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PHYSIOLOGICALLY RELATED TOOLS FOR THE ASSESSMENT OF IRRIGATION SYSTEMS PERFORMANCE MONITORING WATER STATUS IN CROP PLANTS

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SUMMARY - The objectives of management of irrigation systems may be defined as high crop productivity per unit land per unit applied water with equity in distribution. Some of the key elements of irrigation system management are: (i) performance monitoring and evaluation, (ii) diagnostic appraisal, (iii) action research, and (iv) farmers' participation. The earlier generation of irrigation performance indicators was based on canal flow data. Commonly, they quantify performance in a command area downstream of a discharge measurement device. There is a need for a refinement in spatial scale as compared to the classically collected flow measurements. This refinement could describe moreover depletion from all water resources. If these possibilities were well implemented, we would expect that a new generation of irrigation performance indicators could be quantified in a cost-effective manner. The objective of this paper is to present some physiological tools that could be used to assess the performance and support management of irrigation systems under Mediterranean conditions. These tools are related to carbon isotope discrimination and remote sensing. These practical guidelines were originally provided to breeders of small grain cereals interested in adopting a physiological approach to crop improvement, but could be adapted into performance indicators related to the functioning and service provided by irrigation systems. Some of the most promising tools for fast, reliable characterization of yield-determining traits are discussed from an ecophysiological perspective. We will focus on the practical aspects and limitations of using relevant screening tools or selection criteria.

Key words: carbon isotope discrimination, remote sensing, irrigation systems performance.

INTRODUCTION

Irrigation water to crops is an effective means of enhancing agricultural production and productivity. In addition, irrigation provides the basis for a better and more diversified cropping pattern and growing of high-value crops, and thus facilitates overall improvement in socio-economic conditions of the farming community. A considerable amount of work has been undertaken in the past 15 years to develop a framework for irrigation performance assessment. Irrigation performance indicators cover the traditional aspects related to adequacy, equity and reliability of the water service (Wolters 1992; Murray-Rust & Snellen 1993; Bos et al. 1994). The framework of performance indicators includes environmental sustainability features to evaluate the longer-term effects irrigation has on the environment such as groundwater table changes (Bos et al. 1991). The literature reported in the last two decades indicates that the performance of irrigation schemes, particularly large areas, is far below expectations. The magnitude of underperformance is well represented by Seckler et al. (1988). Up to the mid-1980s, the lack of performance indicators was the main reason preventing the evaluation of irrigation system performance in quantifiable units. Moreover, monitoring and evaluation have received much lip service in the present decade and have seldom been carried out properly and effectively. One of the main reasons is that the conventional methods of data collection through field observation are difficult, time-consuming and cannot be carried out at the same time particularly in large irrigated commands. In addition, monitoring is not possible at frequent intervals.

ISP assessment based on conventional data. The evaluation of the efficiency of irrigation water use has undergone major modifications during the last 25 years. It moved from the classical irrigation efficiencies (Bos & Nugteren 1974; Jensen 1977) to the current performance indicators (Levine 1982; Small & Svendsen 1990; Bos et al. 1994) and, to the framework of water accounting at a regional scale (Molden 1997; Burt et al. 1997). The required data to calculate all these indicators consist of discharge measurements, crop irrigation water requirements, effective rainfall, actual evapo-transpiration, irrigated area, cropping intensity and crop yield among others.

ISP assessment based on remote sensing data. Remote sensing data to determine actual evapo-transpiration and crop water stress for managing irrigation systems was suggested by several authors in the eighties (e.g. Jackson et al. 1981; Jackson 1984; Ben Asher et al. 1986). However, Azzali & Menenti (1987) showed how high resolution Landsat images could be used to map crops and crop phenology stages in two Italian irrigation districts, and to detect crop-specific effects such as water stress. Menenti et al. (1989) made a list of indicators that could be quantified with remotely sensed data.

ISP assessment based on physiological data. The use of physiological traits as screening tools in breeding for yield is still largely experimental, for different reasons. Sometimes the traits are very indirectly related to yield or there is little ecophysiological understanding of the crop, especially when breeding for yield under stress. Nevertheless, breeding for crop escape has been very successful; phenological changes have been the most important indirect factor in increasing wheat yields under Mediterranean conditions. However, in breeding for crop resistance, the evaluated traits and screening tools are often related to tolerance, not avoidance. An indirect (i.e. physiology-based) breeding strategy could fail to produce yield gains and might even lead to a decrease in yield. Improved plant tolerance, though it protects the crop, can limit yield potential. The most promising ecophysiological methods allow for quick screening of “integrative” physiological traits, so called because they integrate physiological processes either in time (i.e. during the plant cycle) or at the organization level (e.g. whole plant, canopy). Nevertheless, remote sensing detection of fluorescence spectra at the canopy level could become a promising approach for breeding purposes. Despite the objections shown for breeding strategies for yield, the physiological tools will ultimately be related to the performance of the irrigated crop. We propose carbon isotope composition of plant tissues and spectral reflectance methods, as integrative physiological traits that could be used in assessing the performance and the hydrological efficiency of irrigation systems, in order to improve water saving.

PHYSIOLOGICAL TOOLS

The physiological tools presented here were originally proposed to small cereal grains breeders interested in adopting a physiological approach to the improvement of their varieties. The potential contribution of the physiological approach to plant selection, as well as their inherent limitations and the requirements to fit, have been recently reviewed extensively from a purely breeding perspective (for example, Jackson et al. 1996). The theoretical framework to define the physiological determinants of yield of cereal crops, which are the obvious candidates to be evaluated have also been reasonably well established.

One approach to search for 'potential' traits to be used in breeding programs is to identify the physiological processes determining productivity. Therefore, yield can be easily divided in several integrative components or traits. The yield itself is the most integrative trait, because it is influenced by all the (known and unknown) factors which are actually determining productivity. However, there many known limitations in a purely empirical approach to breeding only based in yield. Therefore, any breeding strategy based in a physiological (i.e. analytical) approach should use screening tools or criteria that would allow evaluation the integrative physiological parameters which are determining harvestable yield with a single measurement. For the assessment of the performance of the Irrigation Systems, it should be defined a set of suitable physiological criteria of the crops, easy to be measured with the proposed tools, and with strong correlation with the classical irrigation performance indicators.

In the following pages we will focus on tools used to evaluate physiological traits determining total biomass, not strictly yield. We will discuss two different kinds of screening tools for integrative physiological traits: the carbon isotope discrimination (Δ) and the indexes based on the spectral-reflectance of the canopy. The Δ not only evaluates genotypic differences in water use efficiency, but it used to be much more affected by the environment (e.g. water status) which is most relevant for irrigation scheduling. Thus, Δ is affected by the total amount of water transpired by the crop or by photosynthetic activity. Main limitation of Δ for irrigation scheduling is the time needed for analysis. Nevertheless, fast evaluation of Δ through NIRS is feasible (Ferrio et al 2002). Spectral reflectance of the canopy is one of the most promising remote sensing techniques. Canopy temperature, which is another remote sensing technique, has the advantage of low cost, compared to spectral reflectance equipments and it provides integrative information of the water status of the crop at the canopy level (Reynolds et al. 1994). However, genotype differences in both phenology and canopy architecture can further limit its validity.

Carbon Isotope Discrimination

Brief theory of carbon stable isotopes in plants

There are two stable carbon isotopes (^{13}C and ^{12}C), which occur in the molar ratio of 1:99 in the atmosphere. Nowadays, $^{13}C/^{12}C$ ratios are usually determined by mass spectrometry and referred to the PeeDee Belemnite (PDB) standard, as carbon isotope composition ($\delta^{13}C$) values:

$$\delta^{13}C(‰) = \left[\left(\frac{R_{sample}}{R_{standard}}\right) - 1\right] * 1000 \qquad [1]$$

where R stands for the $^{13}C/^{12}C$ ratio. On this basis, present $\delta^{13}C$ in air CO_2 is about -8‰. However, plants with C_3 photosynthetic pathway contain proportionally less ^{13}C than the CO_2 they fix during photosynthesis, and their typical $\delta^{13}C$ is about -29‰. The difference observed between air and plant $\delta^{13}C$ is usually expressed as carbon isotope discrimination ($\Delta^{13}C$), and can be calculated as follows (Farquhar et al. 1989):

$$\Delta^{13}C(‰) = \frac{\delta_a - \delta_p}{1 + \delta_p} \qquad [2]$$

where δ_a and δ_p refer to air and plant composition, respectively. This parameter reflects the amount in which the heavier isotope ^{13}C is discriminated respect the lighter ^{12}C during the physical and chemical processes involved in the synthesis of plant organic matter (Farquhar et al. 1989). The values of $\Delta^{13}C$ in C_3 plants reflect the balance between diffusion in the intercellular space (mostly through stomata) and carbon fixation by the carboxylating enzyme RuBisCO (Ribulose Bisphosphate Carboxylase-Oxygenase). When stomata are open (see Fig. 1a), the amount of CO_2 available for fixation is greater and the chances for discrimination against ^{13}C during carboxylation increase (which leads to higher $\Delta^{13}C$). In contrast, when CO_2 diffusion is limited by stomatal closure plants are forced to fix a higher proportion of ^{13}C, leading to lower values of $\Delta^{13}C$ (Fig. 1b).

Relationship between $\Delta^{13}C$ of plant material and water availability

Plants typically react against a decrease in water availability through stomata closure and thus Δ from plant tissues provide an integrated record of the water status during the time they were formed (see Farquhar et al. 1989 for further details on carbon isotope theory). Many studies under growth-chamber and field conditions have shown that plants developed under water stress produced leaves with lower $\Delta^{13}C$ (see references in Hubick et al. 1993; Ferrio et al. 2003b). According to these findings, it would be expected to find significant relationships between $\Delta^{13}C$ and environmental parameters related with water availability. Although most of the basic studies on $\Delta^{13}C$ and plant water relations were performed on leaf material (as this is the tissue directly involved in photosynthesis), further works has shown that similar relationships can be established in other plant tissues.

In Fig. 2a, for example, we can see an application of $\Delta^{13}C$ to the analysis of cereal grains. Araus et al. (1997, 1999, 2003) reported a strong relationship between water inputs and $\Delta^{13}C$ values from barley (*Hordeum vulgare*) and wheat (*Triticum durum*/*aestivum*) grains across a wide range of environmental conditions. They included both irrigated and rainfed trials, and total water inputs from heading to maturity (i.e. rainfed plus supplemental irrigation, if any) were considered, as this is the time when grain tissue is formed. Both species gave nearly identical results, showing that, despite their differences, they have similar physiological responses to water stress. On the other hand, it should be noted that in both cases the observed relationship was not lineal, suggesting that $\Delta^{13}C$ was more sensitive to water availability in the driest environments. This could be explained by the fact that the main factor relating $\Delta^{13}C$ with water availability is stomatal conductance, which is supposed to reach its maximum in non-stressed plants. Thus, under near-optimum water status, no further increments in stomatal conductance, and thus on $\Delta^{13}C$, would be expected (Farquhar et al. 1989; Lambers et al. 1998).

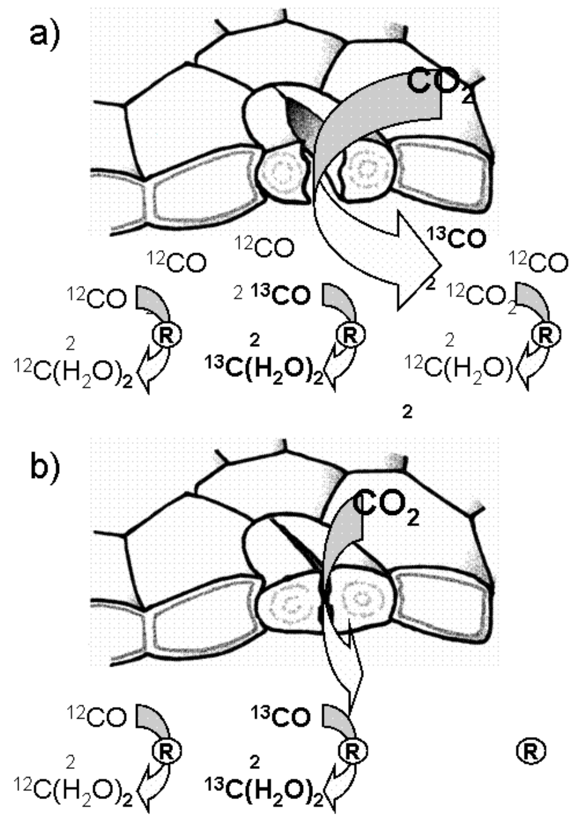

Fig. 1. Simplified scheme of the relationship between carbon isotope discrimination ($\Delta^{13}C$) in C_3 plants and stomatal conductance. A) High stomatal conductance, high discrimination: CO_2 diffusses easily into the intercelular space, the activity of the carboxylating enzyme (represented as **R**) is not limited by CO_2 concentration and thus it has more chances to discriminate against ^{13}C. B) Low stomatal conductance, low discrimination: the flux of CO_2 is reduced, and the limiting factor of photosynthesis is stomatal conductance. In this case RuBisCO is forced to fix a higher proportion of ^{13}C. Redrawn from Ferrio et al. (2003b).

Another example of the various species and compounds where $\Delta^{13}C$ analyses are applicable is shown in Fig. 2b. Ferrio et al. (2003a) studied the $\Delta^{13}C$ from wood samples of Aleppo pine (*Pinus halepensis*) and holm oak (*Quercus ilex).* Both species are typically Mediterranean, but they display contrasting strategies against drought. The former is a clear drought avoiding species, with a fast stomatal closure, whereas the latter relies mostly on a very effective water uptake, and is partly drought tolerant. They also found a strong relationship between $\Delta^{13}C$ and annual precipitation (unlike grains, tree rings are formed throughout the year), which was also steeper among the most arid environments. Interestingly, $\Delta^{13}C$ in Aleppo pine was far more sensitive to water availability than in holm oak. Again, the explanation relies on the close relationship between $\Delta^{13}C$ and stomatal conductance. As the stomata of Aleppo pine showed faster responses to drought, the $\Delta^{13}C$ for this species have greater variations with changes in water availability. In contrast, the holm oak can extract water from drier soils, as well as from deeper water tables, showing relatively low variations in $\Delta^{13}C$ among trees growing in contrasting environments. Thus, although the relationship between $\Delta^{13}C$

and water availability is quite clear for most of C_3, it is species-dependent, as a consequence of the variability in the physiological responses of plants.

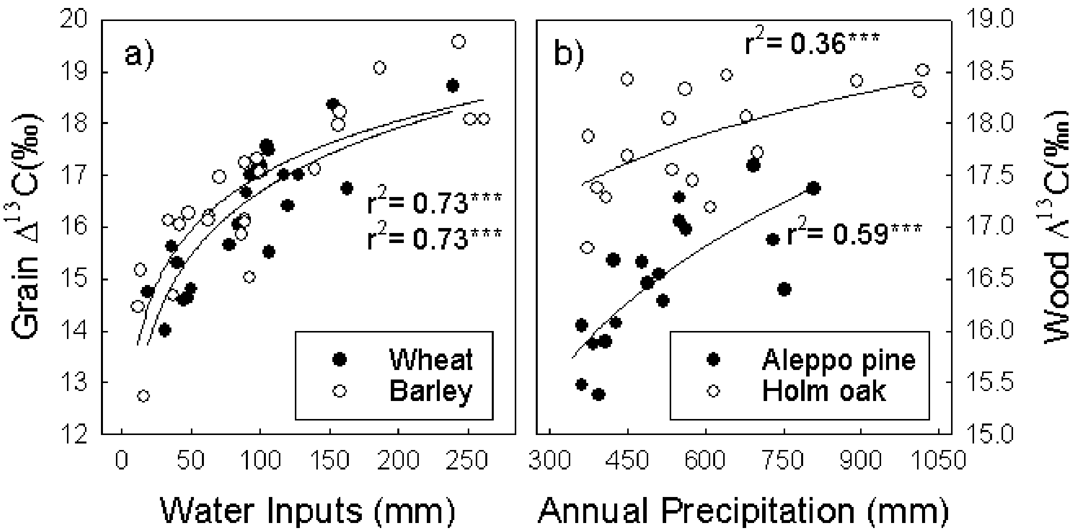

Fig. 2. Relationship between: a) water inputs (WI, rainfall plus irrigation if applied) during grain filling and $\Delta^{13}C$ of barley and wheat grains. Data from Araus et al. (1997a) for barley and from Araus et al. (1999; 2003) for wheat; $\Delta^{13}C_{barley}$= 9.99 + 1.52*ln (WI); $\Delta^{13}C_{wheat}$= 8.50 + 1.78*ln (WI) b) mean annual precipitation of 20-25 years and $\Delta^{13}C$ of wood from the corresponding tree-rings of Aleppo pine and holm oak. Redrawn from Ferrio et al. (2003a); $\Delta^{13}C_{pine}$= 4.63 + 1.91*ln (WI); $\Delta^{13}C_{oak}$= 11.72 + 0.97*ln (WI).

Spectral reflectance methods

The pattern of light reflection on leaves at different wavelengths through the photosynthetically active radiation (PAR, 400-700 nm) and near infrared radiation (NIR, 700-1200 nm) regions of the electromagnetic spectrum is very different from that of soil and other materials (Figure 3). Leaf pigments absorb light strongly in the PAR region but not in the NIR, thus reducing the reflection of PAR but not of NIR. Such a pattern of pigment absorption determines the characteristic reflectance signature of leaves (Figure 4). Similarly, the light spectrum reflected by a canopy (either natural or agricultural) differs from that reflected by the bare soil and varies in a way that can be related to the overall area of leaves and other photosynthetic organs in the canopy, as well as to their pigment composition and other physiological factors (Figure 5). Therefore, the measurement of spectra reflected by vegetation canopies provides information that can be used to estimate a large scope of parameters. Some of them are related to the green biomass of the canopy, its photosynthetic size (i.e. total area of leaves and other photosynthetic organs), the amount of PAR absorbed by the canopy, and its photosynthetic potential. Other parameters are more related to the canopy's physiological status at the time of measurement and can be used to assess the extent of some nutrient deficiencies and environmental stresses. The physiological parameters that can be estimated by spectral reflectance techniques include chlorophyll and carotenoid concentrations, photosynthetic radiation use efficiency (PRUE), and water content. Water Index (WI) has been used to track changes in a number of parameters related with the water status of the crop (leaf water potential, stomatal conductance, and other). Some of these physiological parameters might show a kind of relationships with indicators of classical irrigation efficiencies used for assessment of ISP, in a similar manner than satellite measurements.

Spectral reflectance indices

Spectral reflectance indices are formulations based on simple operations between reflectances at given wavelengths, such as ratios, differences, etc, which are widely used to quantitatively relate changes in reflectance spectra to changes in physiological variables. These indices have the advantage of summing up in a few numbers the large amount of information contained in a reflectance spectrum with narrow waveband resolution.

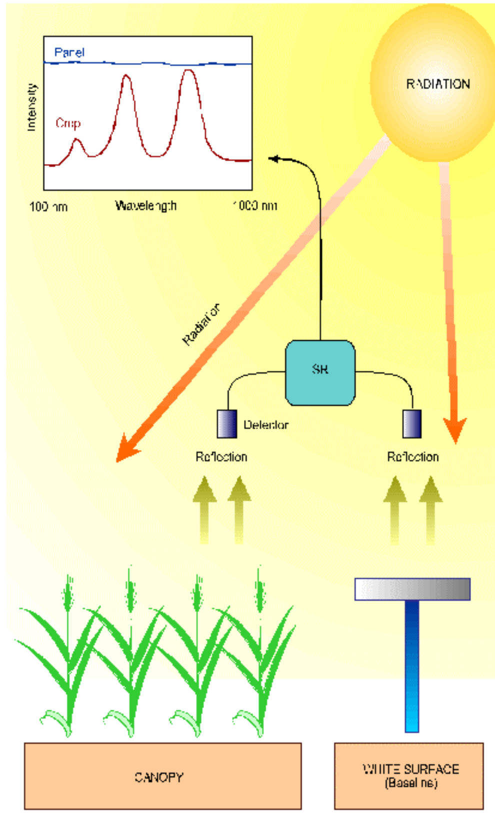

Fig. 3. Spectral reflectance from crop surfaces.

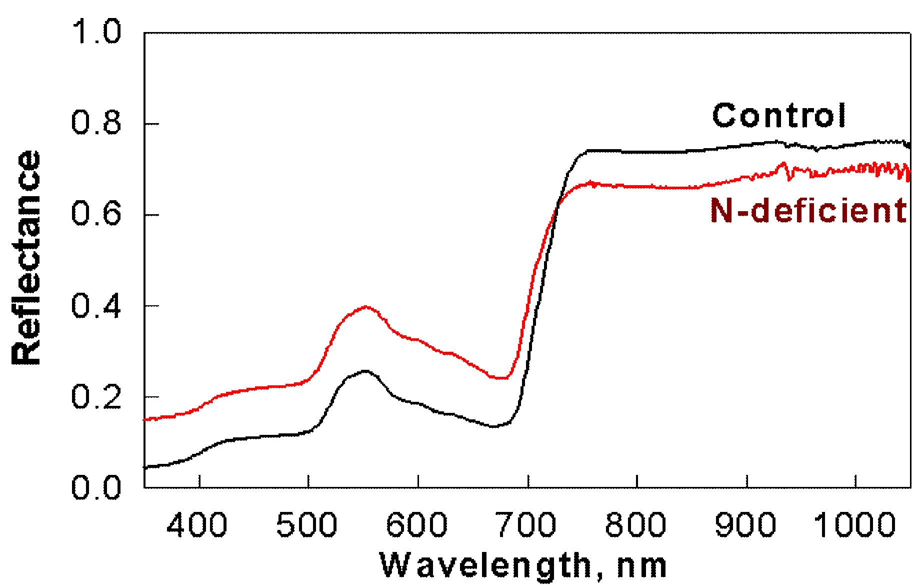

Fig. 4. Reflectance signature of two wheat leaves differing in nitrogen status. Note the higher reflectance in the PAR region of the nitrogen deficient leaf due to lower chlorophyll content in the leaf area.

Originally used in remote sensing by aircraft and satellites, reflectances measured at the ground level are very useful for assessing agrophysiological traits. These traits can be evaluated simultaneously in each sample, at a rate of up to one thousand samples per day, which is much more tedious and time consuming with other methods. This makes spectroradiometric indices ideal for screening for yield potential or for resistance to different stresses, and eventually for assessment of ISP.

Sample applications

Perhaps the most widespread application of reflectance indices is for assessing parameters related to canopy greenness. These parameters are related to the canopy's photosynthetic size and include green biomass, leaf area index (LAI) (total one-side leaf area of the crop relative to soil area), green leaf area index (GLAI) (similar to LAI, but includes only functional green leaves), and green area index (GAI) (similar to GLAI, but includes other photosynthetic organs such as green stems). The amount of green area in a canopy determines PAR absorption by photosynthetic organs, which in turn determines the canopy's potential production. The fraction of the incident PAR that is absorbed by the canopy (fPAR) can be estimated from LAI-related parameters or directly from reflectance measurements. Cumulative PAR absorption, which is one of the parameters determining total biomass and thus final yield, can be assessed by measuring reflectance periodically during the growth cycle.

Some physiological parameters can also be quantified by spectral indices. Leaf pigments can be detected and quantified based on reflectance spectra and can be used as indicators of several physiological processes. Thus, the canopy's nutritional state can be evaluated through pigment concentration, as chlorophyll (Chl) concentration in leaves is (usually) closely correlated to its nitrogen content. Indices that are good indicators of Chl are (usually) also good indicators of N-content. In addition, plants with low N usually have a high carotenoid (Car) to Chl ratio, which can also be assessed by reflectance indices (Figure 5).

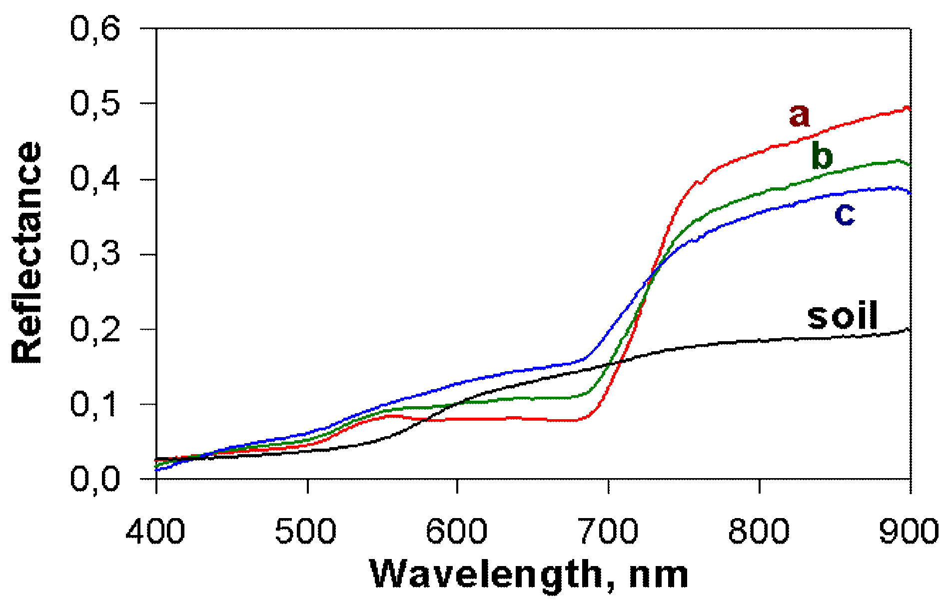

Fig 5. Changes in the pattern of canopy reflectance of a durum wheat grown in the field. Measurements were taken every three days (a, b, c), during the last week of the grain filling period, coinciding with fast crop senescence. Note the decrease, during senescence, in the amplitude of the change in

reflectance in the red-NIR (around 700 nm) edge. Note also the increase within the PAR region of the reflectance in the red compared to the blue band due to a relatively faster decrease during senescence in chlorophyll compared to carotenoids. The pattern of soil reflectance is also included for comparison.

Pigment remote sensing can also be used for assessing the crop's phenological stage (Figure 5) and the occurrence of several stress factors (Blackburn 1998; Peñuelas 1998). For example, the Car to Chl ratio can be associated with senescing processes that result from the plant's natural ontogeny pattern or are triggered by different stresses. Also, phenological stages can be associated with different Car/Chl values. Several indices related to changes in pigment composition have been developed and can be used for the remote detection of nutrient deficiencies, environmental stresses, pest attacks, etc. In such contexts, by periodically assessing leaf area, leaf area duration (LAD) can also be used as an indicator of resistance to certain environmental stresses.

The photosynthetic capacity of a canopy can be estimated by using vegetation indices that correlate to the photosynthetic size of the canopy or indices related to the amount of chlorophyll. However, actual photosynthesis may not match photosynthetic capacity due to the variability of photosynthetic use efficiency of the absorbed radiation, especially when plants are exposed to unfavourable conditions (climate, performance or the irrigation system). The photochemical reflectance index (PRI) was developed to detect pigment changes in the xantophyll cycle associated with changes in PRUE (Filella et al. 1996). PRI has been shown to track the changes in PRUE induced by factors such as nutritional status and midday reduction, across different species and functional types.

Another potential application of reflectance indices is remote detection of relative water content (RWC) of plants. Different levels of water stress, which could be related with the performance of the irrigation system, can be detected indirectly through their effects on vegetation indices related to leaf area, pigment concentration, or photochemical efficiency. Specific indices like Water Index have been developed for the direct assessment of RWC.

Use of Canopy Reflectance Indices

Assessing the photosynthetic size of canopies using vegetation indices

Vegetation indices (VI) estimate parameters related to the photosynthetic size of a canopy based on the reflectances in the red and near infrared regions. Green biomass, LAI, GAI, GLAI, fPAR, etc, can be estimated through their positive correlation (either linear or logarithmic) with vegetation indices (Wiegand and Richardson 1990a, 1990b; Baret and Guyot 1991; Price and Bausch 1995). Measuring vegetation indices periodically during the crop growing cycle allows the estimation of LAD (which can be used as an indicator of environmental stress tolerance) and the total PAR absorbed by the canopy, which is one of the most important factors for predicting yield (Wiegand and Richardson 1990a, 1900b).

Vegetation indices take advantage of the great differences in reflectance at red and NIR caused by vegetation. The most widely used VI are the simple ratio (SR) and the normalized difference vegetation index (NDVI), which are defined as:

$SR = R_{NIR} / R_{Red}$, with a range of 0 to ∞,

where R_{NIR} is the reflectance at NIR and R_{Red} is the reflectance at red.

$NDVI = (R_{NIR} - R_{Red}) / (R_{NIR} + R_{Red})$, with a range of -1 to 1.

SR and NDVI were originally used with the wide wavebands of former radiometers (for example, 550-670 nm for red and 710-980 nm for near infrared in AVHRR radiometers in satellites of NOAA series). With the high spectral resolution of today's radiometers, wavebands can be much narrower. Hall et al. (1990) used a waveband centred at 770 nm for NIR and another at 660 nm for red, while Peñuelas et al. (1997b) used 900 nm and 680 nm for NIR and red, respectively.

Some authors have reported improvements in NDVI performance after changing the wavebands used in the index. Carter (1998) describes an improved correlation with leaf photosynthetic capacity when using a modified NDVI where R701 (+/-2nm) and R520 (+/-2nm) were used for NIR and red, respectively.

Variations of these indices have been proposed to compensate for the effect of soil background, which might be very different depending on the crop type, and on the irrigation system. Thus the soil adjusted vegetation index (SAVI) was defined by Huete (1988) as:

$$SAVI = [\ (R_{NIR} - R_{Red}) / R_{NIR} + R_{Red} + L)\ ]\ (1 + L),$$

where the parameter L was adjusted to minimize noise caused by soil for a large range of soil covers. For most crop conditions L=0.5, while for very low soil covers L=1 would be more appropriate, and L=0.25 would be appropriate for very high covers (Huete 1988).

Other indices include parameters obtained from the soil's reflectance spectrum. One of them is the transformed soil adjusted vegetation index (TSAVI) which was defined by Baret and Guyot (1991) as:

$$TSAVI = a(R_{NIR} - aR_{Red} - b) / [R_{Red} + a(R_{NIR} - b) + 0.08(1+a^2)],$$

where a is the slope and b is the intercept of the linear equation

$$R_{NIRsoil} = a^*R_{Red}\ soil + b.$$

An important drawback in estimating LAI by VI is the saturation of the VI with LAI. Saturation of NDVI starts at about LAI=1, and beyond LAI=2 it becomes insensitive to further increases in LAI (Gamon et al. 1995). Perpendicular vegetation index (PVI) partly overcomes the saturation problem inherent to NDVI (Richardson and Wiegand 1977):

$$PVI =\{(R_{Red.soil}-R_{Red.vegetation})^2 + (R_{NIR.vegetation}-R_{NIR.soil})^2\}^{1/2}$$

Although PVI is more sensitive than NDVI to changes in the viewing geometry, PVI does not become as clearly saturated as NDVI with changes in GLAI (Shibayama et al. 1986).

Examples of assessing LAI-related parameters by VI can be found in the literature (Baret and Guyot 1991; Field et al. 1994; Price and Bausch 1995). Ground level measurement of VI has been used successfully as a tool for assessing early biomass and vigour of different wheat genotypes (Elliott and Regan 1993; Bellairs et al. 1996) and for assessing the intensity of different plant stresses, Peñuelas et al. (1997b).

A practical use of vegetation indices is for making yield predictions. Yield can be predicted from successive VI measurements taken during the growing season, based on the following assumptions (Wiegand et al. 1991, Wiegand and Richardson 1990b, Rudorff and Batista 1990): 1) plant stands integrate the growing conditions experienced and express net assimilation achieved through the canopy, 2) stresses severe enough to affect economic yield will be detectable through their effects on crop development and the persistence of photosynthetically active tissue in the canopy, 3) high economic yields cannot be achieved unless plant canopies fully utilize available solar radiation as the plants enter the reproductive stage, and 4) vegetation indices calculated from remote observations in appropriate wavelengths effectively measure the photosynthetic size of the canopy.

Remote sensing of pigments

<u>Estimation of chlorophyll concentration</u>. Several indices have been developed for estimating Chl concentration using canopy reflectance methods. The simplest indices are just reflectance at 675 and 550 nm. Reflectance at 675 nm (R675) is very sensitive to changes in Chl content. However, the relationship becomes saturated at relatively low Chl values (around 10 µg cm-2) and is a good indicator of chlorophyll content only at very low concentrations. Absorption by Chl at 550 nm is lower than at 675 nm; therefore, the reflectance at this wavelength (R550) is less sensitive to changes in

Chl content but is not saturated at such low concentrations, thus covering a range of higher Chl values (Thomas and Gausman 1977; Jacquemoud and Baret 1990; Lichtenthaler et al. 1996).

Both R675 and R550 are non-normalized indices that can be affected by external factors (Curran 1983). Other indices use more than one wavelength. Analyzing wavelengths that were more sensitive to changes in Chla, Chlb, and Cars in soybean leaves grown at different N levels, Chapelle et al. (1992) developed the ratio analysis of reflectance spectra (RARS) indices (RARSa = R_{675} / R_{700}; RARSb = R_{675} / (R_{650} * R_{700}); RARSc = R_{760} / R_{500}), which optimized the estimation of Chla, Chlb, and Cars, respectively, in soybean leaves. Other reflectance indices that can be used for estimating pigment concentration are summarized in Table 1.

In addition to the wide variety of indices related to absolute Chl concentration, the normalized phaeophytinization index (NPQI) can be used to detect chlorophyll degradation.

NPQI = (R415 - R435) / (R415 + R435) (Peñuelas et al. 1995c)

NPQI was introduced as an indicator of pest attacks on apple trees (Peñuelas et al. 1995c).

Estimation of the Carotenoid to chlorophyll ratios. Estimating the Car : Chl ratio by reflectance indices can be useful for assessing the extent of some plant stresses and eventually the performance of the irrigation system, given that increases in Cars concentration relative to Chl are often observed when plants are subjected to stress (Young and Britton 1990).

Both Chl and Car absorb in the blue, but only Chl absorbs in the red. Indices that are combinations of the reflectance in these two regions are correlated to the Car : Chl ratio. The simplest indices are pigment simple ratio (PSR) and normalized difference pigment index (NDPI), which are formulated in an analogue way to SR and NDVI and defined to estimate the ratio of total pigments to Chla (Peñuelas et al. 1993a):

PSR = R_{430} / R_{680}, NDPI = (R_{680} - R_{430}) / (R_{680} + R_{430})

Both PSR and NDPI are affected by disrupting effects introduced by leaf surface and structure. A new index was developed to avoid such problems: the structural independent pigment index (SIPI), which was defined by Peñuelas et al. (1995a) as:

SIPI = (R_{800} - R_{435}) / (R_{415} + R_{435})

SIPI uses wavelengths showing the best semi-empirical estimation of the Car : Chla ratio, and its formulation minimizes the disrupting effects of leaf surface and mesophyll structure (Peñuelas et al. 1995a). R_{800} is used as a reference where neither Cars nor Chl absorb and are only affected by the structure.

Indices related to the Cars : Chl ratio change during the crop growing cycle. They are low during vegetative growth and start to increase before the beginning of senescence (Filella et al. 1995). They can be used in assessing the nutritional state of a crop (Filella et al. 1995), shown by high values of the indices when N is low, and for detecting pest attacks (Peñuelas et al. 1995c).

Assessing radiation use efficiency by PRI

Canopy photosynthesis can be roughly estimated based on the estimation of the canopy's photosynthetic size or Chl concentration. However, these parameters are associated with potential canopy photosynthesis, which does not always correspond to actual photosynthesis, especially for plants growing in stressful environments. While VI are correlated with PAR absorption by the canopy (a slowly varying trait, in a range of days to weeks), the photochemical reflectance index (PRI) is correlated with photosynthetic radiation use efficiency (PRUE) of absorbed PAR, a rapidly varying process, in a range of hours (Gamon et al. 1997).

Part of the PAR absorbed by Chl cannot be used for photosynthesis and is lost mainly through heat dissipation, which is linked to the xanthophyll-de-epoxidation cycle (Demmig-Adams and Adams

1996). PRI reflects changes in reflectance of around 531 nm, which have been associated with pigment changes in the xanthophylls cycle (Gamon et al. 1992; Peñuelas et al. 1995b). It is defined as:

$PRI = (R_{531} - R_{570}) / (R_{531} + R_{570})$,

where PRI is correlated with the de-epoxidation stage of the xanthophylls cycle, with zeaxanthin, and with radiation-use efficiency (Filella et al. 1996). Higher PRI values indicate greater efficiency.

Directly assessing plant water status

Some bands of radiation absorption by water exist in the 1300-2500 nm region, but due to its high absorptance in this region, reflectance becomes saturated (i.e. it does not respond to further increases in RWC) even in a canopy with low water content. In the 950-970 nm region, there is some weak absorption of radiation by water that is not saturated for a moderately dry canopy. The reflectance at 970 has been used in the definition of the water index (WI).

$WI = R_{900} / R_{970}$, (Peñuelas et al. 1993b, 1997a)

In WI, reflectance at 970 nm is taken as a wavelength sensitive to water content, while reflectance at 900 nm is taken as a reference which is similarly affected by canopy and leaf structures but with null absorption by water.

WI has been used to track changes in RWC, leaf water potential, stomatal conductance, and foliage minus air temperature differences when plant water stress is well developed (RWC<0.85) (Peñuelas et al. 1993b). Peñuelas et al. (1997a) reported a correlation coefficient of around 0.55 between WI and RWC for a range of species measured at different times of the year in their natural Mediterranean environment. As for stress detection, Peñuelas et al. (1997b) showed that WI was a good indicator of water status in response to salinity.

WI might be the most relevant spectroradiometrical index for decision-making in irrigation scheduling.

CONCLUSIONS

Physiological tools of common use in agronomical assessment of yield performance and environment adaptation of crop canopies could be of use, with some adjustments and/or calibrations, in the assessment of the performance of Irrigation Systems

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