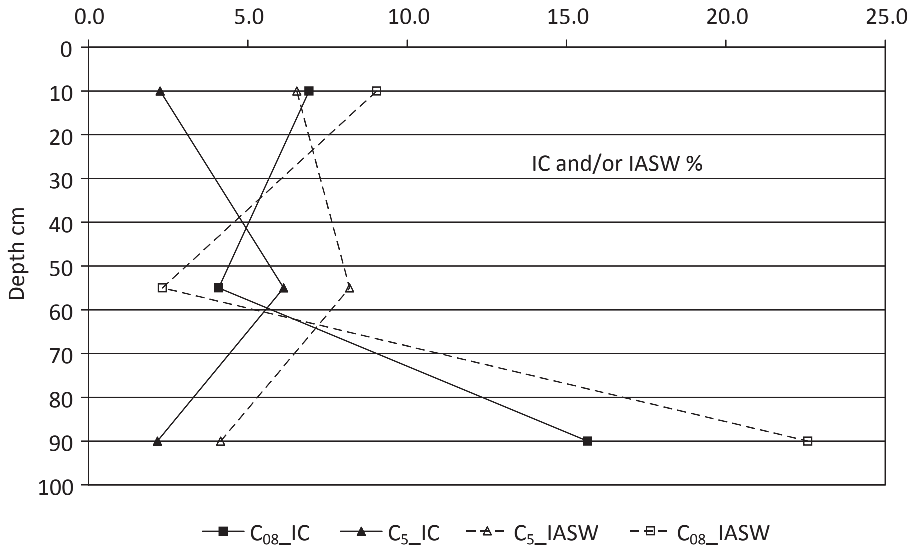

Figure 3. Aggregate stability index expressed as IC (%) and IASW (%) for the soil C_{08} and C_5 at different depth

2. Numerical experiments

A. Model calibration

SWAP calibration was performed on the 2007 experiment. The van Genuchten parameters determined by both the pedotransfer approach and the laboratory experiments were used in different runs to evaluate which one better describes the soil profile and leads to higher accuracy of numerical simulations. The calibration was done by comparing the soil water content measured throughout the crop growth season at different depths and the soil water content calculated with SWAP. The comparison between the results obtained by the simulation and the measured data was done by computing the RMSE (root mean square error). Both the results obtained by the pedotransfer or the laboratory were rather good. The absolute RMSE for the soil profile (100 cm) of the C_{08} treatment shows a value of 0.0586 $cm^3\ cm^{-3}$ obtained with the pedotransfer against the 0.0603 $cm^3\ cm^{-3}$obtained with the laboratory experiments for the same C_{08} treatment. The C_5 treatment gave a value of absolute RMSE of 0.0425$cm^3\ cm^{-3}$ with the pedotransfer and 0.0454$cm^3 cm^{-3}$ with the laboratory experiments.

Overall, the agreement is good, moreover the difference between the use of Van Genuchten parameters estimated by pedotransfer or determined in laboratory are very small. We decide to use the laboratory parameters because are based on real measurements and were able to detect the discontinuity present in the soil profile that the pedotransfer of course cannot due, since it is based on soil texture only.

B. Model application

SWAP can be applied to analyze the effect of saline water by relating crop yield to the ratio of actual to potential transpiration, T_{act} / T_{pot}. This ratio is often used as a measure of moisture availability. Hanks (1974) stated the reduction in crop yield Yact/Ypot , when moisture is the only limiting factor can be estimated as : Yact/Ypot=Tact/Tpot. This concept was based on De Wit (1958), who found a linear relationship between total dry matter and seasonal transpiration for a number of field experiments.

Table 3. Estimation of the potential and actual yield for several scenarios and the water use efficiency for each (kg m^{-3}) moreover the water productivity is reported (lt Kg^{-1})

Scenarios	Yr* (swap output)	Yact = Ypot *Yr Dry matter (kg ha^{-1})	Tact m^3	WUE (kg m^{-3})	Water productivity lt kg^{-1}
207_C_{08}	0.76	3158	1892	1.67	599
207_C_5	0.51	2119	1382	1.53	652
205_C_{08}	0.47	1953	1996	0.98	1022
205_C_5	0.28	1163	1397	0.83	1200
202_C_{08}	0.62	2576	2100	1.23	815
202_C_5	0.40	1662	1513	1.10	910

This relationship will be used to evaluate the water use efficiency (WUE) for all treatments included in our study. In fact SWAP directly gives the results of the following relationship Yr* = Yact/Ypot. To estimate the unknown Y_{pot} for our crop, soil and environmental conditions we assumed that the value of T_{act} / T_{pot} is correct and used the observed actual yield for the non-saline, fully irrigated treatment $C_{08,}$ i.e. 3158 (kg ha^{-1}) for the year 2007. This gives Y_{pot} = 3158 kg ha^{-1} / 0.76 = 4155 kg ha^{-1}. Given the ratio T_{act} / T_{pot} and the value of T_{act} obtained with SWAP for each treatment and case we can then estimate WUE = Y_{act} / T_{act} (Tab. 3).

The model estimate can be compared with observed actual yield for the scenario 207_C_5, i.e 1962 kg ha^{-1}., in good agreement with the *calculated* Y_{act} = 2119.

We have also evaluated the impact of climate conditions (Table 3) using meteorological data collected between 2001 and 2006. The driest and wettest year were selected on the basis of the difference between yearly reference ET and rainfall: the largest the difference, the drier the year. The driest year in this period was 2005 and the wettest 2002. Crop yield was 2576 kg ha^{-1}

respectively 1662 kg ha^{-1} for the C_{08} respectively the C_5 treatment in 2002. In 2005 it was 1953 kg ha^{-1} for C_{08} , respectively 1163 kg ha^{-1} for the C_5. It should be noted that yield in 2007, the reference year for model calibration, was higher than 2002, since 2007 was wetter than 2002.

The Water Use Efficiency (WUE) was calculated for each case considered in Table 3. The C_{08} treatment had a higher WUE than the C_5 treatment in all cases. The WUE for the C_{08} treatment was higher in the wet year than in the dry year (e.g. 1.23 against 0.98; and 1.1 against 0.83).

In 2007 and for the C_{08} treatment the WUE calculated with field data was 1.32 kg m^{-3} against the 1.67 kg m^{-3} obtained with model values, while for the C_5 treatment was 1.0 kg m^{-3} with field data against 1.53 kg m^{-3}. Such results show that model simulations, due to the estimated Y_{pot}, overestimate WUE, but provide useful informations about differences in irrigation treatments and climate conditions and, as such, have significant value for comparative analyses. All results taken together indicate that yield was either water or salt-limited or both under all conditions, since both higher water deficit and salinity of irrigation water led to lower yield and lower WUE.

To evaluate the adequacy of applied irrigation gifts to replenish actual soil water deficit, we have estimated the soil water content of the layer 0-60 cm on the day before the irrigation and then calculated the irrigation volume required to restore the root zone to field capacity (Table 4). For the C_{08} treatment, irrigation water gifts were excessive for the first two irrigations and much lower than needed for the last irrigations. For the C_5 treatment, irrigation water gifts were insufficient throughout the crop growth season.

As regards: 1) the local irrigation management, 2) the water volume to recover the ET0 and 3) an irrigation volume to restore root zone to field capacity; we can conclude that for our study area:

- due to water scarcity resource the full recovery of ET0 is not feasible because it would lead to excessive water use;
- the local farmer management is suitable for the local situation but stress the plant in, a particular and important phenological stage.
- An intermediate irrigation strategy between local farmer management and restoration of the root zone to field capacity, coupled with shorter irrigation intervals, could improve yield and reduce the duration of water stress spells

Table 4. Water volume applied throughout the season. Water volume calculated to recover a layer of 0-60 cm at field capacity by the water content obtained by the SWAP output throughout the irrigation season.

	Treatment							
	θ SWAP (cm^3 cm^{-3}) 0-60 cm		Irrigation volume calculated to restore root zone to field capacity m^3 ha^{-1}		Irrigation water applied		Difference between applied and estimated. m^3 ha^{-1}	
Doy	$C_{0.8}$	C_5	$C_{0.8}$	C_5	Doy	m^3 ha^{-1}	$C_{0.8}$	C_5
164	0.23	0.18	370.30	537.20	165	510	+140	-27.2
179	0.24	0.19	300.30	483.35	180	390	+89.70	-93.35
191	0.23	0.18	403.25	536.70	192	390	-13.25	-146.7
208	0.19	0.15	632.15	703.95	209	337.5	-294.65	-313.95
225	0.18	0.14	702.70	765.20	226	337.5	-365.20	-375.2

C. Occurrence and severity of soil water deficits

The numerical experiments for the dry and wet years were carried out to evaluate the impact of observed differences in soil hydrological properties.

The accumulated duration of soil water deficit, i.e. the number of days with AW < WRC in the root zone (0 to 60 cm), was calculated for all numerical experiments.

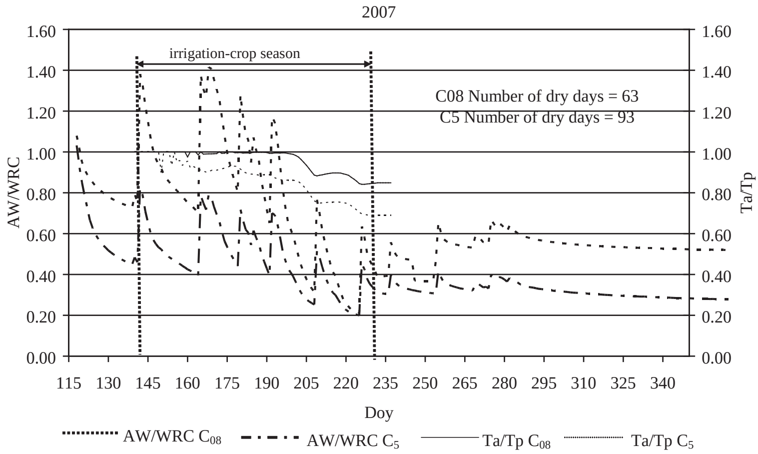

Figure 4. Relation of AW on WRC and the relation Ta/Tp for the 2007, for C_{08} and C_5 treatments, the number of dry days is reported.

For the C_{08} treatment AW < WRC for 84 days in 2005 (dry year) and 71 in 2002 (wet year). For the C_5 treatment, instead, AW < WRC for the entire irrigation season of 93 days in all years. Very evident is the impact of soil water content on actual transpiration, T_a, in response to applied irrigation water. For the C_{08} treatment the applied irrigation water is in excess of actual water deficit and gives T_a close to potential transpiration, T_p, up to the fourth water gift. Conversely, for the C_5 treatment T_a drops below T_p right past the first irrigation already. On the other hand the significant water deficit (AW < WRC) for the C_5 treatment during the entire irrigation season does not lead to extremely large differences in T_a between the C_{08} and C_5 treatments.

V – Conclusion

The results of the laboratory analyses showed higher value of θ at the pressure head of 100 cm for the C_5 treatment than the C_{08}. The different behaviour of the C_{08} soil at depth 45-60 cm could depend by a compaction of the layer due to the depth of the ploughing, that usually it is around 45-50 cm .

The compaction effect on the soil structure was detected also by the IASW index. IASW was significantly lower for C_5 at all depths, while at the depth 45-60 cm IASW was lower for the C_{08}. This depth it is the same at which the C_{08} h(θ) curve has an anomalous behaviour, with a consequence on WRC, which was larger for the C_5 treatment for all depths considered, except the 80-100 cm layer. Overall WRC was 121.09 mm for the C_{08} and 249.53 mm for the C_5 , both for the 0 – 100 cm soil layer. The lower WRC for the C_{08} treatment can be explained by higher percentage of macropores and by a partial redistribution for the C_5 treatment of the porosity in smaller and more retentive micropores. For the layer 45-60 cm WRC is even lower and it depends on a strong reduction in porosity, as above confirmed by IASW.

The model calibration on the 2007 was rather good as showed by the RMSE for the soil profile (100cm) that gave a value of 0.06 cm^3 cm^{-3} for the C_{08} and 0.045 cm^3 cm^{-3} for the C_5 both by using soil hydrological properties determined in the laboratory on undisturbed soil cores.

In 2007, estimated Y_{act} = 2119 kg ha^{-1} for the C_5 treatment was in good agreement with the observed Y_{act}.= 1962 kg ha^{-1} The results on the estimation of the WUE from the simulation data show higher WUE on the C_{08} treatment than the C_5 treatment for all the years considered. In 2007 and for the C_{08} treatment the WUE calculated with field data was 1.32 kg m^{-3} against the 1.67 kg m^{-3} obtained with model values, while for the C_5 treatment was 1.0 kg m^{-3} with field data against 1.53 kg m^{-3}. Such results show that model simulations, due to the estimated Y_{pot}, overestimate WUE, but provide useful informations about differences in irrigation treatments and climate conditions and, as such, have significant value for comparative analyses. All results taken together indicate that yield was either water or salt-limited or both under all conditions, since both higher water deficit and salinity of irrigation water led to lower yield and lower WUE.

Acknowledgements

This research was supported by scientific bilateral cooperation 2004-2007 between CNR/Chinese Academy of Science and by the Short Term Mobility program funded by CNR, 2007.

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Preliminary analysis of salinity distribution in a solute transport process at field-scale

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Abstract. Salt concentration and water content profiles were intensively measured within an area of 40x7 m^2 to a depth 1.0 m in a sandy (Ando) soil. A few models were considered to simulate salt movement in the soil. Comparison of simulation results with the field experimental data showed that the convective dispersive (CD) model with effective parameters well describes the mean concentration profiles. The failure of other models is probably due to the neglect of pore scale dispersion, which in the considered experiment seems to have a relevant impact.

Keywords. Solute transport – Heterogeneity – Stochastic modelling.

Analyse préliminaire de la distribution de la salinité dans un processus de transport des solutés à l'échelle du champ

Résumé. *Les profils de concentration du sel et du contenu en eau ont été intensivement mesurés dans une aire de 40x7 m², à une profondeur de 1,0 m d'un terrain sablonneux (Ando). Quelques modèles ont été considérés pour simuler le mouvement des sels dans le sol. La comparaison des résultats des simulations avec les données expérimentales, a démontré que le modèle de convection/dispersion (CD), avec ses paramètres effectifs, décrit bien les concentrations moyennes des profiles. L'échec des autres modèles est probablement du au fait qu'ils négligent la dispersion à l'échelon du pore, ce qui semble par contre avoir un impact important dans ce cas d'étude.*

Mots-clés. *Transport du soluté – Hétérogénéité – Modélisation stochastique.*

I – Introduction

Reliable and simple models for solute transport in unsaturated porous media are required for many application purposes like the optimal management of agricultural practices, designing proper strategies to preserve soils or assessing the potential pollution risks of groundwater. Numerous models have been proposed to account for the complicated physical/chemical processes occurring in soils (e.g. Brusseau *et al.*, 1989). Although the wide variety of mathematical models available in the literature (for a comprehensive review, see Sardin *et al.*, 1991), finding analytical solutions is not an easy task. Another complicating factor is represented by the unsteadiness of the water flow which especially in the case of soils is a quite common situation.

Due to its relevance, solute transport at field scale has been recently monitored in a typical soil of the Campania Region with the target to acquire a proper data-set to verify the capability of existing transport models to mimic salt transport in heterogeneous soils.

II – Convection-Dispersion (CD) model

The convective-dispersive model for solute transport taking place in one dimensional homogeneous porous medium can be cast in terms of the following five non dimensional quantities (see e.g. Bear, 1972).

$$T = \frac{vt}{L}, \qquad X = \frac{z}{L}, \qquad Pe = \frac{vL}{D}, \qquad C = \frac{C_r - C_i}{C_r - C_i}, \qquad R = 1 + \frac{\rho k}{\theta} \tag{1}$$

where v=q/θ (L/T) is the effective velocity in the liquid phase (L/T), q (L/T) the flux, θ (L^3/ L^3) is the volumetric water content, L (L) is the characteristic flow domain length, z (L) is the depth, t (T) is the current time, *D* (L^2/T) is the pore-scale dispersion, C_r and C_i (M/L^3) represent the resident and initial concentrations, respectively, whereas C_0 is the concentration at the inlet, ρ (M/L^3) the bulk density, and k (L^3/M) the characteristic coefficient of the linear isotherm.

Thus, the convective-dispersive equation writes as

$$R\frac{\partial C}{\partial T} + \frac{\partial C}{\partial X} = Pe^{-1}\frac{\partial^2 C}{\partial X^2}. \tag{2}$$

In order to account for the spatial variability of the parameters *D* and *v* appearing into (1), in equation (2) one can introduce the "effective" parameters D_{eff} and v_{eff}. Following Salzman and Richter (1995) the effective dispersion coefficient D_{eff} and the effective velocity v_{eff} are given by

$$D_{eff} = \langle D \rangle + \frac{45.45\sigma_v^{2/0.93}}{(1+\langle v \rangle)^{1.104}}\left(1 + \frac{\sigma_v^2}{\langle v \rangle}\right) - 0.291\sigma_v^{2/0.64}\left(1 - \frac{1}{1+\langle D \rangle}\right)^{-0.056}\left(1 + \frac{\sigma_v^2}{\langle v \rangle}\right)^{-0.264} \tag{3}$$

$$v_{eff} = \langle v \rangle - 0.28\left(\frac{\sigma_v^2}{\langle v \rangle}\right)^{0.8} - 0.281\sigma_v^2 + 0.07\sigma_v^4 \tag{4}$$

where it is assumed that both the pore scale dispersion *D*, and the local effective velocity *v* are log-normally distributed.

III – A brief description of the field experiment

Monitoring tracer transport was conducted in a 40 m x 7 m transect, located at Ponticelli, Naples (Italy). The soil is sandy (USDA) and pedologically classifiable as Andosoil. The soil texture in the upper 1.5 meters was studied in details and results are summarized in Comegna *et al.*, (2008). Field investigations showed that the soil is uniform with no layering within the first top meter. In particular, the soil bulk density had a mean value of 1.15 g/cm^3 (σ=5.07·10-2 g/cm^3) in the upper layer whereas, at higher depths, the soil showed its original andic features, with bulk density lesser than 1.0 g/cm^3.

The plot selected was covered with a greenhouse to control the influence of the rainfall. The irrigation system consisted of 96 (40 lh^{-1}) static sprinklers arranged with a spacing of 1.5 m in the longitudinal and 2.5 m in the transversal direction. The water application rate was controlled by a peristaltic pump, connected to 5 m^3 water storage tank. Sprinkler system uniformity was checked with the Christiansen Uniformity Coefficient (UCC) (Christiansen, 1942). The observed UCC over the entire field was estimated to be 80 %. To minimize a possible risk of changes in application rates and water flux, an on-off system was introduced.

Prior the solute application, the transect was irrigated for several days in order to guarantee steady-state flow conditions. Then, a solution of 67.5 Kg of KCl was dissolved in 1500 liter of water, and subsequently applied (105 g/m^2) in a pulse-like form to the soil surface. Transport was forced by the same constant flux q=0.042 cm/h which were established before the salt application. Soil cores were collected at 7 time intervals (t=97, 167, 263, 335, 407, 573, 742 hours after solute application). At each site, 40 different points were sampled. The soil samples were taken from the surface to a maximum depth of 90 cm in 20 cm increments. At the end of the tracer experiment ≈4000 soil cores were collected, sealed in plastic bags and returned to the laboratory for Cl^- analysis. Soil solution was extracted using a 1:2 soil-water mixture; after mixing and equilibrating, solution extracts were obtained using suction funnels lined with filter paper.

Chloride ion concentration in the extracts was determined using a Methrom ion analyzer, model 781. All samples were oven dried for 48 hours to determine water contents.

IV – Discussion

The mean water content $\langle\theta\rangle$ and the corresponding error (with confidence of 68%) at t=97 h is depicted in figure 1 as function of the depth z. It is seen that $\langle\theta\rangle$ is uniformly distributed up to z=0.55 m, whereas the increase which is observed at higher depths is due to the different (pedological) structure of the soil at such depths. As first step to characterize the mechanisms affecting chloride migration, we have computed the so called "mobile water content" θ_m=qt/z where q=0.0417 cm/h is the flux density at the soil surface, t the sampling time, and z the depth at which the maximum concentration value is detected. It resulted θ_m=0.23 to be compared with $\langle\theta\rangle$=0.34, suggesting that the chloride in mean is transported at higher depths as compared with the mean concentration value.

Subsequently, convective-dispersive parameters have been determined by matching analytical solution pertinent to our case (van Genuchten and Wierenga, 1986) with real data. Results of such a procedure suggest that the most stringent feature is the high variability of v and D along the transect, thus suggesting a deep impact of the soil heterogeneity.

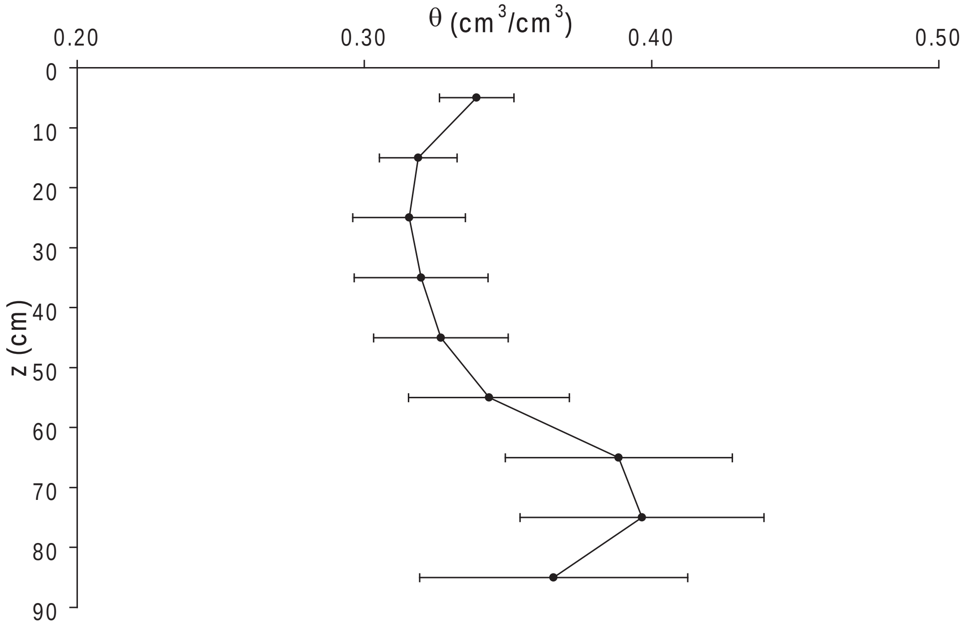

Figure 1. Mean water content distribution at t=97 h.

In particular, it is seen that both the dispersion coefficient *D*, and the local velocity v can be approximately considered as log-normally distributed. In order to model solute transport at field scale we have compared the CD with other models (for details, see Comegna *et al.*, 2005). In addition, we have also considered the convective dispersive model as obtained from effective parameters. The result is that the CD model with effective parameters is the best performing model for predicting purposes.

V – Concluding remarks

Even if the water content is apparently scarcely affected by the soil heterogeneity, a huge spatial variability in the salt spatial distribution (especially in the surroundings of the peak of concentration values) has been observed.

The absence of preferential flows as well as fractures suggests that a possible transport model is the classical convection-dispersion equation with effective parameters. Indeed, good matching between real data and simulation have been obtained.

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Hydro-salinity balance to monitor soil salinity at field scale due to brackish irrigation water

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Abstract. A "hydro-salinity balance" could be considered as an objective method to detect salt increase into the root soil layer due to brackish water irrigation.

A permanent experimental field-unit was established in autumn 2006; three plots of 100 m^2 each (6.4 x 15.6 m) were delimited; at the center of each plot an artificial draining basin was arranged digging the soil out of a trench, 3.2 m wide, along the entire plot length; the bottom of each trench was covered with a plastic sheet in order to prevent water percolation; a set of drains (two groups per trench, three drains per group) were displaced over the plastic cover to collect the percolating water and conveying it into thanks placed at the edge of each plot (two thanks per plot). The trenches were then filled with the same soil obtained by the excavating procedure, trying to correctly reproduce the original soil stratification.

In this very first cropping season (summer 2007) the aim of the trial was to detect the risk of soil salinity build up due to the ordinary irrigation practice applied by the farmer, according to the real context of a farm of the Apulian Tavoliere, close to the coast of the Manfredonia gulf (Adriatic sea), where brackish irrigation is a diffused and frequent practice due to seawater intrusion into the groundwater.

Tomato was transplanted on 20 April and harvested on 26 July. The electrical conductivity of the irrigation water (ECi) increased from 4.7 to 5.3 dS m^{-1} along the crop cycle. Soil ECe (electrical conductivity of soil saturated water extract) was periodically measured (approximately every 10 days) by soil samplings.

Seasonal farmer irrigation was 544 mm while rain amounts were equal to 117 mm; thus the total water supply was 661 mm. Along the crop cycle, an increasing soil salinization occurred, starting from a value of 2.4 dS m^{-1} up to a maximum value of 6.6 dS m^{-1}. Due to leaching, at harvest the soil ECe decreased to an average value of 4.8 dS m^{-1}. Approximately, a 25% of yield reduction was recorded as compared to contiguous field irrigated with good water quality. The irrigation water supplied by the farmer exceeded the plant water consumptions, particularly in the closing part of the crop cycle, thus producing drainage that, on average, was equal to 61 mm. A leaching fraction of approximately 10% resulted from the water balance while almost the 20% of salt was removed from the soil profile with respect to the salt load bring about with irrigation. That means an actual leaching efficiency of approximately 220 kg ha^{-1} per each percent point of leached water.

Keywords. Soil salinity – Salt balance – Brackish irrigation – Drainage water – Salt leaching – Tomato.

L'utilisation du bilan hydro-salin pour le contrôle de la salinité du sol dûe à l'usage de l'eau d'irrigation saumâtre

Résumé. *Le bilan hydro-salin pourrait être considéré comme une méthode directe pour détecter les conditions qui causent l'augmentation de la salinité de la zone racinaire. Un champ expérimental permanent a été établi en automne 2006; trois parcelles de 100 m^2 chacune (6.4 x 15.6 m) ont été délimitées; au centre de chaque parcelle un bassin de drainage artificiel de 3.2 m de large a été construit tout au long de la parcelle; le fond de chaque tranchée a été couvert par des feuilles de plastique pour prévenir l'infiltration de l'eau ; un ensemble d'égouts (deux groupes par tranchée, trois égouts par groupe) a été installè sur l'abri en plastique pour rassembler l'eau stagnante et la véhiculer dans des canaux placés au bord de chaque parcelle (deux canaux par parcelle). Les tranchées ont été remplies, alors, du même sol obtenu par excavation, en essayant de reproduire correctement la stratification du sol original .*

Dans cette première saison de récolte (été 2007), le but de cet essai, donc, était de détecter le risque de la formation de la salinité du sol due à l'irrigation ordinaire pratiquée par l'agriculteur et où l'usage de l'eau d'irrigation saumâtre est assez répandu et fréquent dans les domaines agricoles de la région Puglia-Tavoliere (Sud de L'Italie), près de la côte du golfe de Manfredonia (mer adriatique). Celle-ci est caracterisée par l'infiltration de l'eau de mer dans l'eau du sous-sol.

La tomate a été transplantée le 20 avril et a été recoltée le 26 juillet. La conductivité électrique (CE) de l'eau d'irrigation a augmenté de 4.7 jusqu'à 5.3 dS m^{-1}. ECe du sol a ètè périodiquement mesuré (approximativement chaque 10 jours) grâce à des prélèvements d' echantillons du sol.

L'approvisionnement de l'eau d'irrigation totale était de 661 mm (544 mm d'eau d'irrigation et 117 mm d'origine pluiviale). La salinité du sol est augmentée au fur et à mesure du cycle de la culture, débutant d'un minimum de 2.4 dS m^{-1} et arrivant jusqu'à une valeur maximale de 6.6 dS m^{-1}. A cause du lessivage et pendant la récolte, la Ece du sol, a diminué pour une valeur moyenne de 4.8 dS m^{-1}. Approximativement 25% de réduction du rendement a été enregistré en comparaison avec un champ adjacent irrigué avec de l'eau de bonne qualité . L'eau d'irrigation fournie par l'agriculteur a dépassé la capacité de consommation de la plante, en particulier à la fin du cycle de la culture, en produisant un drainage équivalent à une moyenne de 61 mm. Approximativement 10% de lessivage s'est produit dû à l'equilibre hydrique tandis que 20% des sels ont été éliminés du profil du sol vis à vis du sel apporté par l'eau d'irrigation. Cela implique un lessivage réel d'approximativement de 220 kg ha^{-1}.

Mots-clé. *Drainage – Bilan hydro-salin – Irrigation saumâtre – Salinité du sol – Lessivage.*

I – Introduction

Salinity is of great concern in all the irrigated agricultural areas of arid and semi-arid climate because of the limited contribution of rainfall to soil leaching and the often poor quality of water available for irrigation. This is particularly true along the coastal areas of the Apulian region (South Italy) where shortages in water availability are often recurring and brackish water is ordinarily exploit to manage crop irrigation (Monteleone *et al*., 2006).

The risk related to a long-term use of this low quality irrigation water is extremely emphasized when an intensification in the farming systems occurs; the change from a fallow-wheat system, with an intermittently irrigated summer-crop, to a continuous sequence of irrigated horticultural crops, highly increases the overall yearly salt load on the soil and decreases the possibility to benefit of the autumn-winter rainfalls (typical of the Mediterranean kind of climate) in order to promote salt leaching from the soil.

However, in order to broaden water availability, there is today a general consensus (Rhoades *et al*., 1992; Hamdy, 1994) about the opportunity to use irrigation water of higher salinity then those which were strictly classified as suitable, for instance according to the U.S. Salinity Laboratory (1954). The re-examination of those traditional standards implies the considerations of several factors influencing soil salinity besides water quality and pertaining to soil characteristics as well as crop or variety tolerance traits and, most important, irrigation management. The combination of all such issues allows to considerably relax the conventional, too restrictive, guidelines.

Irrigation and drainage are essential to control soil salinity due to irrigated agriculture in arid and semi-arid environments. The detection of the salt amounts brought into the soil by brackish irrigation water and that removed by drainage, accurately accounts for salt loads and soil salinity build up. Therefore, a "hydro-salinity balance" could be considered as the only direct method to assess the conditions that cause salt increase into the root soil layer and check the trend of soil salinity along time. Unfortunately, the performance of this balance is not straightforward and could be out of the reach of the single farmer. Indirect and simple method to estimate soil salinity hazard and forecast soil salinization under definite cropping conditions are hence needed.

The two contrasting features of the problem are the following: irrigation is essential to reach a proper crop yield and drainage is also needed in order to leach the salts away from the crop soil profile, but leaching only occurs when extra-irrigation volumes are delivered, thus also increasing the overall salt amount brought into the soil and the threat of salt accumulation.

Soil salinity does not reduce crop yield significantly until a threshold level is exceeded; beyond this threshold, yield decreases almost linearly with respect to soil salinity (Maas and Hoffman, 1977), generally measured as electrical conductivity of the soil saturation water extract (ECe). To avoid yield loss when salt concentration exceeds the crop tolerance limit, a water leaching requirement (LR) must be applied to the ordinarily irrigation (I), approximately equal to the ratio between the electrical conductivity of the irrigation water (ECi) over the electrical conductivity of the drainage water (ECd) above which yield reduction occurs. This simple relation does not take into account the dilution effect carried out by the rain precipitations (P) eventually registered along the irrigation season; thus (assuming that ECd = 2 ECe) the complete relation is:

$$LR = \frac{I}{I+P} * \frac{ECi}{ECd} = \frac{I}{I+P} * \frac{ECi}{2ECe}$$

How to fulfil this LR during the irrigation season is a question of optimization that pertain to the irrigation scheduling. There are evidences suggesting that the best scheduling consisting in a limited number of irrigations while using larger application volumes (Crescimanno and Garofalo, 2006; Shalhevet, 1984); this criterion is in contrast with what has long been assumed: more frequent irrigations reduce the effect of salinity as a consequence of a higher soil water content that partly decreases the osmotic potential able to limit the soil water uptake by the crop. The consideration that both water soil evaporation (E) and plant transpiration (T) tend to concentrate the salts on the upper soil layer when they are frequently wetted explains why frequent irrigation may produce a negative effect.

In the frame of a long-term trial, this work is aimed to detect the build up of soil salinity along the course of the very first irrigation season carried out along a tomato crop cycle and on a soil initially affected by salinity problems to a limited degree only. The time trend of soil salinity was followed in order to detect the right time to start leaching according to the crop tolerance characteristics; the final soil salinity level was also determined in order to account the effect on the subsequent crop; moreover, the actual leaching ratio and its efficiency was calculated with respect to soil texture and irrigation frequency.

II – Materials and Methods

The experimental trial was carried out in a field 15 km apart from the coast of the Manfredonia gulf (Adriatic sea), on a loam soil (sand 45.8%; silt 34.3%; clay 19.9%), with an organic matter content equal to 1.6%; a total N content of 1.08 ‰ and a P_2O_5 content of 62.4 ppm. The field water capacity (-0.03 MPa) was equal to 29.9% d.w. and the wilting point (-1.5 MPa) equal to 17.4% d.w. Furthermore, the soil pH was of 7.6 and its ECe initial value was approximately equal to 2.45 dS m^{-1}.

In the preceding autumn 2006 a permanent experimental set-up was arranged. It consisted of three adjacent and identical plots of 100 m^2 (6.4 m wide and 15.6 m long).

At the center of each plot an artificial draining basin was arranged. It was obtained by digging the soil out of a trench of 50 m^2 (3.2 m wide and 15.6 m long), covering the bottom of each trench with a plastic sheet in order to prevent water percolation and displacing a set of drains (two groups per trench, three drains per group) over the plastic cover in order to collect the percolating water.

Each set of drain was connected to a tank placed at the edge of the plot (two tanks per plot) in order to drain away the percolating water, whenever the drainage occurred.

Finally, the trenches were filled with the same soil obtained by the excavating procedure, trying to correctly reproduce the original soil stratification.

This experimental set-up mimics the condition of a shallow water table (0.7 m of depth); in our intention, it will be used over a long period of time, allowing the performing of hydro-salinity balance over several cropping seasons, in order to check the effect of brackish water irrigation on soil salinity and outline the criteria to optimize the management of irrigation and drainage, according to the general aims of the CLIMESCO Project (*).

The seedlings of the processing tomato cultivar “*Perfect Peel*” were transplanted on 20 April 2007 and the fruits were harvested on 26 July 2007.

Prior to tomato transplanting, the soil was harrowed to a depth of 0.40 m and fertilized with 100 kg ha^{-1} of P_2O_5.

The plants were displaced in the field according to coupled-row arrangement, 1.60 m apart one to another while the distance between each single row was 0.40 m; the plants were 0.40 m apart along the row; an overall plant density of approximately 31,250 plants ha^{-1} was thus established.

All the cropping operations were carried out according to the ordinary farming techniques of the surrounding agricultural area without any significant differences with respect to what a common farmer would performed.

Fertilization and ferti-irrigations were performed during the crop cycle, according to the growth dynamic, supplying a total amount of 100 kg ha^{-1} of N; 35 kg ha^{-1} of P_2O_5 ; 50 kg ha^{-1} of K_2O; besides proper microelements amounts such as Ca and Mg.

Weeds and pest controls were performed during the cropping season according to currently management practices.

It is worth to remind that the irrigation scheduling (times and volumes of crop water supply) was entirely in charge of the farmer who had the task to perform irrigation according to his own technical decision criteria.

A drip irrigation system was set-up; every dripping line was displaced at the centre of each coupled-row with the dripping points placed 0.40 m apart along the line and a water capacity of 3 l h^{-1}. A water flow meter was placed at the head of the irrigation system to accurately measure the amount of irrigation water supplied.

A weather station was positioned in the experimental field in order to hourly record the meain meteorological variables such as air temperature (°C), relative air humidity (%), wind speed (m s^{-1}), rains amount (mm) and incident solar radiation (W m^{-2}) according to standardized criteria.

The crop growth was detected through a periodical sampling of 12 plants from each plot, approximately every 10 days; the measure of leaf area index (LAI), fresh and dry weight (g m^{-2}) of the plants, partitioned in stem, leaf and fruits, as well as of the root depth (m) was carried out.

The electrical conductivity of the soil saturation water extract (ECe – dS m^{-1}) was periodically measured through soil sampling (approximately every 10 days), at three different depth (0.20; 0.40; 0.60 m) and in four repetitions, in correspondence to two different characteristics points of the experimental plot, respectively inside and outside of the coupled row of tomato plants.

The electrical conductivities of the irrigation water (ECi – dS m^{-1}) as well as of the collected drainage water (ECd – dS m^{-1}) were periodically measured, together with their volumes.

With respect to each plot of the experimental set-up, a long-term experimental irrigation treatment was assigned, according to the following criteria:

L0 – control – brackish groundwater was supplied at each irrigation and no leaching requirements was fulfilled during the crop cycle but, eventually, only after the crop harvest, in case a critical soil ECe threshold was exceeded;

L1 – brackish leaching – brackish groundwater was supplied at each irrigation but the leaching requirements was timely fulfilled both during the crop cycle or after the crop harvest whenever a critical soil ECe threshold was exceeded;

L2 – limited fresh water availability – irrigation was ordinarily performed with brackish water but a limited amount of good quality water (200 mm as a maximum) was available in order to irrigate the crop at some critical phenological stages (establishment, flowering, fruit set-up, etc.) or eventually to perform leaching whenever a critical soil ECe threshold was exceeded both during the crop cycle or after the crop harvest.

With reference to the tomato crop, the critical ECe threshold value was fixed at 5 dS m^{-1}, corresponding to an estimated 25% of reduction in tomato yield according to the model of Mass and Hoffman (1977); the yield reduction was determined with respect to the tomato potential yield in case a good quality water was used for irrigation.

Daily ETc was estimated according to the evapotranspiration method and the “two step approach” ($ETc = ET_0 * Kc$); reference evapotranspiration (ET_0) was calculated using the Monteith’s equation (Allen *et al*., 1998) from the meteorological data collected during the trial.

The restoring of the ETc is arranged each time the depletion of the available water reached the threshold value of 40%. The water balance was daily updated in order to theoretically schedule the time and volume of irrigation and comparing them with the actual irrigation performed by the farmer.

Only the data pertaining the soil and water salinity and the water balance along the tomato crop cycle are presented and discussed in the paper.

III – Results

The actual seasonal water supply performed by the farmer was equal to 544 mm; this total water irrigation high was reached with 22 irrigations all over the crop cycle, from transplanting to harvest, corresponding to an average irrigation volume of approximately 25 mm.

Several rainfalls occurred during the tomato crop cycle even though they were gathered in the first half of the cropping season only while the second half was completely dried. The total rain amount was equal to 117 mm.

Considering altogether the artificial (irrigations) and the natural (rains) water supply, the tomato crop availed of a total water amount equal to 661 mm.

A seasonal irrigation equal to 424 mm was calculated based on the water balance book keeping, a value significant lower than the value actually supplied.

The comparison between the cumulated values of the calculated irrigation heights and those actually applied by the farmer along the crop cycle is showed in Figure 1.

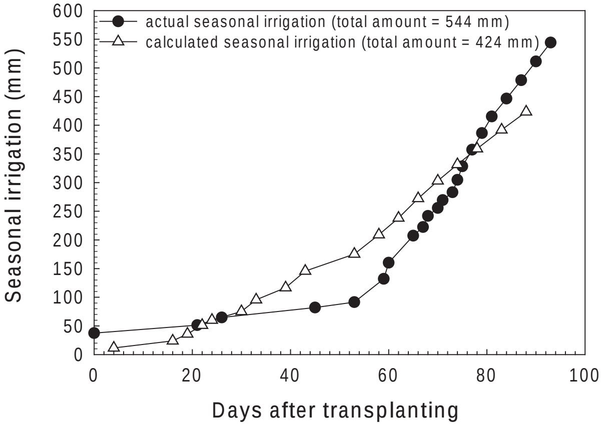

Figure 1. Calculated and actual seasonal irrigation during the tomato crop cycle.

It is easy to observe, from Figure 1, a general lower amount of the actual water availability as compared with that theoretically determined, specifically in the central part of the crop season.

It's worth to say, however, that in no way the crop experienced water stress and, according to farmer's opinion, a less frequent irrigation in the first part of the season is generally performed in order to promote root deepening and achieve a better capacity to exploit water by the crop in the deeper soil layers.

In the third part of the season the frequency of irrigations increased a lot thus exceeding the expected crop needs and generating plentiful drainage (Figure 2).

In response to brackish irrigation, soil salinity rapidly grew up (Figure 2); an increase in soil salinization was recorded during the first thirty days after transplanting, from a value of 2.4 dS m^{-1} up to a value of 3.6 dS m^{-1}.

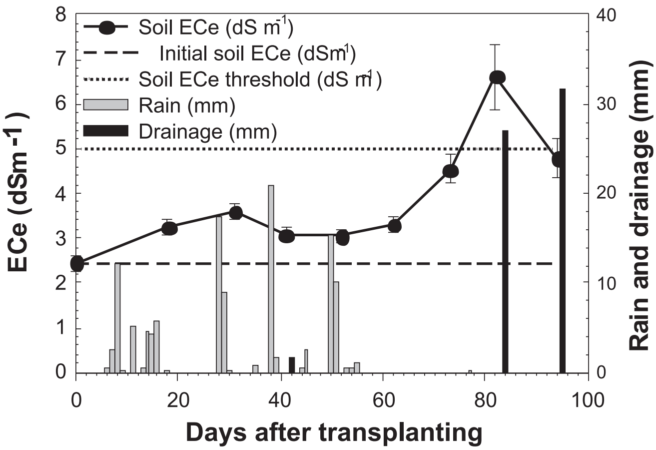

Figure 2. Average electrical conductivity of the soil saturation water extract (on the left axis), rain and irrigation water contributions to the crop (on the right axis), during the tomato cropping season

In the middle part of the cropping season frequent and abundant rains occurred determining a limited but important drainage event, on average equal to 2 mm; due to soil leaching and drainage a limited ECe decrease was observed along the active soil layer.

In the third part of the cropping season ECe rose up again, reaching the maximum value of 6.6 dS m^{-1}, thus overcoming the prefixed critical ECe threshold.

But at the end of the cropping season, approximately ten days before harvest, the frequent irrigations supplied by the farmer largely exceeded the crop water consumptions, thus producing a very copious drainage.

The drainage water was collected twice and, on average, their amounts were equal to 27 and 32 mm respectively. Due to leaching, at harvest, the soil ECe significantly and rapidly decreased to an average value of 4.8 dS m^{-1} (Figure 2).

With the increasing ECe values along the crop cycle, also their variability (standard error of the mean) increased (Figure 2); this was due to the progressively larger differences detected between the ECe value measured on the soil sampled along the dripping line as compared to the soil sampled far apart from that line; the former displayed higher salinity values while the latter significantly lower values. This remarkable spatial differences are directly related to the drip irrigation method applied.

The three irrigation experimental treatments defined for the long run were not applied during this first and short trial; this was due to the purpose to follow the farmers ordinary irrigation management but also because the fixed ECe threshold value was reached only at the end of the cropping season, when the crop was not particularly vulnerable to salinity; moreover, non-intentional leaching actually occurred due to farmers behaviour.

Approximately, a 25% of tomato yield reduction was recorded as compared to the contiguous fields of the farm which were irrigated exactly with the same amount and the same frequency but with good water quality.

In the course of the trial, the EC value of the irrigation water (ECi) progressively increased, from 4.7 to 5.3 dS m^{-1}. This was probably due to the generalized and overwhelming use of the ground-water resources to allow summer-crop irrigation and the consequent lowering of the water-table and the pumping out of the heavier and deeper salty water.

The hydro-salinity balance was performed by measuring the volume, salt concentration and salt mass of the water input (irrigation) and output (drainage). Table 1 shows the key variables, the terms of the balance and some important derived performance parameters.

Table 1. Components and derived indexes of the hydro-salinity balance

Parameters	Units	Code	Formula	Average	St. err.
Water balance					
Seasonal irrigation	m^3 ha^{-1}	I	measured	5442	-
Seasonal rain amount	m^3 ha^{-1}	R	measured	1166	-
Seasonal water supply	m^3 ha^{-1}	W	I+R	6608	-
Seasonal drainage	m^3 ha^{-1}	D	measured	605	± 10.89
Leached water fraction	%	LF_W	D/W	9.16	± 1.65
Salt balance					
Irrigation added salts	t ha^{-1}	S_I	measured	10,80	-
Drainage leached salts	t ha^{-1}	S_D	measured	1.93	± 0.37
Salt loading	t ha^{-1}	S	$S_I - S_D$	8.88	± 0.37
Leached salt fraction	%	LF_S	S_D / S_I	17.98	± 3.43
Loaded salt fraction	%	SF	S / S_I	82.02	± 3.43

The overall leached water fraction (LF_W) was the result of the ratio between seasonal drainage (D) and total seasonal water supply (I plus R); it reached approximately the value of 10%. This value can be considered relatively small compared to the high electrical conductivity of the water employed for irrigation (ECi). It must be considered, however, that the soil was almost free from salts at the beginning of the trial so that the performing of leaching would be really justified only at the end of the irrigation season.

With reference to the salt balance, the overall leached salt fraction (LF_S), resulted from the ratio between drainage leached salts (S_D) and irrigation added salts (S_I), was almost equal to 18%; it means that the 18% of the salt load bring about with brackish irrigation was removed from the active soil layer while the remaining 82% accumulated in it and gave rise to soil salinity.

The net salt loading S (t ha^{-1}) as well as the leached salt fraction LF_S (%), were linearly related to the values of leached water fraction actually registered in the three experimental plot (with two replications per each plot) as graphically reported in Figure 3.

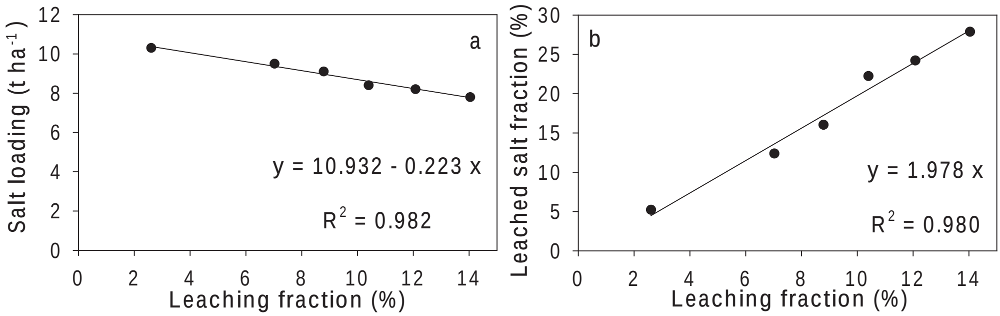

Figure 3. Salt loading (a) and leached salt fraction (b) as related to the leaching fraction with respect to the overall tomato crop cycle.

In both cases, the linear equation fitted the data very well (significantly high R^2 were obtained), pointing out the model suitability.

Quite obviously an increasing leaching fraction determined a decrease in the soil net salt loading. The intercept value of the equation line (Figure 3a) was equal to 10.9 that matched almost perfectly to the value of the irrigation added salts (S_I).

The slope of the same line equation expresses the actual leaching efficiency gained during the irrigation season; it was equal to 223 kg ha^{-1} per each percent point of leached water achieved. This value, if compared with homologous values from other experimental trials (Monteleone *et al.*, 2004; 2006) seems to be relatively lower; it must be considered, however, that this was an open field experiment while the others were all carried out in glasshouse were single tomato plants were cropped into cylindrical polyethylene containers (lysimeters); another important consideration pertain to the value of the total irrigation added salts: the higher this value the higher the value of the leaching efficiency; since the former value is quite low as compared to the preceding experimental trials, also the latter showed a lower level.

The leached salt fraction (%) showed to have almost a doubled value than the leached water fraction (%) as proved by a slope coefficient of the line equation equal to 1.98 (Figure 3b). The drainage water that leached the soil profile, therefore, was able to drag along and carry out a greater proportion of salts with respect to water; the value registered in this trial was consistently similar to those from other experiments, thus indicating that the model whose coefficients are expressed in relative terms can be of more general application.

IV – Conclusions

Based on the experimental data collected during the trial and previously outlined, it is possible to trace out some schematic remarks:

– the present work was not other than the starting trial in the frame of a long-term experiment aimed to check soil salinity with respect to farmer irrigation management and the role played by autumn-winter rains to promote salt leaching;

– soil salinity is a fast growing process and only one irrigation season could be sufficient to reach ECe value able to hamper soil productivity, taking account of the irrigation water quality and the seasonal irrigation volume (i.e. the total salt load);

– the rains eventually occurring along the season showed to be very effective in the delay of the soil salinity build up, even if of limited amounts; that was observed in the first part of the tomato cropping cycle;

– a non-intentional leaching occurred at the end of the crop cycle due to much frequent irrigations; this extra-water supply succeeded in partially removing the cumulated salts, significantly reducing the soil ECe;
– therefore, leaching showed to be effective but its efficiency increased from low to high soil salinity content; this confirms to apply leaching only when soil salinity reached a threshold level, particularly when the irrigation water quality is poor;
– the salt balance patently closed with a net salt load but without leaching the ECe end point should be very dangerous and potentially able to impair soil productivity in the succeeding cropping seasons;
– crop yield was only limited affected by the salts demonstrating the possibility to actively employ this poor quality water resource in order to broaden irrigation water availability and generally improve the productivity of a rural area, on condition that a proper technical skill is acquired by farmers.

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(*) This work has been funded by Italian Ministry of Education, University and Research (CLIMESCO Project, D.D. 20/02/2006 n. 285)."

Effects of electrical conductivity of irrigation water on the growth and production of *Solanum lycopersicum* L. var. cerasiforme grown in greenhouse

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Abstract. Tomato (*Solanum lycopersicum* L.) is commonly considered moderately tolerant to salinity and its tolerance varies in relation to genotype and the plant's organ. With regard to the latter aspect, it was found that the negative effects of salinity become apparent with electrical conductivity values of the circulating solution starting from 2.5 - 3.0 dS m^{-1} for the fruits, from 4.5 - 5.0 dS m^{-1} for the stems and leaves and from 6.0 dS m^{-1} for the roots. Furthermore, cultivars with small fruits show less marked reductions in fruit weight and production; they may therefore represent a solution for environments with only saline water. The aim of the research was to study in tomato var. *cerasiforme* "Naomi" cultivated in greenhouse, the residual effects of irrigation carried out for 10 consecutive years with saline water. At 75 - 90 and 105 days after transplantation, five plants and corresponding soil samples from 0 to -40 cm, were collected from each plot. On each plant, the number and the weight of marketable fruits per cluster and the epigeal biomass dry weight (stems + leaves + fruits) were recorded. On each soil sample the electrical conductivity of extract saturated (ECe) was determined. The use of irrigation water with ECw fluctuating around 2.0 dS m^{-1} over a decade, determined values of ECe in the soil above the tolerance limit only for the fruit production (3.8 compared to 2.5 - 3.0 dS m^{-1}). With ECw equal to 6.0 + 10.0 dS m^{-1}, levels of ECe exceeded those considered detrimental to the production of dry epigeal biomass (stems + leaves + fruits). The effects of increasing ECe on the fruit production were constantly determined through the reduction of fruit dry unit weight.

Keywords. Saline water – Long-term salinization – Tomato – Biomass – Production.

Les effets de la conductivité électrique de l'eau d'irrigation sur la croissance et la production de Solanum licopersicum L. var. cerasiforme cultivé sous serre

Résumé. *La tomate (Solanum lycopersicum L.) est souvent considérée modérément tolérante à la salinité et, cette tolérance varie en fonction du génotype et des organes de la plante. Considérant cet aspect, il s'avère que les effets négatifs de la salinité commencent à être évidents pour des valeurs de la conductivité électrique de la solution circulante à partir de 2.5 - 3.0 dS.m^{-1} pour les fruits, 4.5 - 5.0 dS.m^{-1} pour les tiges et les feuilles, et 6.0 dS.m^{-1} pour les racines. En plus, les cultivars à petits fruits montrent des réductions moins considérables en terme de poids du fruit et production ; par conséquent, ils peuvent présenter une solution pour les environnements qui disposent seulement d'eau saline. L'objectif de cette expérimentation est d'étudier les effets résiduels de l'irrigation avec eau saline réalisée pour dix années consécutives sur la tomate var. cerasiforme «Naomi» cultivée sous serre. Aux jours 75, 90 et 105 après la transplantation, cinq plantes et les correspondants cinq échantillons de sol de 0 jusqu' a 40 cm, ont été collectés de chaque parcelle. Le nombre et le poids des fruits commercialisables par grappe et la biomasse en poids sec (tiges + feuilles + fruits) ont été enregistrés pour chaque échantillon de plante. La conductivité électrique de l'extrait de pâte saturé (EC_e) de chaque échantillon de sol, a été déterminée. L'utilisation, pour une décade, d'une eau d'irrigation ayant une EC_w fluctuant autour de 2.0 dS m^{-1}, a déterminé des valeurs de la EC_e du sol au-dessus de la limite de tolérance seulement pour la production de fruits (3.8 comparé à 2.5 - 3.0 dS.m^{-1}). Avec des EC_w de 6.0 + 10.0 dS m^{-1}, les valeurs de l'EC_e ont dépassé les limites de tolérance de la biomasse (tiges + feuilles + fruits). Les effets de l'augmentation d'EC_e sur la production des fruits ont été déterminés par la réduction du poids sec unitaire des fruits.*

Mots-clés. *Eau saline – Salinisation à long terme – Tomate – Biomasse.*

I – Introduction

Salt stress responses in crop plants throughout their growth cycle depend on several interacting variables, including the cultural environment, the plant developmental stage, the salt concentration and the duration of the stress over time (Munns, 2002). The damages to plants caused by saline irrigation may be enhanced by high temperatures and low relative humidity as well as long-term salinization of the soil that undergo to permanent modifications of its physicochemical properties; as a consequence in applying saline water for irrigation, an integrated approach, which should account for soil, crop and water management, should be adopted.

Plant salt tolerance may be expressed by plotting the relative yield as a continuous function of root zone salinity (Maas and Hoffman, 1977). This relationship is represented by two intersecting linear regions, which identify a threshold, after which the yield begins to decline as well as the yield reduction rate (slope) at increasing salinity. The salinity tolerance threshold is a specific target for improving plant salt stress tolerance (Maggio *et al*., 2001; 2007).

Tomato (*Solanum lycopersicum* L.) is commonly included among the species that are moderately tolerant to salinity, and moreover it could be a model crop for saline water use because it is already grown in large areas with saline conditions, and because the physiology and genetics of this species are well known; its salt tolerance varies in relation to genotype (Cuartero *et al.,* 2006; Villalta *et al.,* 2007) and the plant's organ. With regard to the latter aspect, many researches showed that the negative effects of salinity become apparent with electrical conductivity values of the circulating solution starting from 2.5 - 3.0 dS m^{-1} for the fruits, from 4.5 - 5.0 dS m^{-1} for the stems and leaves (Cuartero and Fernandez-Munoz, 1999) and from 6.0 dS m^{-1} for the roots (Nanawati and Maliwal, 1974; Papadopoulos and Rendig,1983, reviewed by Cuartero and Fernandez-Munoz, 1999; Marchese *et al*., 2007).

In researches conducted on large fruit cultivars, reductions in fruit weights by 10% with 5.0 - 6.0 dS m^{-1}, by 30% with 8.0 dS m^{-1} and by 40% with over 10.0 dS m^{-1} were observed (Gonzalez-Fernandez and Cuartero, 1993; Cuartero and Fernandez-Munoz, 1999; Reina-Sànchez *et al.,* 2005). Cultivars with small fruits reveal, however, less marked reductions in fruit weights (Cruz and Cuartero 1990) and production (Caro *et al.*, 1991). They may therefore represent a solution for environments with only saline water. The use of drip irrigation for irrigated vegetable cropping like tomato in soils exposed to salinization is a more general solution to the salinity problem, reducing the effects of salt stress as the drip irrigation is applied more frequently and keeps the soil water content high enough, thus reducing the osmotic pressure and the negative impact of salinity on water uptake (Flowers *et al.,* 2005; Malash *et al.,* 2005; Hanson *et al.,* 2006; Incrocci *et al.,* 2006; Karlberg *et al.,* 2007).

The objective of this experiment was to study the residual effects of irrigation carried out for 10 consecutive years with saline water on salt accumulation in the soil and on growth and yield of tomato var. *cerasiforme*.

II – Materials and methods

The trials of this research were conducted in an area south east of Sicily, highly representative for the cultivation of tomato in greenhouse and for saline irrigation.

The study was were conducted in Pachino (Southern-East Sicily) on sandy soil (sand > 80%), lying on particularly permeable limestone owing to the fissures. An unconditioned greenhouse was used that during the period 1997-2006 hosted tomato crops for fresh use (two cycles per year) irrigated with water whose electrical conductivity (ECw) fluctuated around 2.0 dS m^{-1} (well water) or 6.0 dS m^{-1} in the seven years from 1997-2004 and 10.0 dS m^{-1} in the next three years (well water + table salt).

Irrigation was performed by dripping near the plants. In 2006, the residual effects of irrigation were assessed in "Naomi" cultivated in winter-spring cycle. An experimental design with randomized blocks, repeated 3 times, was adopted; the plot measured 17 m^2 (8.5 x 2.0 m). At 75 - 90 and 105 days after transplantation, five plants and corresponding soil samples from 0 to -40cm, were collected from each plot.

On each plant the number and the weight of marketable fruits per bunch, and the epigeal biomass dry weight (stems + leaves + fruits) were recorded. On each soil sample the electrical conductivity of extract saturated (ECe) was determined.

The relationships between the ECe and the productions were evaluated through Pearson's correlation and regression analysis. For the calculation of the latter, values for the biomass and fruit production, expressed as percentages of the maximum recorded, were used.

III – Results and discussion

The increase of ECw from 2.0 to 6 +10 dS m^{-1} led to a significant increase in ECe (Fig. 1). This latter appeared appreciable already after 75 days from transplanting and after 105 days was equal in average to 4.7 dS m^{-1} (3.4 compared to 6.1 dS m^{-1}); the highest values of ECe occurred since late spring were due probably to saline irrigation associated to intense evapotranspiration.

Owing to the ECe increase, the dry weight of the epigeal biomass and fruits per cluster showed significant decreases which, after 105 days from transplant, reached the maximum values equal to 20% and 15%, respectively (Figs. 2 and 3).

Of the production components, only the average dry unit weight of the fruit revealed a significant ($P \leq 0.01$) and negative correlation with ECe (r = -0.680); also this parameter showed a significant decrease which, after 105 days from transplant, was 8% (Fig. 4).

The regression analysis between ECe and the parameters examined, expressed as percentages of the maximum recorded (relatives values), showed that the increase of ECe determined a significant ($P \leq 0.01$) decrease of epigeal biomass, fruit production per cluster and fruit unit dry weight. The *b* coefficient identifies a specific slope, which defines the parameter reduction at increasing salinity. The increase of 1 dS m^{-1} of ECe, led to a calculated reduction of 8% for epigeal biomass and of 7% both for production per cluster as well as for fruit unit weight (Figs. 5-6-7) showing that the decrease of fruit unit weight determined the production reduction.

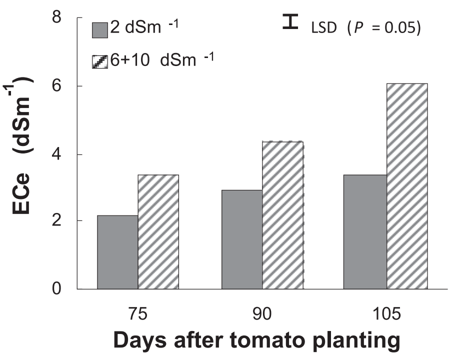

Figure 1. ECe variation in relation to ECw.

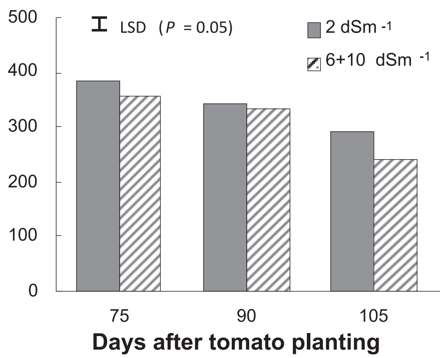

Figure 2. Dry epigeal biomass in relation to ECw.

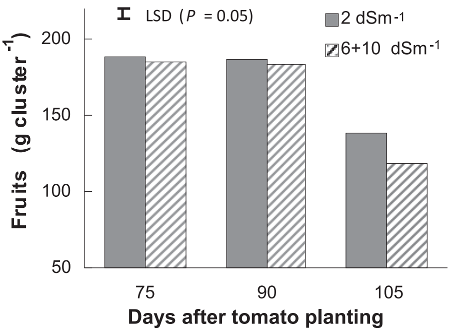

Figure 3. Fruit dry weight per cluster in relation to ECw.

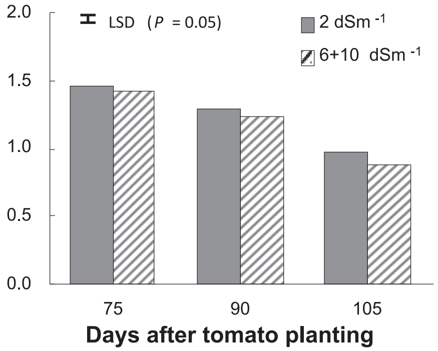

Figure 4. Fruit dry unit weight in relation to ECw.

At maximum ECe value observed (6.0 dS m^{-1}), the calculated decreases were 43%, 36% and 40% for epigeal biomass, fruits per cluster and dry unit weight of the fruit, respectively.

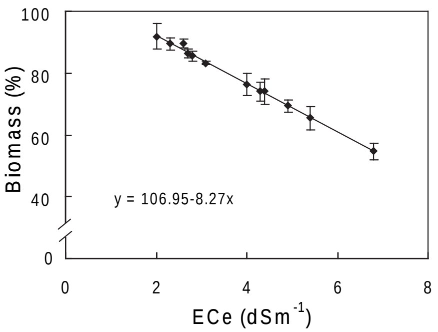

Figure 5. Relative plant dry biomass in response to increasing of ECe.

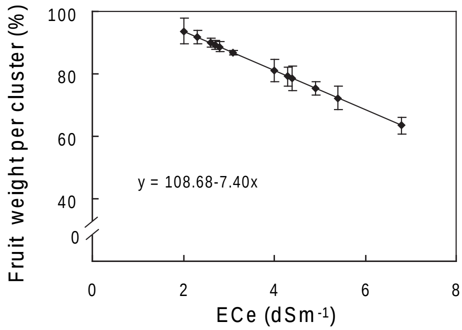

Figure 6. Relative fruit dry weight production per cluster in response to increasing of ECe.

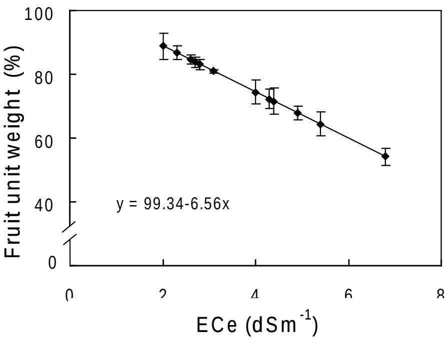

Figure 7. Relative fruit unit dry weight in response to increasing of ECe.

IV – Conclusions

The results gathered after 10 years of irrigation with saline water on tomato indicate that, in the given conditions, the use of irrigation water with ECw fluctuating around 2.0 dS m^{-1} over a decade, determined values of ECe in the soil above the tolerance limit only for the fruits production (3.8 compared to 2.5 - 3.0 dS m^{-1}). With ECw equal to 6.0 +10.0 dS m^{-1}, levels of ECe exceeded those considered detrimental to the production of dry epigeal biomass (stems + leaves + fruits). The effects of in,creasing ECe on the fruit production were constantly determined through the reduction of fruit dry unit weight.

The effect of salt stress on growth and production depends by ECw as well as evapotranspiration and water management strategies, in particular by irrigation method.

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Spatial Variability of Solute Transport Mechanisms Based on Generalized Transfer Function Model

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Abstract. The flexible generalized transfer function model (GTF) and TDR based time normalized resident concentrations were combined in order to characterize solute transport mechanism both at local and field scale. A leaching experiment was carried out in a plot under greenhouse, where TDR probes were installed at three different depths at 37 sites along a 40 m transect. The field plot was brought to steady-state water content; a pulse application of 3.87 mm of KCl solution was applied. Measurements of water content (θ) and impedance (Z) were simultaneously taken to follow the KCl solution propagation through the soil profile. Time series of relative resident concentrations for each site where effectively interpreted in terms of GTF model. The field scale behavior was described by calculating a local average and an integral average, by averaging local scale parameters and local scale original measurements, respectively. The two different averaging schemes resulted in two significantly different field scale solute transport behaviors.

Keywords. Soil water content – Solute transport models – Time Domain Reflectometry (TDR) – Spatial variability.

Variabilité spatiale des mécanismes de transport des solutés basée sur la Réflectométrie dans le Domaine Temporel et la Fonction de Transfert Généralisée

Résumé. *Ce travail associe la fonction de transfert généralisée flexible (modèle GTF) et les concentrations massiques normalisées à l'égard du temps se basant sur la Rêfléctométrie dans le Domaine Temporel (TDR), pour caractériser le transfert des solutés dans le sol. Un essai de lessivage a été mené sur sol dans une parcelle de 40 m de long sous serre où des sondes TDR ont été installées à trois différentes profondeurs à 37 points le long de la parcelle. La teneur en eau du sol a été ramenée à l'état d'écoulement permanent; Une impulsion de 3.87 mm de solution de KCl a été appliquée. Les mesures de la teneur en eau (θ) et d'impédance (Z) ont été prises simultanément pour suivre la propagation de la solution de KCl le long du profil du sol. Les concentrations massiques relatives à chaque point ont été caractérisées avec succès par le modèle GTF. Les moyennes des paramètres locaux (moyenne locale) et des mesures locales (moyenne intégrale) ont été estimées pour représenter le transfert des solutés et les paramètres correspondants a l'échelle parcellaire. Les deux moyennes ont montré deux comportements de transfert des solutés à l'échelle parcellaire très différents.*

Mots-clés. *Teneur en eau du sol – Modèles de transfert des solutés – Réflectométrie dans le domaine Temporel (TDR) – Variabilité spatiale.*

I – Introduction

In the last decades, particular attention has been focused on the hazards posed by widespread pollution of groundwater resources, which are especially vulnerable due to the extent of the surface area directly affected by land use (Jury *et al.*, 1991; Carravetta, 1996). Major progresses have been achieved through parallel studies in setting up experimental techniques for monitoring inorganic, organic and biological substances to be found in soils and aquifers (Kachanosky *et al.*, 1992; Comegna *et al.*, 1999), using mathematical models and having widespread recourse to numerical calculations (Santini, 1992), as well as characterizing natural systems on a statistical basis (Jury *et al.*, 1987; Kutilek and Nielsen, 1994; Comegna and Vitale, 1993). However, according to most recent studies, it is becoming increasingly clear that such models fail to exhaustively describe the phenomena in their totality and are also difficult to apply on a regional level because of the heterogeneity of natural porous media and the large number of chemical, physical and biological parameters to be considered (Jury and Flühler, 1992). The heterogeneity of natural porous media may limit the applicability of the CD equation in the field. In such conditions, an alternative path to describe the transport of solutes is the stochastic–convective approach, SC, in which the solute is assumed to move in isolated stream tubes at different velocities without any lateral mixing (Dagan and Bresler, 1979). The effectiveness of this approach in the field has been amply demonstrated (Jury, 1982; Butters and Jury, 1989; Heuvelman and McInnes, 1999). The SC approach was also applied successfully at a laboratory scale on undisturbed soil columns (Khan and Jury, 1990; Comegna *et al.*, 2001). The complex heterogeneity of soil has encouraged the development of transport theories based on conceptual models, such as the transfer function approach (Jury, 1982). A transfer function model can predict the flux density from a system with definite boundaries depending on the input flux without any need to describe the complex process that takes place within the porous system. Jury (1982) suggested a log-normal travel time probability density function and set up the convective log-normal transfer function model (CLT). This model was shown to supply an accurate prediction of solute transport in field experiments. The CDE and the stochastic–convective model represent two extreme processes for solute dispersion. In the CDE, perfect lateral mixing is assumed, whereas the stochastic–convective process assumes that the solute moves at different velocities in isolated stream tubes without lateral mixing. These models are limited to describing solute transport characterized by either a linear or a quadratic increase in the travel time variance with depth (Liu and Dane, 1996). However, solute transport in heterogeneous porous media cannot always be conceptualized as being either a convective–dispersive or a stochastic–convective process. Therefore, it is necessary to develop a general model that can describe not only the two extremes, but also other transport processes. Zhang (2000) presented a flexible generalized transfer function models (GTF). The GTF is a four-parameter flexible transfer function able to describe both the convection-dispersive (CD) and the stochastic-convective (SC) process of dispersion in a soil. In additional the GTF model can also be used to characterize solute transport processes in heterogeneous soils such as those in which the mean travel time increase non-linearly with depth and those in which the dispersivity is a scale dependent function. The GTF is thereby a comprehensive transfer function model allowing the solute transport process in heterogeneous soils to be formalized in a synoptic way. Regarding solute transport modeling several researches have calculated values of local and field-scale dispersion behavior during unsaturated flow. In a stony soil field-scale dispersivities were four times greater than the average local-scale dispersivity (Schulin *et al.*, 1987). Similar findings were reported by Butters et al. (1989), who observed that the field scale variance of the field average solute BTC was twice as great as the average local-scale variance.

To date, no method has been proposed for determining the scale at which the true field-scale variance is reached. For monitoring and modeling at the field scale, it is important to know the scale dependence of solute travel-time variance to accurately characterize transport phenomena at this site. Given the expected variation in the soil properties in space and time (Mulla and McBratney, 1999), we must develop effective mean to characterize them across representative field areas.

Recently, great progress has been made in identifying transport processes by applying TDR technology to measure solute concentration (see, e.g., Vanclooster *et al.*, 1995; Coppola and Damiani, 1997; Comegna *et al.*, 1999). Major advantages of using TDR technology for characterizing solute are related to the possibility of easily applying it to undisturbed soil material and of measuring transport with a high spatiotemporal resolution. This latter property is a prerequisite for validating transport concepts for undisturbed soil. A major problem in the earlier studies of solute transport with TDR was the need for a soil and layer specific calibration equation, relating signal attenuation to the resident solute concentration of an ionic tracer (Mallants *et al.*, 1996; Vanclooster *et al.*, 1994; Vogeler *et al.*, 1997). However, to avoid this, Vanderborght *et al.*, (1996) introduced the time-normalized resident concentration in terms of the two-parameter CLT solute transport model, which allows the CLT parameters to be directly identified from TDR output readings. Jacques *et al.*, (1998) extended the approach for the two-parameter CD model.

Finally, Javaux and Vanclooster (2003) presented an analytical solution for time normalized resident concentration for the GTF model. A unique advantage of TDR is its ability to rapidly measure both resident concentration of a solute and water content with the same probe and in the same sampling volume.

The general objective of this study is to improve our understanding about the link between the small scale variability of the local transport properties and large scale transport behavior. The structure of solute transport mechanism variability in the soil will be drawn up by integrating TDR based resident concentrations measurements and the Generalized Transfer Function model.

Firstly, the local solute transport mechanism will be characterized on several sites along transect area by using TDR probes at different depths and in terms of GTF model.

Second, The local scale measurement and parameters will be integrated along the whole transect and normalized for the different local water contents, in order to build a time-integral normalized resident concentration at each depth to be used as field-scale curves.

II – Materials and methods

1. Experimental procedure

A snapshot of the experiment layout is given in figure 1. The experimental layout consists of irrigation system, TDR probes and the drainage system. The experimental area was covered by plastic mulch in order to avoid soil evaporation and to assure only downward movement of the applied water and solution. Then the drip irrigation was adapted to apply the rate of 10 mm/day at 5 a.m.. An automatic irrigation scheduler was used to maintain the desired rate.

Figure 1. The experimental layout.

The field plot was pre-irrigated with fresh water having an EC of 1.05 dS/m until a steady state water condition was attained.

After reaching the steady state condition, a depth of 3.87 mm of KCl solution (23.5 g/l with specific mass of 50 g/m2 of Cl-) was applied through the drip irrigation system as a pulse application (δ-Dirac type top boundary condition), while keeping the same supply rate of 10 mm/day.

Then, the fresh water was newly applied to clean the drip system and to force the KCl solution downward into the soil.

The volumetric water content, θ, and the impedance, Z, monitored before applying KCl solution were considered as initial values for the experiment.

After KCl solution application, daily measurement of θ and Z were taken in the morning and evening to follow the KCl solution propagation through the soil profile.

A time domain reflectometry (TDR100) device and TDR probes were used to measure the water content and the impedance.

The transmission line consisted of an antenna cable (RG58, 50Ω characteristic impedance, 210 cm length and with 0.2Ω connector impedance) and of three wire probe, 15 cm length, 2 cm internal distance, 0.3 cm diameter. The TDR probes were inserted at three different depths in 37 sites, at 1 m intervals, along the transect. The surface probes were installed vertically (0-15 cm) while the deeper probes were inserted horizontally at 20 and 40 cm from the soil surface.

III – Results and discussion

1. Actual situation of the reservoir R.1

The experiment was realized under steady-state water contents in the soil profile compatible with the characteristics of the different sites and with the boundary conditions adopted.

For each position where TDR probes were located, a temporal series of water content were obtained as shown as Figure 2 (a, b, c) which describes the water content variability along the transect at the three different times, the initial time, the final time, the middle time.

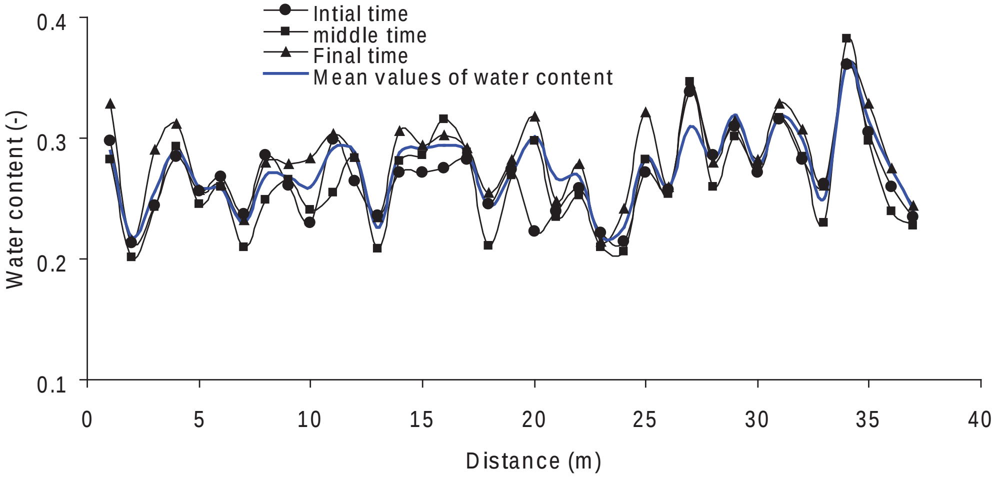

Figure 2a. Water content variability along the transect at 0-15 cm observation depth, at three different times, the initial time, the final time, the middle time.

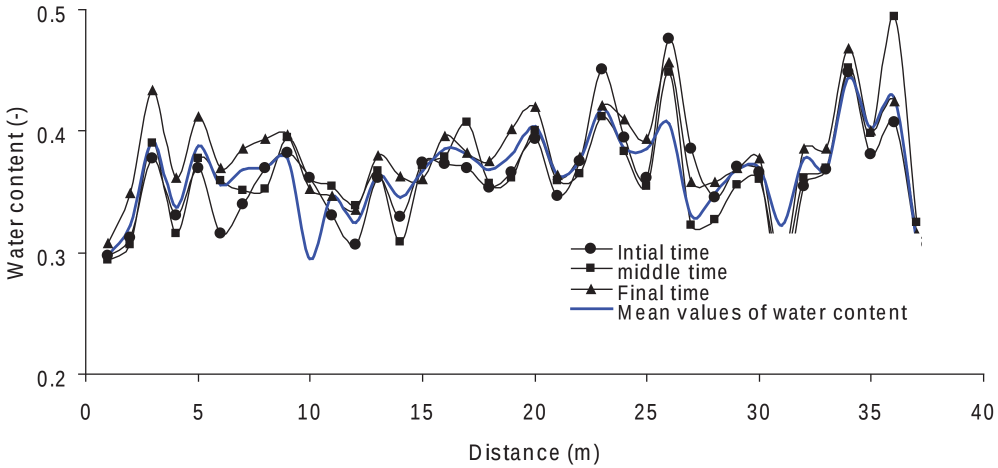

Figure 2b. Water content variability along the transect at 20 cm observation depth, at three different times, the initial time, the final time, the middle time.

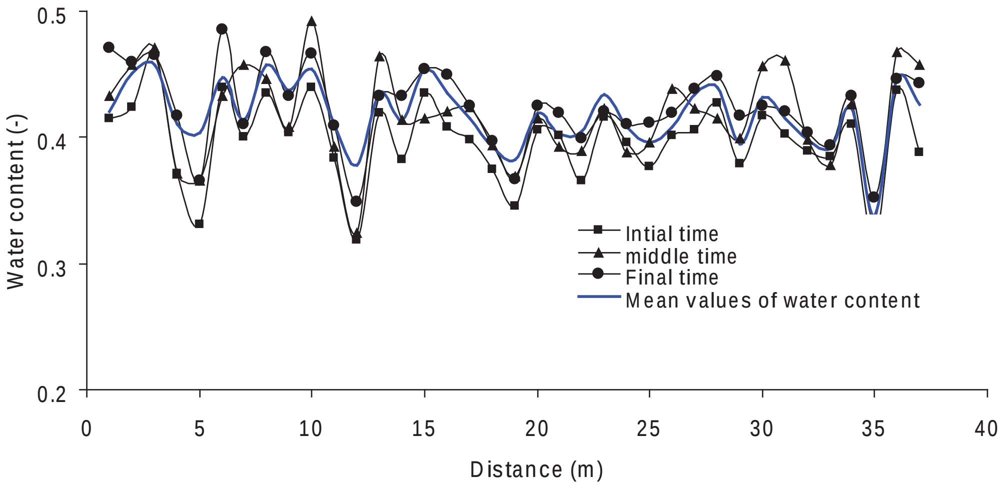

Figure 2c. Water content variability along the transect at 40 cm observation depth, at three different times, the initial time, the final time, the middle time.

The mean values of water content are also shown. Notwithstanding the variability along the transect, which is strictly related to the variability of soil physical characteristics and to some differences in the supply rate along the drip lines, what should be noted is the relatively constant water content for each location. This is confirmed for each depth. This result suggests that the steady-state conditions required for the experiment were effectively fulfilled, but it also implies that the important variability of the water content along the transect can not be neglected and has to be explicitly taken into account in all the calculations require use of the measured water contents.

The solute propagation along the soil profile was monitored by measuring TDR impedance loads at large times. Just as an example, the temperature corrected TDR impedance loads as a function of time for the 25cm and 40 cm depths of the measurement site labelled as site 18 are shown in Figure 3.

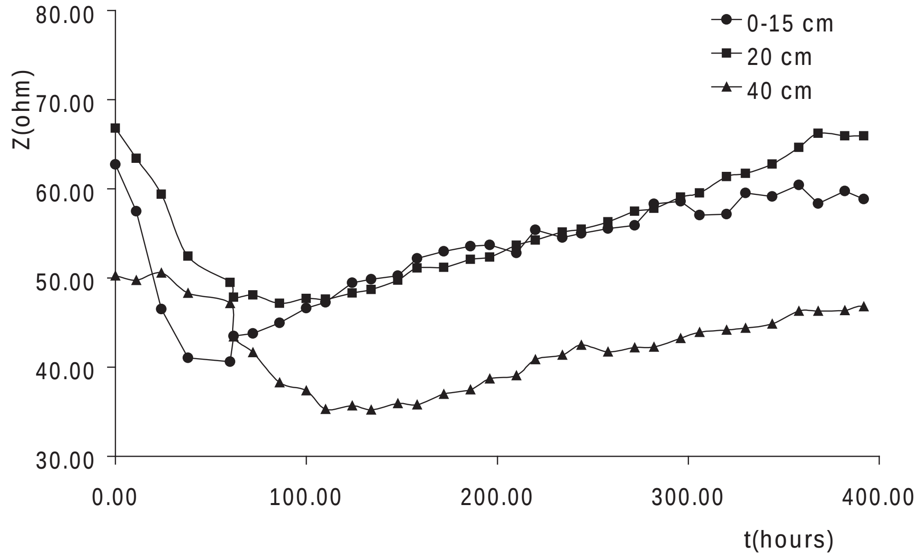

Figure 3. Temperature corrected TDR impedance loads for the three depths of site 18.

The impedance load changed more gradually while the solute reached in sequence the other two measurement depths. A different propagation velocity was observed for different locations. Such differences may be attributed to the different physical characteristics of the soils examined.

The reflectograms were than used for calculating time normalized resident concentrations, Crt*, for each depth and for each site according to the method given by Vanderborght et al. (1996). The pertaining curves for the site 18 are shown in Figure 4.

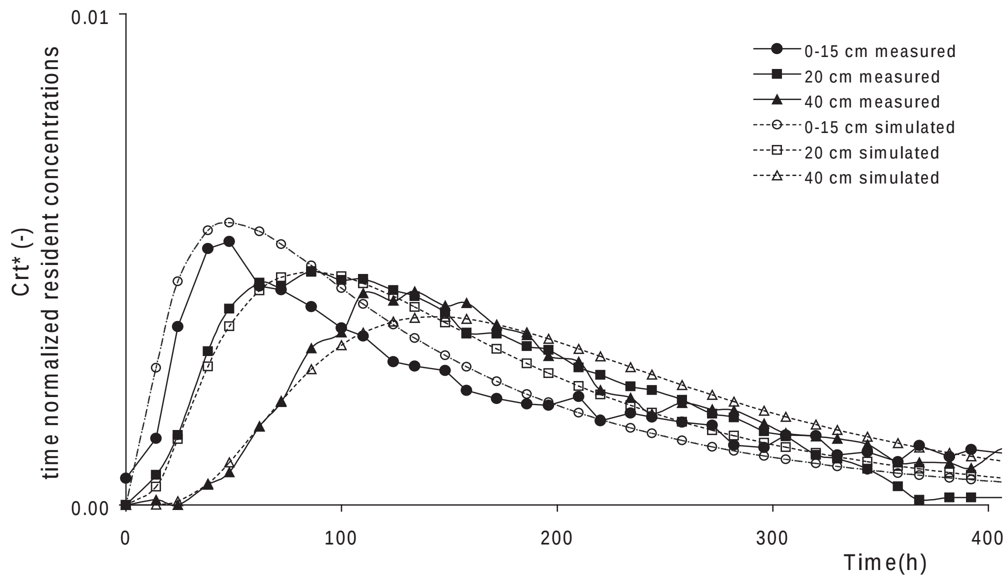

Figure 4. Observed and fitted normalized resident concentrations, Crt*, for site 18.

GTF parameters were obtained by fitting the following nonlinear four-parameter function:

$$C^{rt*}(z,t) = \frac{a\ln(t) - a\sigma_z^2 - a\mu_z + \lambda_1}{t\lambda_1\sigma_z\sqrt{2\pi}} \exp\left[-\frac{(\ln(t) - \sigma_z^2 - \mu_z)^2}{2\sigma_z^2}\right]$$
$$a = \frac{(\lambda_2 - \lambda_1)}{\sigma_z^2}\left[1 - \frac{1}{\exp(\sigma_z^2)}\right] \qquad (1)$$

to the Crt* curves (see Figure 4). In equation 1, μ and σ are the mean and standard deviation of lnt and λı and λ2 are parameters of the time moments (Zhang, 2000).

In order to identify robustly the governing transport mechanisms, the least square optimization simultaneously were applied to all the three Crt* curves measured at three different depths. Since the model is able to describe a wide range of dispersion processes evolving with depth, fitting the model to all the depths together resulted in only one parameter set through which the transport process could be directly identified. The difference between the two fitted parameters, λ1 and λ2, characterizes the evolution of the dispersivity with depth while λ1 provides information on the variation of solute velocity with depth.

Thus, transport mechanisms can be classified in function of the difference λ1- λ2: i) if λ1-λ2=0, that is the variance of the ln(t) is constant with travel distance, the process is SC; ii) if λ1-λ2<0, the variance of ln(t) increases with travel distance and the process is scale dependent; iii) if λ1-λ2>0, the variance of ln(t) decreases with travel distance as in the CD model (λ1-λ2=0.5).

In the same way, transport processes can be classified in terms of the relationship between dispersivity, α, and depth. In this study the dispersivity was calculated in terms of GTF parameters. The convection-dispersion (CD) and the stochastic-convective with log-normal distribution of travel times (SC) models represent two radically different solute transport mechanisms. The models respectively conceptualize independent and correlated solute travel times with depth. The depth dependency of the dispersivity will reveal whether the solute transport process meets the CD or the SC assumptions. A linear increase of α(z) for SC and constant α(z) for the CD are expected. In some cases the variance of ln(t) increases with the travel distance and a scale-dependent transport process different from CD and SC should be used.

Thus, a plot of α(z) enables us to identify whether the solute transport mechanism meets the CD or the SC assumptions or whether different scaling parameters for the travel time distribution moments should be used.

Figure 5 shows the evolution with the distance of the λ1-λ2 values obtained along the transect.

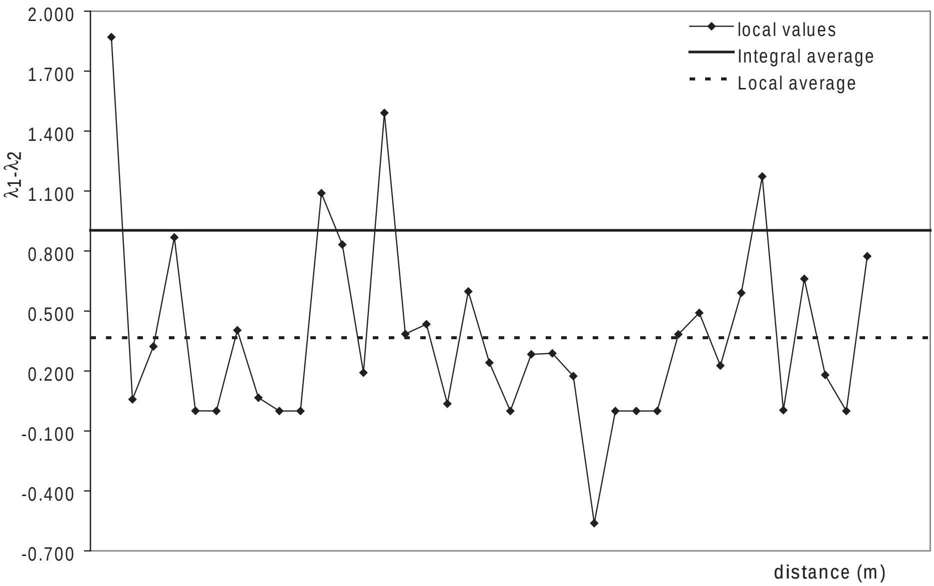

Figure 5. The evolution with the distance of the λ1-λ2 values obtained along the transect.

The maximum value observed was of 1.87 and the average was 0.366.

The difference is at all but one site positive, thus indicating a transport mechanism which is in general of the CD type. Nevertheless, if one couples the graph in Figure 5 and graph in Figure 6, showing the dispersivity as a function of the depth for three sites along the transect one can see that the transport process is frequently a scale dependent process with a contrasting behaviour. In some cases the dispersivity is constant with depth, as in the CD model, while in other cases dispersivity may increase (as predicted by the SC model) or even decrease with depth.

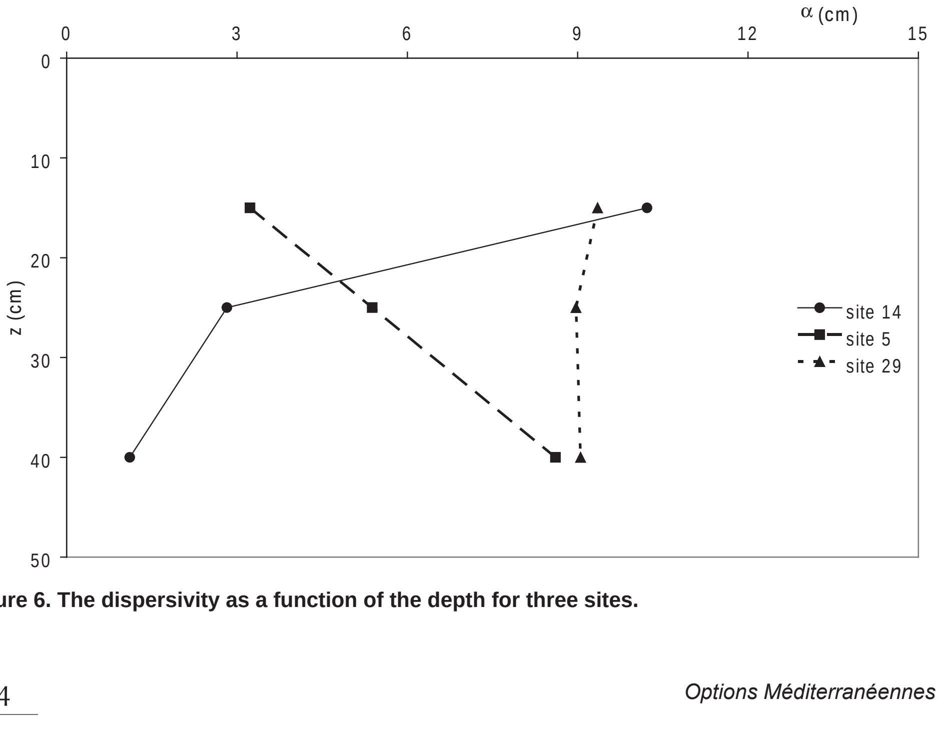

Figure 6. The dispersivity as a function of the depth for three sites.

Figure 7 shows the evolution with distance along the transect of the dispersivity at the three depths.

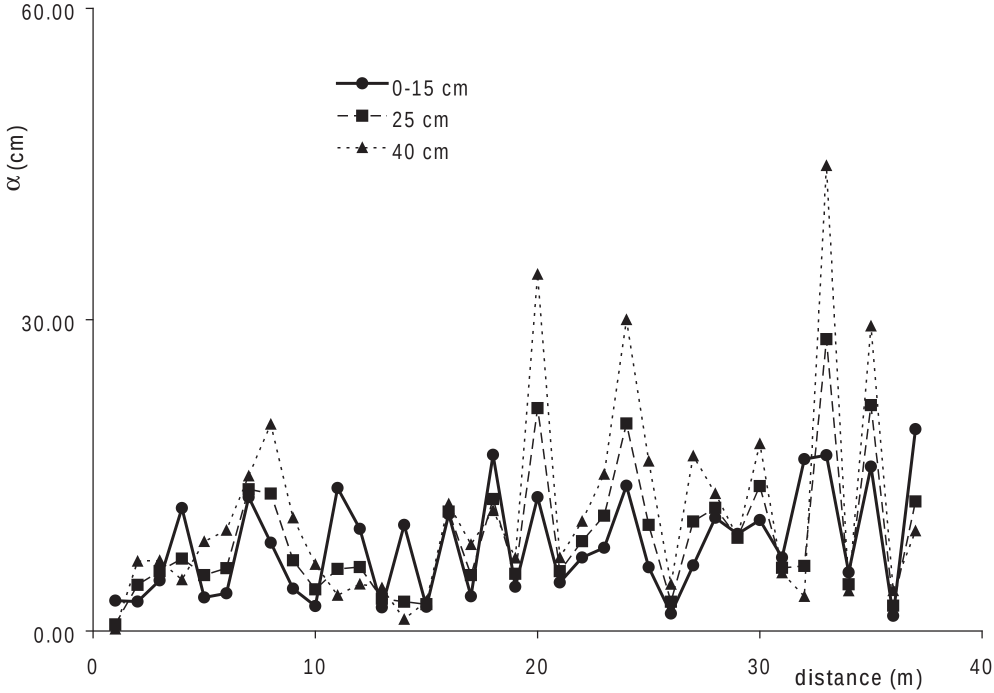

Figure 7. The evolution of dispersivity along the transect at the three observation depths.

The figure shows generally increasing values of dispersivity with depth (SC transport mechanism). However, there are cases were an inverse behaviour was observed. The values of dispersivity at 40cm allow also to discriminate two different zones along the transect, one with relatively small values and one with large values of dispersivity. As dispersivity is generally considered an intrinsic property of porous media related to the soil particle aggregation and the consequent pore-size distribution, higher values of the parameter could be related to a better soil structure, even at large depths, in the second part of the transect. Like for the water content, variograms for the dispersivity showed no significant spatial dependence for all depths, beyond the minimum separation distance of the TDR probes (1m).

However, one should be aware that estimating soil solute transport parameters at local scale is only a first step toward the prediction of solute transport at field scale, which is the shortest scale of applicative interest. Extrapolating local scale solute transport experiments to field situations remain a complex issue because of the natural heterogeneity of soils. Accordingly, the second objective of this work was to assess the transition from the local scale to the field scale during unsaturated flow conditions.

Two limiting horizontal spatial scales were considered in terms of solute transport mechanism and parameters: the local scale and the field scale. The field scale behavior was analyzed in terms of what we call a local parameter average and an integral measurement average.

The first one was obtained by determining the local scale solute transport mechanism and related parameters for each location and then by averaging the parameters over locations. The average value (0.366) for $\lambda 1$-$\lambda 2$ is shown as a dashed line in figure 5.

Figure 8 shows the local average dispersivity values in function of depth, z (8.28, 8.91 and 11.35 cm for the depths of 0-15, 25 and 40 cm, respectively).

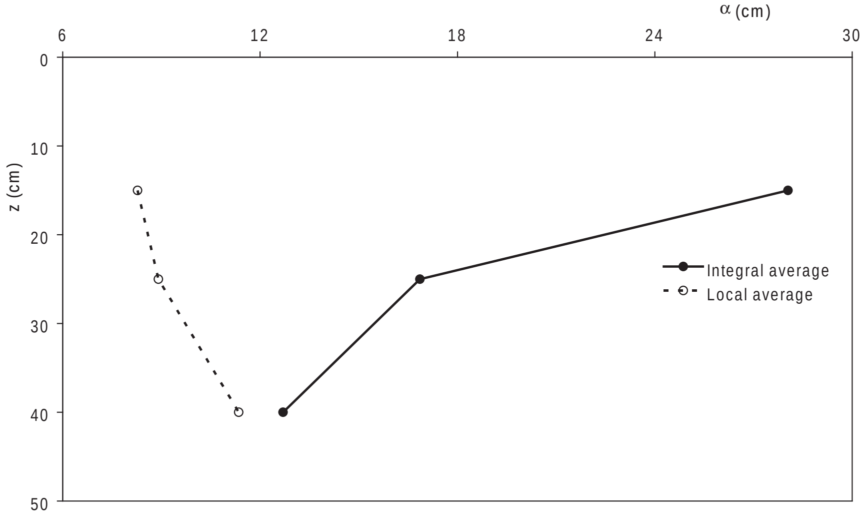

Figure 8. Local and integral average dispersivity values as a function of depth.

It can be seen that the dispersivity behaviour follows a SC transport mechanism even if it seems to start as a CD like mechanism. A dispersivity increasing with depth was observed.

The integral measurement average was obtained from the same measurements by firstly averaging the time normalized resident concentrations to get a single global curve for the whole transect and then evaluating the global scale solute transport mechanism and related parameters.

Figure 9 shows the integral average curves for the three depths, along with the best fitting obtained in terms of GTF parameters.

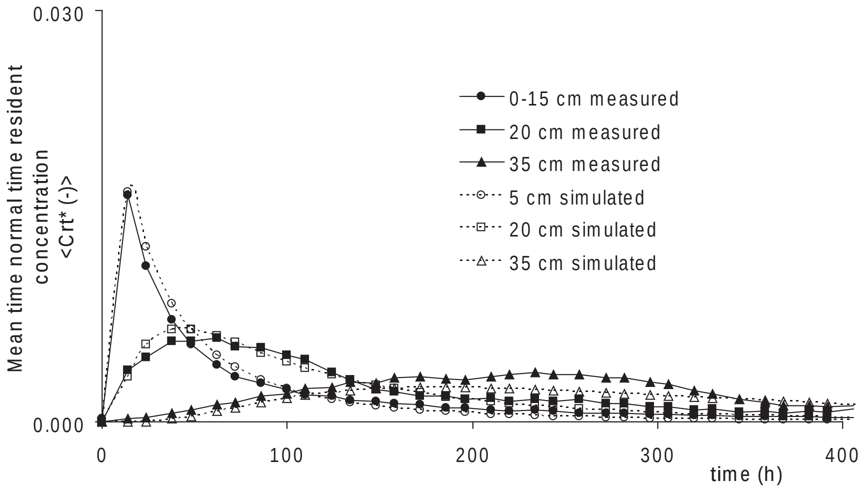

Figure 9. The integral average curves for the three depths, along with the best fitting obtained in terms of GTF parameters.

A difference $\lambda1-\lambda2=0.904$ was obtained, along with integral average values of dispersivity of 28.05, 16.86 and 12.70 cm, for the three depths, respectively. These dispersivity values are plotted in figure 8.

In general, the comparison between local average and integral average approach results in a global process (as indicated by the corresponding $\lambda1-\lambda2$ values, which differ significantly). Concerning the dispersivity, a contradictory behaviour has been estimated with the two different averaging approaches. The integral average approach results in dispersivity values decreasing with depth, thus resulting also in very different predictions of solute travel time distributions.

The only way for solving the complex dilemma of choosing the appropriate averaging scheme the local scale behavior (measurement or parameters) for a correct transition from the local scale to the field scale behavior would be a comparison of measurement at different scales.

Unfortunately, this study was not a true comparison of measurements at different scales but rather a comparison of estimates of parameters at two scales based on measurements at single locations. Anyway, the results confirm that the transfer of information (upscaling) from the local scale to a larger scale is a practice which remains to a large extent unresolved due mainly to the complex variability of soil hydrological properties. Understanding this transition is crucial to effectively predict transport processes for applicative uses.

IV – Conclusion

TDR measurements at the local scale were used to estimate solute transport parameters at both the local and field scale. In a sense, this study was not a true comparison of measurements at different scales but rather a comparison of estimates of parameters at two scales based on measurements at single locations.

In this study, closed-form expressions for the time normalized resident concentrations, Crt*, for the generalized transfer model (GTF model) have been applied. The Crt* pdf was fitted to the measurements in all the 37 sites and gave excellent results. This means that with real data, the transport process can be directly identified by observing the $\lambda1$and $\lambda2$ fitted parameters. The difference between these two parameters characterizes the evolution of the dispersivity with depth while $\lambda1$ provides information on the variation of solute velocity with depth.

The least square optimization was applied simultaneously to all the three Crt curves measured at three different depths. Since the model is able to describe a wide range of dispersion processes evolving with depth, fitting the model to all the depths together resulted in only one parameter set which should have a better predictive power.

The additional parameters $\lambda1$ and $\lambda2$ can be robustly estimated as the information on the propagation mechanism is significantly carried by the three curves used simultaneously in the fitting procedure.

With the local scale parameters at hand, there is the successive problem of defining an aggregation rule to obtain large scale parameters for large scale simulations. This frequently involves a transfer of information (upscaling) from the microscale to a larger scale, a practice which remains to a large extent unresolved due mainly to the complex variability of soil hydrological properties.

Two limiting horizontal spatial scales were considered in terms of solute transport mechanism and parameters: the local scale and the field scale. The field scale behavior was analyzed in terms of what we called a local parameter average and an integral measurement average. The first one was obtained by determining the local scale solute transport mechanism and related parameters for each location and then by averaging the parameters over locations. The second one was obtained from the same measurements by firstly averaging (taking into account the different water content measured at each location) the time normalized resident concentrations to get a single global curve for the whole transect and then evaluating the global scale solute transport mechanism and related parameters. It was shown that the average of the local set of parameters does not represent effectively the integral average of the measurements.

The only way for solving the complex dilemma of choosing the appropriate averaging scheme of local scale behavior (measurement or parameters) for a correct transition from the local scale to the field scale behavior would be a comparison of measurement at different scales.

Unfortunately, this study was not a true comparison of measurements at different scales rather than a comparison of parameters estimation at two scales based on measurements at single locations. Specific design of experiments was prepared to determine the validity of estimating solute transport behavior at field scale as the average of all point measurements or the average of the local scale parameters over that spatial scale.

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