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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.

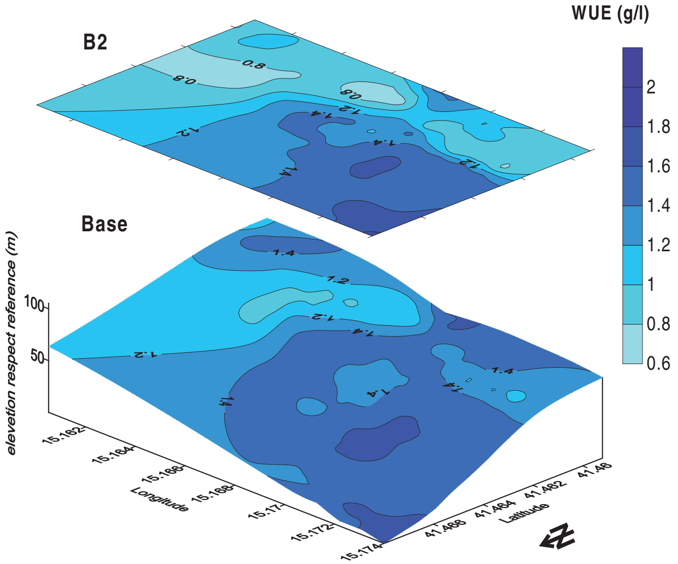

Figure 1. Distribution of the simulated WUE in the Volturino catchment during the baseline and the B2 scenarios.

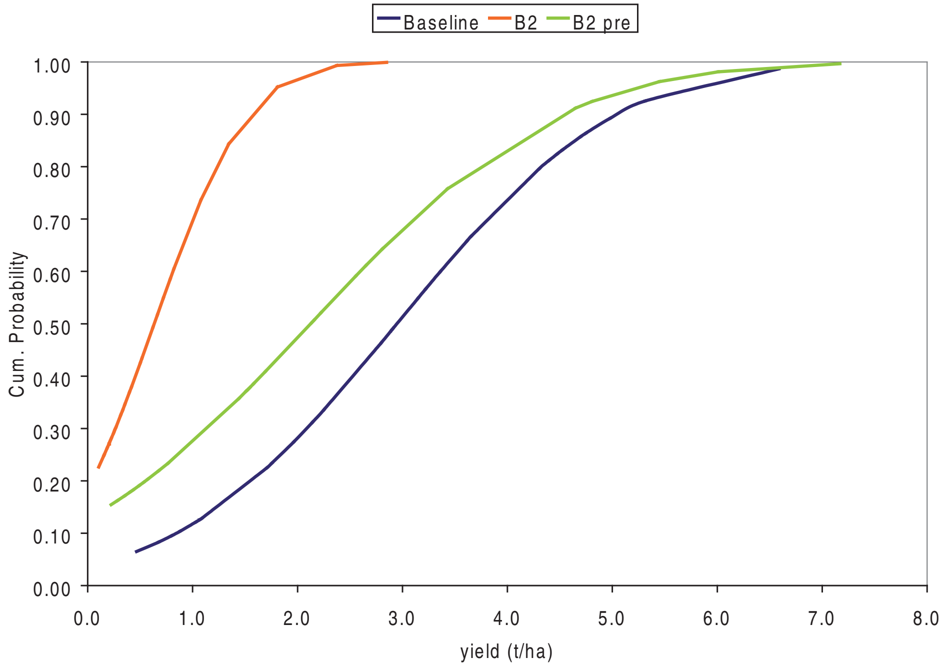

Figure 2. Cumulative probability of simulated yield for baseline and B2 scenarios, considering the traditional sowing date and a early sowing date in the future scenario (B2 pre).

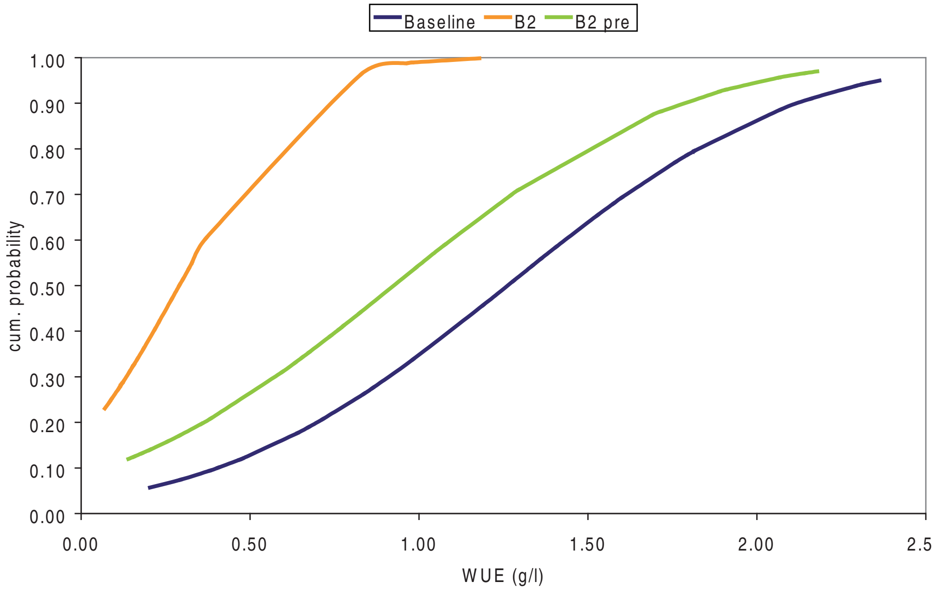

Figure 3. Cumulative probability of simulated WUE for baseline and B2 scenarios, considering the traditional sowing date and a early sowing date in the future scenario (B2 pre).

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.

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