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Agricultural Water Management Research Trends

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AGRICULTURAL WATER MANAGEMENT RESEARCH TRENDS

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MAGNUS L. SORENSEN
EDITOR

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CONTENTS

PREFACE

Agricultural water management includes many topics: farm-level and regional water management, irrigation, drainage, and salinity management of cultivated areas, collection and storage of rainfall in relation to soil properties and vegetation; the role of groundwater and surface water in nutrient cycling, exploitation and protection of water resources, control of flooding, erosion, and desertification. This new book presents leading-edge research from around the world.

Expert Commentary - Eddy covariance technology has been used for crop water use measurements (evapotranspiration, ET) widely because its operation is relatively simple and the equipment is less expensive than constructing a lysimeter. However, this technology has energy closure problems. These problems can be caused by low wind speed, stable conditions, horizontal flux or/and canopy roughness. In addition, wind sensor leveling, air humidity, and footprint can affect the ET measurement accuracy. This commentary discusses how to check ET measurement accuracy and how to measure accurate ET using eddy covariance technology.

Chapter 1 - According to climate change assessments, less precipitations and higher temperatures can be expected in the Iberian Peninsula and other Mediterranean zones. Besides, an increment in droughts and other extreme events can be expected as well. Such climatic conditions require an effort to optimize irrigation technologies and to improve water management efficiency. There are currently available water-use and crop-growth simulation models, which can be combined to climate scenarios and weather generators in order to recommend, through many simulations, the most reliable irrigation management. The Preliminary Assessment of the Impacts in Spain due to the Effects of Climate Change and the National Plan for Adaptation to Climate Change recommend the use of such simulation tools in Spanish climate-change impact assessments. Those tools, however, have not been used yet to support irrigation decision-making in the authors country. In that sense, the EU-funded proposal AGRIDEMA, leaded by Spain, has been addressed to introduce such tools, connecting the tools “providers” from Universities and high-level research centres, with their “users”, located in agricultural technological or applied-research centres. AGRIDEMA comprised courses and Pilot Applications of the tools. Local researchers knew in the AGRIDEMA courses how to access to GCM data and seasonal forecasts, they receive also basic knowledge on weather generators, statistical and dynamical downscaling; as well as on available crop models as DSSAT, WOFOST, CROPSYST, SWAP and others. About 20 pilot assessments have been conducted in several European countries during AGRIDEMA, applying the modelling tools in particular cases.

The AGRIDEMA results are commented, mentioning particularly the Pilot Assessments that were held in Spain and in the Mediterranean area. Furthermore, several “users” opinion regarding the available climate and crop-growth simulation tools are also pointed out. Those opinions can be used as important feedback by the tools “developers”. An illustrative example on how modelling tools can help to manage Sugarbeet irrigation under present and future climate conditions in Spain is also shown. Several future research directions are pointed out, as followed from the shown example and the AGRIDEMA results. Those research directions agree with the actions recommended in the Spanish National Plan for Adaptation to Climate Change, as well as in the European and international guidelines. Stakeholder will adopt climate-change mitigation options only if they realize the reliability of such options on their specific cases. To achieve this, the “users” of the modelling tools must develop local demonstration proposals, aimed to model calibration and validation, etc. Particularly, some demonstration proposals should be aimed to recommend productive and efficient irrigation water managements under the adverse climate conditions that Spanish farmers will eventually face in the next years.

Chapter 2 - Castilla-La Mancha is located in the middle of the Iberian Peninsula. Due to its location, the water resources of this area are essential to the development of the neighbouring coastal regions. These areas have one of the most competitive agricultural systems in the European Union, an important industrial sector and tourism industry, and a high percentage of the Spanish population. For these reasons, the volume of water assigned to cover the demands of Castilla-La Mancha is approximately one third of the generated water resources.

The agricultural sector is the main water consumer in the region (more than 90%), which plays an important economic and social role. The transformation of large rainfed areas into irrigated lands during the last 30 years has limited the emigration of rural populations to cities or other industrialized regions of Spain. The water used for this transformation is mainly groundwater. Due to the lack of previous studies about the natural recharge of the aquifers and to an obsolete legislation, the three main irrigated areas of the region (08.29 Mancha Oriental: 8,500 km^2 and 100,000 ha of irrigated land; 04.04 Mancha Occidental: 5,000 km^2 and 153,000 ha of irrigated land; and 04.06 Campo de Montiel: 2,500 km^2 and 7,000 ha of irrigated land), suffer groundwater overexploitation.

In Castilla-La Mancha there are several institutions that try to optimize the use of water for agriculture and to improve the competitiveness of this sector to achieve sustainable development. In general, all these institutions work together with farmers in carrying out an integral and integrated management of the water resources.

CREA is the only institution that works in the entire region. In consequence, the irrigated areas experience different levels of advisory. In addition, it is necessary to emphasize that, water resources in Castilla-La Mancha are managed by seven different public authorities. This situation, together with the characteristics of each basin, causes a high variability in management methodology.

This paper attempts to elucidate the research, management, and dissemination actions carried out in Castilla-La Mancha, where agriculture is an essential sector with problems of water scarcity due to both semiarid climatic conditions, and the importance of the resources generated in Castilla-La Mancha for the development of other regions.

Chapter 3 - Irrigation management requires information on evapotranspiration (ET). The ET of a well irrigated crop (ETc) is usually approached through an empirical equation using reference ET (ETo) and crop coefficients (Kc): ETc = ETo × Kc. Discrepancies have been observed between Kc measured in several row crops and Kc values recommended in currently used manuals. Therefore, a need arises to address this problem via further field measurements of ET. Some limitations to the application of micrometeorological and hydrological methods to measure ET in small fields or in woody crops are briefly described and sap flow methods (SF) are presented as an alternative to quantify transpiration (T), the major component of ET. A clear underestimation of T with SF data was observed in several conditions, when compared to data from eddy covariance (EC) micrometeorological method. By combining robust, low cost SF methods with reliable EC measurements, an EC-SF relationship can be developed to correct SF measurements. Using this combination, ET and Kc data series can be extrapolated in time (e.g., for a whole season) or space (when micrometeorological methods are not suitable, as in small areas). Some case studies show the combination of complementary EC-SF methods to follow the seasonal variation of ET and Kc (vineyards, kiwi and peach orchards) proving its usefulness in long term studies. A second aspect discussed is the fact that calculating crop ET as ETo × Kc implicitly assumes continuous adequate available soil water for optimum plant growth. However, even for irrigated crops, ET is often below ETc and called actual ET (ETa). Besides, due to growing water scarcity, deficit irrigation strategies are increasingly being explored. Under water stress, the reduction of ET due to stomatal closure is higher for rough canopies and/or woody crops than for low crops and cannot be neglected. Therefore, for practical purposes, ETa can be estimated as ETo × Kc × Ks where Ks is a stress coefficient (Ks = ETa/ETc). The relationship between Ks and soil water depletion (ET since last irrigation) can be used to estimate how much water to apply and when to irrigate. This relationship varies with soil type, ET rate, and root distribution. Hence, it must be adjusted, which can be done empirically as a function of observations of plant water status. The use of relationships between water stress indicators improves the identification of threshold values for practical purposes.

Chapter 4 - In this chapter the author is presenting a methodology and basic equations permitting to establish models to monitor water, nutrient and salt distribution in the oasis soil under different irrigation system, to determine the best oasis architecture for an efficient use of resources, to estimate the amount of water really needed by plants and the oasis productivity, to test the efficiency of irrigation and drainage network, to detect the eventual diseases that can attack the three vegetable stories, to predict plant species distribution, to search indicators for environmental planning and ecosystem risk analysis. Finally, a method to scale up or extrapolate results from one stand to all the region have been evoked and a case study have been presented.

Chapter 5 - Agricultural activity in Chile is very important both in terms of economic impact and in particular in terms of social aspects. This activity depends on great extent, and over most of the territory, on the availability and the efficient use of water for irrigation purposes. Taking this into account, both the Chilean government and the private sector have made significant investment efforts for the improvement of irrigation infrastructure. For example, the Law 18.450 has provoked an important increment on the irrigated surface in Chile. Also, the water code, which dates from 1981, was recently modified, with the aim of introduce modifications allowing a better access and use of water by the privates.

Within this context, it is also worth to mention that the Chilean Government has defined as one of the strategic lines of actions of the governmental plan to transform Chile into a leading producer of agricultural goods and food by 2010. Although it is true that this goal include several components, it seems rather clear that water management in relation with agriculture will continue to be a key aspect of the strategy as well as Chilean Governmental efforts. Moreover, recently (2006) it was published, by a Chilean Governmental Institution the “Agricultural Innovation Agenda”, where are defined and proposed innovation actions in 15 key productive chains and themes, being one of them water resources. There are several specific lineaments and actions described in the referred document representing the visions of public entities (Universities, Research institutions) as well as the private sector. Some of the lineaments defined in that document, can be summarized in the following way: “To promote an integrated vision of water resources at the watershed level, in relation with the water market improvement and to the availability and use of base information of water to be used for irrigation purposes, avoiding environmental pollution problems”. Based on this premise, and considering the information gathered and obtained by the authors, an analysis is done in relation to current agricultural water resources situation as well as research opportunities for the Chilean irrigated agricultural activity, mainly based on particular, but widely representative, experiences in two basins of the North-Central South-Central zones.

Chapter 6 - A frequent response of fruit trees to deficit irrigation (DI) is a promotion of flowering. This response is often explained because of a lesser competition with exuberant vegetative growth. Here, the authors report the effects of regulated DI on loquat shoot growth and flowering and discuss the possible mechanisms involved in the promotion of flowering in water-stressed trees. Loquat is a subtropical tree crop that bloom in autumn after a period of summer dormancy. Loquat flowers develop in panicles formed at the apex of the new shoots, therefore shoot growth has to cease before flower initiation can take place. In the authors experiments, the flowering of fully irrigated trees of ‘Algerie’ loquat was compared with the bloom in trees undergoing three different levels of DI implemented at post-harvest from mid-June to the end of July. DI levels during these six weeks were: light (50% of the water applied to controls), moderate (25% of the water applied to controls) and severe (no watering). Minor effects due to DI were found on flowering intensity. In contrast, water-stressed trees reached bloom before controls (between 10 and 27 days, depending on treatment). The more severe the water stress was, the earlier the blooming resulted. Blooming advancement was produced despite final shoot length and leaf number remained essentially the same. On the contrary, DI profoundly altered the pattern of shoot growth that changed from a single sigmoid to a double sigmoid. This shift was the result of water stress causing an early, but transitory, cease of growth, which was reassumed up to the length of controls when water deficit ended. Observations carried out under scanning electron and conventional microscopy indicate that panicle initiation occurred days before the fully establishment of summer dormancy, when growth rate in the apical meristem slowed down. The advancements of summer dormancy and panicle initiation correlates well with blooming date advancement.The authors results question the hypothesis of resource competition between flowering and vegetative growth and suggest that flowering promotion is the result of a diminished growth rate in the apical meristem due to hormonal changes that favour the process of flower induction. This theory is coherent with the promotion of flowering in response to growth inhibitors and with the negative effects that gibberellins have on tree blooming. The modification of reproductive phenology by the management of the agricultural water may represent a new avenue for improving profitability in tropical and subtropical fruit crops.

Chapter 7 - It is increasingly realized that water resource management has played a vital role in Australia’s economic, environmental and social sustainable development. However, many water-related issues face growing scrutiny and policy debate. A major part of the Council of Australian Governments (COAG) water reforms was the development and implementation of consistent and tradable water entitlements, which represent key attempts to standardize approaches to water resource management at a national scale. As part of this process, the Murray-Darling Basin (MDB) has faced a number of challenges in designing a robust system of water entitlements that jointly meet the needs of entitlement-holders, community and the environment. This chapter aims to identify the features of different water entitlements arrangements and develop a classification system. First, the chapter outlines an overview of water management in the MDB. Next, it provides a property rights analysis of existing water entitlements arrangements and the broad directions that governments may take in the light of water entitlements system reforms. Then, a water entitlements classification system is proposed and its policy implications are discussed. The chapter concludes that significant challenges remain to be overcome before implementing a consistent and tradable water entitlements system in the MDB.

Chapter 8 - Potato, maize, sunflower, sugar beet, soy-bean, and tomato were cultivated in a lysimeter set-up on two soil types, loam and clay, simultaneously during the same season Crops were grown under the same conditions of climate, mineral nutrition and plant density and were well-watered during the whole crop cycle.

As for potato, sunflower and sugar beet, stomatal conductance, evapotranspiration, leaf area, yield, and radiation use efficiency (RUE) were systematically lower on clay than on loam. The other three species were not sensitive to soil texture, excepted for the yield of maize.

The results cast doubt on RUE’s values being independent from soil texture, as is commonly hypothesized by models simulating the productivity under well-watered conditions.

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Expert Commentary

EDDY COVARIANCE MEASUREMENTS OF CROP WATER USES: THE ENERGY CLOSURE PROBLEM AND POTENTIAL SOLUTIONS

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ABSTRACT

Eddy covariance technology has been used for crop water use measurements (evapotranspiration, ET) widely because its operation is relatively simple and the equipment is less expensive than constructing a lysimeter. However, this technology has energy closure problems. These problems can be caused by low wind speed, stable conditions, horizontal flux or/and canopy roughness. In addition, wind sensor leveling, air humidity, and footprint can affect the ET measurement accuracy. This commentary discusses how to check ET measurement accuracy and how to measure accurate ET using eddy covariance technology.

INTRODUCTION

Current measurement methods for crop water use (evapotranspiration, ET) mainly include lysimeter, eddy covariance, energy balance, surface renewal, Bowen ratio, and remote sensing technologies. Lysimeter measurement of ET is the standard, Eddy covariance represents the next level of accuracy, and the other methods follow.

Eddy covariance technology has been used widely because of its relatively simple operation and lower expense for equipment compared to constructing a lysimeter. An eddy covariance system consists of a vapor concentration sensor (e.g., infrared open-path Licor-7500, Campbell Sci., Inc., Logan, Utah) and a high-frequency sonic wind velocity sensor (e.g., CSAT3, Campbell Sci., Inc., Logan, Utah) to measure ET, which can be expressed as latent heat of vaporization, LE. In addition, the system can measure virtual air temperature and H, where H is sensible heat to the atmosphere (Wang et al., 2007). However, this technology has energy closure problems in cases where net radiation (Rn) does not equal LE + H + G, where G is sensible heat to the soil. For example, the average energy closure rate at the Fluxnet (22 towers) is 75%, and the rate is sometimes below 40% (Wilson et al., 2002). (FLUXNET is a global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide, water vapor, and energy between terrestrial ecosystems and the atmosphere.) This problem can be caused by low wind speed, stable conditions or horizontal flux. The apparent underestimate of LE may also relate to canopy roughness. In addition, wind sensor leveling, air humidity, and footprint can affect the ET measurement accuracy.

This commentary discusses how to check ET measurement accuracy and how to measure accurate ET using eddy covariance technology.

ENERGY BALANCE

The common way to check the accuracy of and calibrate covariance measurements is to check the energy balance. One can install net radiometers and soil heat flux plates to complete the energy balance measurements and use the energy balance method to check the result of LE calculations from the eddy covariance method (Sammis et al., 2005; Simmons et al., 2007).

The energy budget equation is:

$$LE + H + G = Rn$$

If the energy is not balanced, there must be problems in one or more of the energy components. Problems in Rn measurements can occur when the sensor is not level or the domes have not been kept clean. Also, the net radiometer must be high enough to represent the average Rn over the canopy cover. Another problem is the measurement of G using soil heat flux plates. The number and distribution of the heat flux plates must be sufficient to give an average value for the canopy conditions. Because measuring the H component with the eddy covariance method involves a simpler technology than does measuring LE, it is assumed that the eddy covariance system measures H accurately except under certain conditions (low wind speed, stable stratification, in high canopies, or in any case when air mixing is significantly reduced or/and atmosphere-surface are decoupled. http://www.licor.com/env/Products/GasAnalyzers/eddyPresentation/EC_master_Presentation_files/_frame.htm). If all the components are measured accurately except LE, then one can calibrate the LE measurements of the eddy covariance equipment using the LE obtained from the energy budget equation (Sammis et al., 2005; Simmons et al., 2007). Researchers have used the Bowen ratio to correct both H and LE to get energy closure (e.g., Cleverly et al., 2002), but no rational reason is given to assume that both H and LE are in error using the eddy covariance technology. Before calibrating the LE measurements using energy closure, it is important to make all the proper corrections for the calculation of H and LE from the eddy covariance technology.

HUMIDITY CORRECTION

Air moisture can affect flux measurements (Schotanus et al., 1983). An air temperature and humidity sensor (e.g., CS500, Campbell Sci., Inc., Logan, Utah) needs to be mounted next to an eddy covariance system in order to obtain the vapor pressure in the air, which can be used to make moisture corrections to H (Schotanus et al., 1983). In addition to this correction, when the turbulent flux of any constituent is measured by the eddy covariance system, the simultaneous flux of any other entity needs to be taken into account. In particular, heat or water vapor can cause expansion of the air and thus affect the constituent's density and flux. Corrections can be done for LE flux based on the vapor and heat flux's effects on the densities of moist air (Webb et al., 1980). In flux measurements for a full-canopy pecan orchard in Las Cruces, New Mexico, USA (Wang et al., 2007), humidity-corrected ET was only 3% different from uncorrected values; the corrected sensible heat flux was 30% different from the uncorrected (sensible heat flux was near zero at this orchard). Usually the error related to the uncorrected fluxes can be 0-50% (http://www.licor.com/env/Products/GasAnalyzers/eddyPresentation/EC_master_Presentation_files/_frame.htm).

COORDINATE ROTATION

If the sonic sensor in a covariance system is not well leveled, the covariance calculations will produce errors. One may rotate the data to obtain the accurate ET data. There are different rotation methods. The traditional method is to set the vertical wind velocity (W) to be zero and the mean wind direction to be perpendicular to the W direction (Tanner and Thurtell, 1969; Kaimal and Finnigan, 1994). Other rotation methods were also developed (Lee et al., 2004). The errors (unrotated flux) depend on the instrument tilting level. The larger the tilting angle, the larger the errors (unrotated flux). Usually, the error is about 0-25% (http://www.licor.com/env/Products/GasAnalyzers/eddyPresentation/EC_master_Presentation_files/_frame.htm).

APPROPRIATE AVERAGING TIME

Appropriate averaging time should be chosen for eddy covariance measurements. Usually daytime averaging time is longer than nighttime. Vickers and Mhart (2006) provide a cospectra method and corresponding software to determine the averaging time. Using this paper and its software we obtained averaging times for an eddy covariance system for a full-canopy pecan orchard at Las Cruces, NM, USA. An infrared open-path Licor-7500 (Campbell Sci., Inc., Logan, Utah) and a high-frequency sonic wind velocity sensor (CSAT3, Campbell Sci., Inc., Logan, Utah) were set up above the pecan canopy. A CR23X was used to record the data (Campbell Sci., Inc., Logan, Utah). The sampling frequency was set to 20 Hz. For the pecan orchard in the nighttime, the averaging time should be 100 seconds (the intersection point of cospectra curve and the x axis) (Figure 1). The daytime averaging time should be 32,768 seconds (54 minutes) (Figure 2).

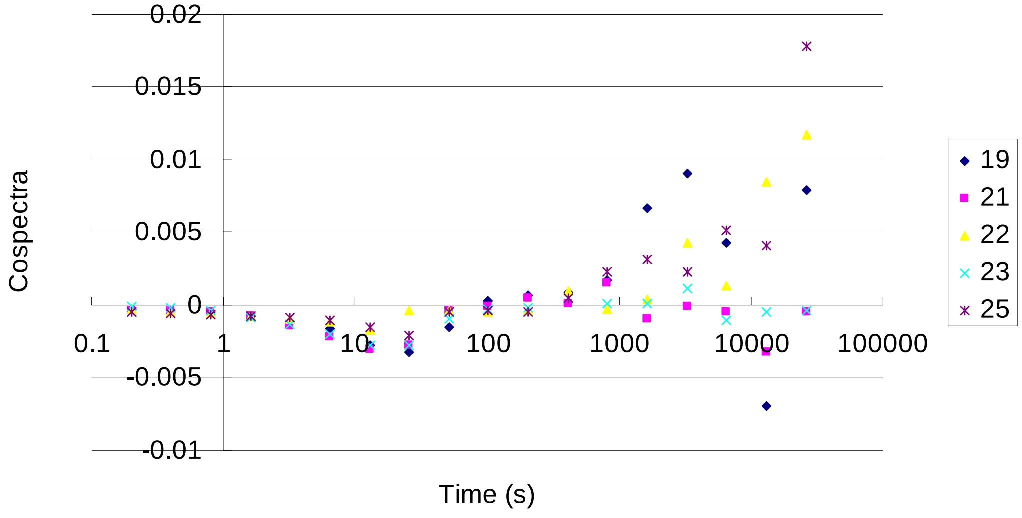

Figure 1: The ET cospectra in nighttime (21:00–5:00) on August 19, 21, 22, 23, and 25 for a full-canopy pecan orchard at Las Cruces, NM, USA.

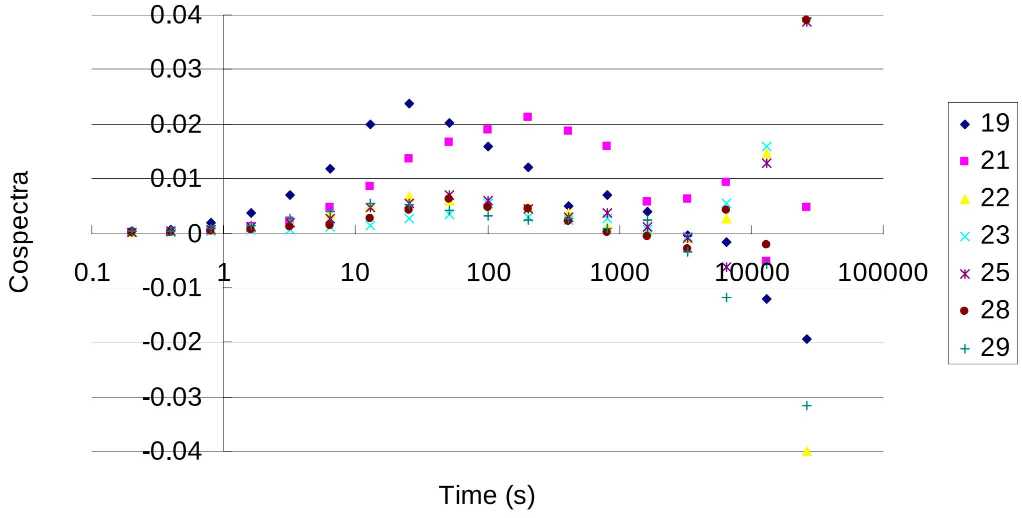

Figure 2: The ET cospectra in daytime (9:00–17:00) on August 19, 21, 22, 23, 25, 28 and 29 for a full-canopy pecan orchard at Las Cruces, NM, USA.

If one uses a 30-min averaging time (commonly used in the literature), the absolute error of ET measurements will be 33.7% in nighttime (ET is close to zero in the nighttime) and 3% in daytime, based on the data in Figures 1 and 2 (Vickers and Mahrt, 2005).

FOOTPRINT

The spatial scale of a surface flux estimate depends on the height of the sensor in relationship to the upwind distance of the canopy crop to be measured. If the surface is considered an infinite plane, the source weight function or footprint model for turbulent transfer has a distance that contributes the maximum source that is located in the upwind direction. The area right next to the sensor does not contribute because the flux is downwind by the time the flux reaches sensor height. As one continues upwind less of the measured flux come from the upwind source.

The sensor height, horizontal location, wind speed, and roughness length affect the footprint. One can run a footprint model to find out the appropriate sensor setup location and height for an eddy covariance system. Some footprint models can be found in Horst and Weil (1993), Kristensen et al. (1997), Kormann and Meixner (2001) and online at: http://www.indiana.edu/~climate/SAM/ExpDes/ExpDesignNEW.htm.

Figure 3 shows a footprint model results. The model was run under wind speed of 2 m/s at 2 m height for an alfalfa field (1-m canopy height). It shows that when the ET sensors are set 0.5 m above the canopy the sources within 150 m contribute 95% of the ET flux measurement; when the sensors are 2 m above the canopy sources within a distance of 640 m can contribute 95% of the ET measurement.

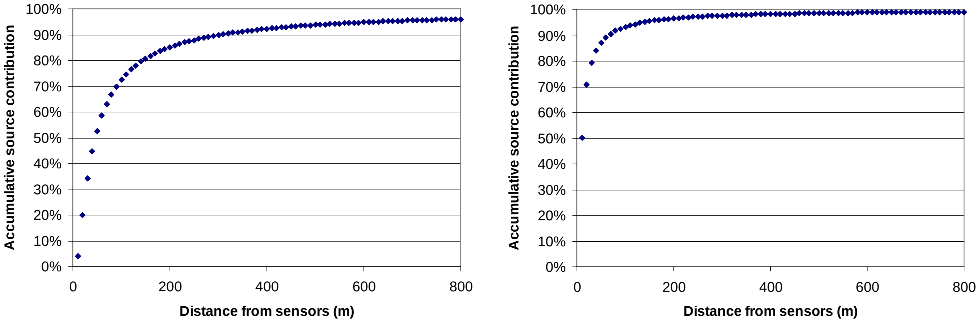

Figure 3: One footprint model results. Left: ET sensors are 2 m above canopy; right: sensors are 0.5 m above canopy. Wind speed = 2 m/s at 2 m height, u* = 0.1 m/s, roughness length = 0.1 m (1-m alfalfa field).

CALIBRATED WITH OTHER INSTRUMENTS

Another way to check the eddy covariance measurements is to compare other eddy covariance instruments to the current set of instruments. For example, a Kryppton Hygrometer (KH20, Campbell Sci., Inc., Logan, Utah) can be used instead of a Licor-7500 to measure LE flux, and the results of the Kryppton measurements can be used to calibrate the Licor-7500. The Kryppton hydrogometer resulted in 95% energy closure when used over a pecan orchard, but failed whenever it rained. Consequently, it was used to calibrate the Licore-7500 because the Licor-7500 over a rough tall surface did not result in energy closure.

However, when both the Kryppton Hydrogometer and the Licor-7500 were operated over a smooth grass cover no correction was needed for the Licor-7500.

SAMPLING FREQUENCY AND OTHERS

Sampling frequency must be at 10 Hz or higher and data loggers that are not able to sample at this or higher frequencies should not be used with eddy covariance equipment.

In addition to the above corrections, some other corrections may be needed also. Details may be found at: （http://www.licor.com/env/Products/GasAnalyzers/eddyPresentation/EC_master_Presentation_files/_frame.htm).

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Chapter 1

INTRODUCING MODELLING TOOLS TO SUPPORT WATER-MANAGEMENT DECISION-MAKING UNDER CLIMATE CHANGE CONDITIONS: A SPANISH EXPERIENCE

Angel Utset Suastegui

ABSTRACT

According to climate change assessments, less precipitations and higher temperatures can be expected in the Iberian Peninsula and other Mediterranean zones. Besides, an increment in droughts and other extreme events can be expected as well. Such climatic conditions require an effort to optimize irrigation technologies and to improve water management efficiency. There are currently available water-use and crop-growth simulation models, which can be combined to climate scenarios and weather generators in order to recommend, through many simulations, the most reliable irrigation management. The Preliminary Assessment of the Impacts in Spain due to the Effects of Climate Change and the National Plan for Adaptation to Climate Change recommend the use of such simulation tools in Spanish climate-change impact assessments. Those tools, however, have not been used yet to support irrigation decision-making in our country. In that sense, the EU-funded proposal AGRIDEMA, leaded by Spain, has been addressed to introduce such tools, connecting the tools "providers" from Universities and high-level research centres, with their "users", located in agricultural technological or applied-research centres. AGRIDEMA comprised courses and Pilot Applications of the tools. Local researchers knew in the AGRIDEMA courses how to access to GCM data and seasonal forecasts, they receive also basic knowledge on weather generators, statistical and dynamical downscaling; as well as on available crop models as DSSAT, WOFOST, CROPSYST, SWAP and others. About 20 pilot assessments have been conducted in several European countries during AGRIDEMA, applying the modelling tools in particular cases.

The AGRIDEMA results are commented, mentioning particularly the Pilot Assessments that were held in Spain and in the Mediterranean area. Furthermore, several "users" opinion regarding the available climate and crop-growth simulation tools are also pointed out. Those opinions can be used as important feedback by the tools "developers". An illustrative example on how modelling tools can help to manage Sugarbeet irrigation under present and future climate conditions in Spain is also shown. Several future research directions are pointed out, as followed from the shown example and the AGRIDEMA results. Those research directions agree with the actions recommended in the Spanish National Plan for Adaptation to Climate Change, as well as in the European and international guidelines. Stakeholder will adopt climate-change mitigation options only if they realize the reliability of such options on their specific cases. To achieve this, the "users" of the modelling tools must develop local demonstration proposals, aimed to model calibration and validation, etc. Particularly, some demonstration proposals should be aimed to recommend productive and efficient irrigation water managements under the adverse climate conditions that Spanish farmers will eventually face in the next years.

1. CLIMATE CHANGE, AGRICULTURE AND WATER RESOURCES IN THE MEDITERRANEAN REGION

The last IPCC (2007) report pointed out clearly the climate variability observed in the last decades, very probably due to the higher concentration of CO_2 and other gases emissions related to human activity. Particularly, the increment in the frequency of extreme event, as droughts and flooding, has been considered also as a climate-change consequence. Despite that temperature rising could be expected all over the world, rainfall changes are different according to the regions. Northern regions might expect increment in yearly rainfall, while total precipitation in other zones, as the Mediterranean regions, could be significantly lower during the second half of the 20 century (IPCC, 2007).

Climate change will bring important consequences to agriculture, perhaps the man activity most dependants on meteorological conditions. According to IPCC (2007), general yield changes, freezing-loosing reductions, increment in crop and livestock damages due to higher temperature and other adverse and positive changes can be expected in the future. Those consequences will be different according to the regions.

The IPCC Working Group II, aimed to assess Climate Change Impacts, Adaptation and Vulnerabilities on natural managed and human systems; reported significant changes on several physical and biological systems in Europe from 1970 to 2004. Most of those changes are consistent with the expected response to temperature rising and cannot explained by natural variability (IPCC, 2007). According to the IPCC Working Group II, Climate Change is expected to magnify regional differences in Europe's natural resources and assets. In Southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability, hydropower potential, summer tourism and, in general, crop productivity (IPCC, 2007).

One of the main achievements of the IPCC (2007) fourth assessment is its confirmation, through new data and documentary proves, of many previsions that had been already made in the previous IPCC assessments. For instance, the IPCC (2001) report already pointed out the Climate-Change related risks on European and World agriculture.

Olesen and Bindi (2002) studied the climate change impact to European agriculture, considering several regions within Europe. According to them, Mediterranean agriculture will be the most affected, due to precipitation reduction in the zone, which will bring lesser water availability. Water scarcity, combined to higher transpiration rates due to temperature increments, will mean a challenge for irrigated agriculture in Southern Europe. Those conclusions agree with the IPCC (2007) last report. Despite rainfall changes are less confident than temperature rising at the global scale, many of the modelling assessments included in the IPCC (2007) report coincided in predicting less rainfall in the Mediterranean region.

Besides long-term climate-change effects, its related climate variability and the increment in extreme-events frequency (IPCC, 2007) can mean important constraints to agriculture. The higher mean temperature of 2003 summer is a good example of that. Such warm summer brought many agricultural loosing, particularly in France (Seguin et al., 2004).

The European Commission is aware about the Climate Change risks that can be expected in Europe. The European Environmental Agency released a Technical Report aimed to point out the vulnerability and adaptation to Climate Change in Europe (EEA, 2006). The report indicates that Southern Europe, the Mediterranean and central European regions are the most vulnerable to Climate Change. Considering vulnerabilities by issues, the EEA (2006) technical report considered that Climate Change and increased CO_2 atmospheric concentration could bring a beneficial impact on Northern European agriculture, through longer growing season and increasing plan productivity. However, in the South and parts of Eastern Europe the impacts are likely to be negative (EEA, 2006). The EEA (2006) report gives special attention to water resources availability in Southern Europe as one of the most important Climate-Change expected risks. The report remarks the importance of adopting concrete measures and policies on National and EU Adaptation plans to Climate Change, although it is a relative new issue.

Due to the importance of water resources management under Climate Change conditions, the European Environmental Agency released recently a Technical Report addressed to this issue (EEA, 2007). Two main impacts are recognized in the report: Flooding risks in Northern and Central Europe, as well as water scarcity in Southern countries. According to EEA (2007), several adaptation measures have been taken regarding flooding, but few have been addressed to water scarcity. Furthermore, three priorities are pointed out in the EEA (2007) report. The top priority for adaptation in the water sector should be to reduce the vulnerabilities of people and societies to shifts in hydro-meteorological trends, increased climate variability and extreme events. A second priority is to protect and restore ecosystems that provide water resources services. The third priority should be to close the gap between water supply and demand by enhancing actions that reduce demands (EEA, 2007). The report also recognize the need of research on climate-change impacts in water sector, as well as the interactions among European, national and local decision-making levels.

Besides the EEA (2006) and (2007) reports, the European Commission is preparing a “Green Book” regarding Climate Change to be released late 2007. The first draft (EC, 2007) of such “Green Book” identifies also the Mediterranean region as the most risky zone within Europe, due to the combination of temperature rising with precipitation reductions. Concerning the future of European agriculture, the Green Book points out that Climate Change would be one of several challenges, as world-trade globalisation and rural population decrement. Furthermore, the Common Agricultural Policy and several other EU policies and directives can effectively influence in climate-change adaptation issues, as water use efficiency and pollution risks (EC, 2007).

1.1 The Spanish Climate-Change Adaptation Plan

Additionally to the EU concerns, the Spanish government and the National institutions are also ready to introduce Climate-Change adaptation actions, taking into account that Spain is one of the most risky countries within Europe. The huge assessment comprised in the Preliminary Evaluation of Climate Change effects in Spain (Moreno, 2005), including the risks of Spanish agriculture (Minguez et al., 2005), has been an important guidelines to develop Climate-change adaptation strategies at the country level.

In general, the Minguez et al. (2005) assessments agree with the IPCC (2007) and the EEA (2006) reports. They all point out that the increase in CO_2 concentration and air temperature, as well as changes in seasonal rainfall, would have counteracting and non-uniform effects. The positive effect of CO_2 on photosynthetic rates can be compensated by greater temperatures and less precipitation. They also agree that while milder winter temperatures will allow higher crop growth rates if water is sufficiently available, higher summer temperatures can increase evaporative demand and hence irrigation requirements. As highlighted in all the above-cited reports, Minguez et al. (2005) indicated that he expected increase in extreme weather years will difficult crop management and will require more analysis of agricultural systems sustainability.

Minguez et al. (2005) also pointed out that crop simulation models using climate data from Regional Climate Models are nowadays the most efficient tools for impact analysis, as they are able to quantify the non-linear effects of climate change. Furthermore, they indicate the need of identifying regions with different impacts in order to recommend the corresponding adaptation measures.

According to Minguez et al. (2005), short term adaptation strategies can rely on simple management practices such as changes in sowing dates and cultivars. Nevertheless, in the long term, adaptation of cropping systems to future climate conditions is required. Implications on vegetable crops, fruit orchards, olive groves and vineyards should specifically addressed to assess adaptation at minimum cost (Minguez et al., 2005).

Minguez et al. (2005) summarizes that one of the main constraints of Spanish agriculture will be related to water availability for summer-crops agriculture, due to the expected rainfall decrement combined with the temperature rising, particularly in the summer. Furthermore, drought frequency and intensity will be higher in the near future, since it has been observed already from the last 30 years (IPCC, 2007). Along with the IPCC (2007) and the EEA (2006) and (2007) reports, Minguez et al. (2005) point out that weather variability could be the most critical issue in the coming years. The stability and sustainability of Spanish agroecosystems is affected by interannual and seasonal variations in rainfall, water availability for irrigation, the greater or smaller frequency of frost in springtime and the storms that have especial impact on the fruit and vegetable sector. Furthermore, Minguez et al. (2005) indicated also that improving water management efficiency should be a priority.

Minguez et al. (2005) pointed out particularly the influence of the CAP in crop sequences of both dry farming and in irrigation systems. Crop choices are not always the best in agronomic terms, especially in relation to climate and soil, so the sustainability of these agricultural systems is questionable. The progressive reduction of EU subsidies is beginning to affect management decisions, as can be seen in the restructuring and changing geographic distributions of olive groves and vineyards. Therefore, CAP and other European and national policies should be taken into account.

Following the conclusions of the Preliminary Evaluation of Climate Change effects in Spain (Moreno, 2005), the Spanish Climate-Change Office has prepared the National Plan for Adaptation to Climate Change (PNACC, 2006). The Plan comprises action guidelines for the hydraulic resources, the agricultural sector and several other sectors that can be potentially affected by Climate Change.

The PNACC (2006) includes also a Workplan and a Timetable. The first task is to develop Spanish-based Climate-Change scenarios that can be used further for impact assessments at each involved sector. Developing such regional data base was defined as a priority in the EEA (2006) report. The first version of the Spanish Climate-Change scenarios has been already provided by the National Institute of Meteorology (Brunet et al., 2007). Furthermore, due to its extreme importance, assessing Climate-Change effects on the hydraulic resources in Spain is the second commitment included in the PNACC (2006).

Regarding crop agriculture, the PNACC comprises the following guidelines:

- Mapping climate change effects on Spanish agricultural zones.
- Developing crop models to simulate radiation interception, water and nitrogen balances and yields.
- Evaluating irrigation demands according to different scenarios.
- Providing general recommendations for short-term agricultural management under climate change conditions.
- Identifying long term adaptation strategies, particularly in fruits, olives and vineyards.

1.2 Climate Change and Spanish Irrigated Agriculture: The Challenge

Irrigation is largely the main water user in most countries. Worldwide agricultural production in irrigated area is, in average, more than twice the production in rainfed zones, despite that irrigated area is lesser than 25% of the total agricultural area. The increment of world population and their feeding needs point toward an efficient agriculture and therefore irrigation is an absolute need. Irrigated agricultural land means approximately 350 million ha in the world. Irrigated areas are responsible for approximately 40% of the global food production (Smedema et al., 2000).

According to EUROSTAT data, irrigated area comprised 14 807 980 ha in the EU-25 during 2003. It meant 9.5% of the total EU agricultural area. The irrigated area corresponding to the EU Mediterranean countries (i.e. Spain, Italy, France and Greece) is more than 80% of the total EU-25 irrigated area. Particularly, Spanish irrigated area is 30% of the total EU-25 area, which makes Spain as the country with the largest irrigated area in the EU. Irrigated area is about 20% of the total cropped area in Spain, which means more than twice the average EU ratio. Despite their location corresponds to the temperate climate area, solar radiation rates in Mediterranean countries are relatively high. This radiation conditions could lead to higher crop transpiration rates and hence suitable agricultural productions. However, water availability constraints in Mediterranean agriculture are higher than those found in other places of the world. Therefore, rainfed production in those countries of common crops is usually lower than that found, for instance, in Northern Europe.

Table 1 shows the most relevant crops in Spain, according to the Ministry of Agriculture report (MAPA, 2004). Table 1 shows also the total cropped area, as well as the corresponding rainfed and irrigated area. Moreover, the Table depicts the percent of each crop area, regarding the total agricultural area; as well as the percent of irrigated area of each crop, respecting the total crop area. As can be seen in the Table, rainfed cereals as Barley and wheat are the most important crops in Spain, although olives and vineyards represent an important cropped area as well. Maize shows the largest irrigation area, followed by vegetables and olives. Irrigated cereals mean also an important percent of the total Spanish irrigated area. Vegetables, Sugarbeet, Maize, Alfalfa and Potatoes are mainly irrigated crops in Spain, since more than 70% of their cropped area is under irrigation.

Table 1: Relevant crops in Spain, according to reported rainfed, irrigated and total cropped area (MAPA, 2004)

Crop	*Rainfed (ha)*	*Irrigated (ha)*	*Total*	*% of Total*	*% Irrigated*
Barley	2807592	303281	3110873	21.3	9.7
Olives	2056532	383050	2439582	16.7	15.7
Wheat	2024930	195711	2220641	15.2	8.8
Vineyards	1009407	163390	1172797	8.0	13.9
Fruits	987169	271201	1258370	7.6	28.3
Sunflower	699105	87727	786832	5.4	11.1
Maize	96872	464569	561441	3.8	82.7
Oats	462888	33439	496327	3.4	6.7
Vegetables	28897	396866	425763	2.9	93.2
Alfalfa	49441	191239	240680	1.6	79.5
Rye	104789	3283	108072	0.7	3.0
Potato	28466	72635	101101	0.7	71.8
Sugarbeet	17101	82733	99834	0.7	82.9

Irrigated agriculture in Spain and most of the Mediterranean area was introduced since ancient times and it has been improved through the long farmer' experience. Crops yields under irrigation are indeed quite high. However, irrigation techniques have been kept in the same way for centuries in many Mediterranean countries. Inefficient flooding irrigation systems, for instance, is still the most commonly found in many areas of Spain (Neira et al., 2005) and other Mediterranean countries.

Irrigation is expensive, but assures the farmer productions and keeps rural population in the countryside. It has been shown that farm profitability in Europe is lower than that reported in industrial or technical business. If farming is not profitable then existing farmers will cease their activities, and young people may not be attracted into agriculture. This will mean the long-term decline of the industry and of rural areas. Actually, one of the most important constraints that face European countryside is its continuous depopulation. Most farms are small businesses, often family-run. They are an important local employer in many rural regions and major players in the rural world. Farmers play a positive role in the maintenance of the countryside and the environment by working for secure and profitable futures for themselves and their families. Therefore, to keep good living standards in the European countryside is an important concern of EU authorities, as well as national governs.

A quite large irrigation modernisation is being conducted in Spain (Beceiro, 2003), aimed to replace flooding by sprinkler and other more-efficient techniques with governmental aids. The Spanish program aimed to introduce new engineering irrigation infrastructures in the national agriculture, *Plan Nacional de Regadíos* (MAPA, 2005), is carried out by the Spanish Ministry of Agriculture. The program has been recently revised and its goals comprised not only to increment irrigated areas, but to significantly improve water savings and to avoid groundwater pollution. This kind of effort is in accordance with the Lisbon Strategy and the goals of the EU Commission of Agriculture, addressed to improve farmer's income, to make more competitive their agricultural production and to meet the EU environmental requirements (EU, 2005; Fischer, 2005).

Irrigation modernisations efforts have been made in non-European Mediterranean countries also, as Egypt. However, there is still a big difference in irrigated agricultural production between European and non-European Mediterranean countries. As can be seen in Figure 1, shown below, rainfed crop production, as wheat, is similar in all the compared countries. However, the yields of a usually irrigated crop, as maize, are much larger in European countries than in non-European Mediterranean countries. The above information is a national average; therefore it includes also non-irrigated maize, as well as irrigated wheat. Nevertheless, the figure depicts clearly the mean yields at each country. Maize yields of the European and non-European Mediterranean countries show a considerable difference. This could be mainly due to the large new engineering irrigation infrastructures, which have been available in European Mediterranean countries since the last 20 years.

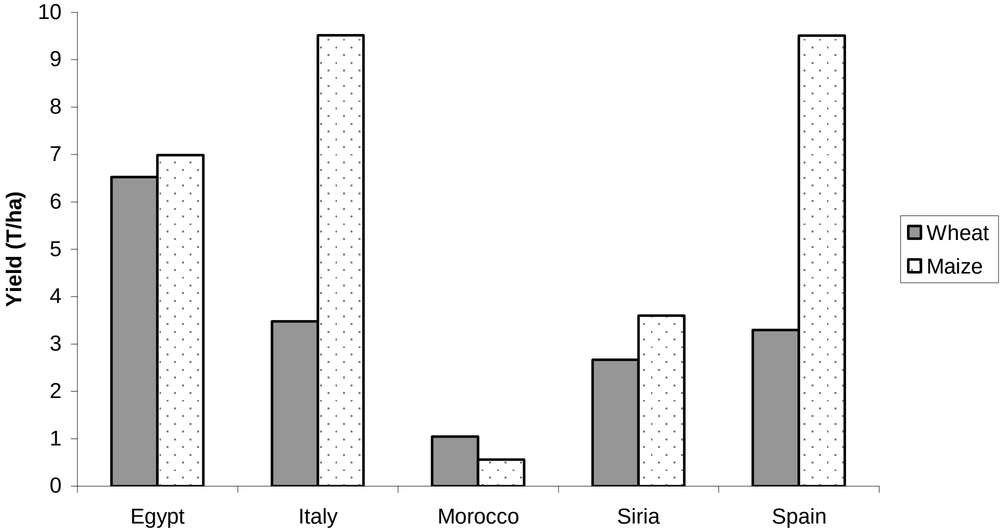

Figure 1: Average yields in 2004 in several Mediterranean countries, according to FAOSTAT data.

Furthermore, Figure 2 depicts the absolute difference in Maize yields (in T/ha) and production (in BT) between Spain and Egypt from 1990 to 2004, following the same FAOSTAT (2005) data. Despite total Egyptian production is higher than that of Spain, the Spanish yields are not only higher than the corresponding Egyptian yields, but their yield differences have been linearly incremented during the last 15 years.

The yield differences between Spain and the European Mediterranean countries as compared to Non-European Mediterranean countries can be due to many reasons, but indeed the new engineering irrigation infrastructures that has been introduced in the European Mediterranean countries, as Spain, during the last 20 years (MAPA, 2005) has a notable influence in this yearly yield increment.

Despite the infrastructures investments in Spain and other European countries, irrigation is still very expensive at the world scale. Water could be not enough under the future-enhanced droughts conditions, particularly considering third-world population rise. However, irrigation must not only been kept, but also enlarged in order to feed the foreseen world population. This contradiction has been pointed out as important concern during the 19th Congress of the International Commission on Irrigation and Drainage (ICID), held in Beijing recently. The ICI Congress focused on the theme of "Use of Water and Land for Food Security and Environmental Sustainability" and they pointed out that: the key to increase future food production lies in expansion of irrigated and drained lands where potential exists; in better water and land management in existing irrigated and drained areas; and in increase in water use efficiency and land productivity, in the Beijing ICID declaration.

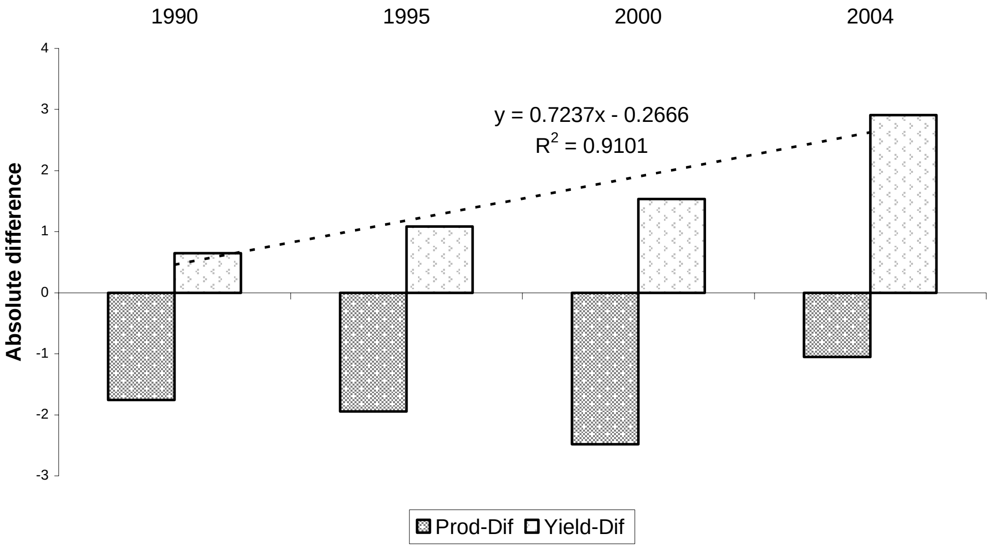

Figure 2: Absolute differences between Egyptian and Spanish Maize productions (in BT) and yields (in T/ha).

Climate change will impose a new challenge to Spanish and Mediterranean irrigation areas. Improving irrigation efficiency is an imperative, although it has been recognized that much water can still be saved in Spanish irrigation systems (Playan and Mateos, 2005). Some climate-change impact assessments have estimated that CO_2 rising will significantly reduce the crop water requirements (Guereña et al., 2001; Villalobos and Fereres, 2004). However, such positive “fertilizing effect” of CO_2 rising seems to have been overestimated according to the FACE results (Craft-Brandner and Salvucci, 2004; Aisnworth and Long., 2005). Hence, Spanish irrigated agriculture might be affordable in the future only by reducing the water consumes. Furthermore, the globalisation of the world market and the “cost recovering principle” included in the EU Water Framework Directive (2000/60/EC) would lead to prices reductions in the future, while incrementing water costs.

Several examples can be pointed out on the challenge that climate change, combined with WFD and other future policies, could bring to the affordability of irrigated agriculture in Spain. Perhaps the most updated situation concerns Sugarbeet cropping. The EU Commission of Agriculture has proposed a reform to current EU sugar production conditions, which has been strongly rejected by Spanish sugar-beet farmers and producers, as well as those from other countries. The reform implies a substantial reduction of current EU prices. Sugar-beet is mainly an irrigated crop in Spain and other Mediterranean countries; hence the production costs are relatively high due to irrigation. Farmers who use groundwater to irrigate sugar beet are the ones facing the highest problem, due to the increment of oil costs. Furthermore, drought conditions, as that found during 2005 in Spain, can be strengthen in the near future, due to global change. Therefore, farmers need to reduce irrigation costs while cropping Sugarbeet under these new prices and climate conditions. They need help in order to find a reliable irrigation management. This is particularly important in those farms where irrigation modernisation or any irrigation investment in new technologies is expected, due to the amortization of the investment costs.

2. CLIMATE SCENARIOS, SEASONAL FORECASTS AND DOWNSCALING ISSUES

Complex Models regarding general atmospheric circulation (GCM) have been developed to predict the future earth climate. Those models are able to simulate the energy and mass exchanges between the atmosphere and the earth surface, according to several man-due scenarios of greenhouse gases emissions (IPCC, 2007). The HadCM3 model, developed by the United-Kingdom Meteorological Office, and the German ECHAM4 model were considered in the IPCC (2007) report, among other non-European GCM’s.

On the other hand, seasonal time-scale climate predictions are now made routinely at a number of operational meteorological centers around the world, using comprehensive coupled models of the atmosphere, oceans, and land surface (Stockdale et al. 1998; Mason et al. 1999; Kanamitsu et al. 2002; Alves et al. 2002; Palmer et al., 2004). Particularly, GCM were integrated over 4-month time scales with prescribed observed sea surface temperatures (SSTs) within the PROVOST project (Palmer et al., 2004). Single model and multi-model ensembles were treated as potential forecasts. A key result was that probability scores based on the full multi-model ensemble were generally higher than those from any of the single-model ensembles (Palmer et al., 2004).

Based on PROVOST results, the Development of a European Multi-model Ensemble System for Seasonal to Inter-annual Prediction project (DEMETER) was conceived, and funded under the European Union 5th Framework Environment Programme (Palmer et al., 2004). The principal aim of DEMETER was to advance the concept of multi-model ensemble prediction by installing a number of state-of-the-art global coupled ocean–atmosphere models on a single supercomputer, and to produce a series of 6-month multi-model ensemble hindcasts with common archiving and common diagnostic software. As a result of

DEMETER, real-time multi-model ensemble seasonal global predictions are now routinely made at the European Centre for Medium-Range Weather Forecasts (ECMWF).

Palmer et al. (2004) showed some DEMETER applications. Results indicate that the multi-model ensemble is a viable pragmatic approach to the problem of representing model uncertainty in seasonal-to-inter-annual prediction, and will lead to a more reliable forecasting system than that based on any one single model (Palmer et al., 2004). On the other hand, Doblas-Reyes et al. (2006), pointed out the potential of DEMETER predictions of seasonal climate fluctuations to crop yield forecasting and other agricultural applications. They recommend a probabilistic approach at all stages of the forecasting process.

The ENSEMBLES EU-funded proposal (Hewitt, 2005) is an important recent effort to improve the skill of seasonal forecasts and to make them available to stakeholders. The ENSEMBLES proposal uses the collective expertise of 66 institutes to produce a reliable quantitative risk assessment of long-term climate change and its impacts. Particular emphasis is given to probable future changes in climate extremes, including storminess, intense rainfall, prolonged drought, and potential climate ‘shocks’ such as failure of the Gulf Stream. To focus on the practical concerns of stakeholders and policy makers, ENSEMBLES considers impacts on timeframes ranging from seasonal to decadal and longer, at global, regional, and local spatial scales.

Several useful tools to assess climate-change impacts on agriculture have been developed during the last years. GCM are among such tools. However, GCM estimations of temperature, precipitation and other meteorological variables are usually made for large areas. For instance, Guereña et al. (2001) showed that those estimations are not very useful to Spanish agricultural climate-change impact assessments, due to the notable topographical changes within the Peninsula for relative small distances. Therefore, a “downscaling” of GCM outputs is absolutely needed before using their estimations for agricultural applications.

Wilby and Wigley (2001) summarized the available downscaling techniques; which can be classified as statistical, dynamical and weather generators. A dynamical downscaling method is to apply numerical regional climate models at high resolution over the region of interest. Regional models have been used in several climate impact studies for many regions of the world, including parts of North America, Asia, Europe, Australia and Southern Africa (e.g Giorgi and Mearns, 1999; Kattenberg et al., 1996; Mearns et al., 1997). The regional climate models obtain sub-grid scale estimates (sometimes down to 25 km resolution) and are able to account for important local forcing factors, such as surface type and elevation. Particularly, the regional climate model RegCM was originally developed at the National Center for Atmospheric Research (NCAR), USA and has been mostly applied to studies of regional climate and seasonal predictability around the world. It is further developed by the Physics of Weather and Climate group at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy. The PRUDENCE Regional Models Experiment has been developed in Europe under the EU Framework Research Program (Christensen and Christensen, 2007). PRUDENCE project provides a series of high-resolution regional climate change scenarios for a large range of climatic variables for Europe for the period 2071-2100 using four high resolution GCMs and eight RCMs.

Wilby and Wigley (2001) classified statistical downscaling in regression methods and weather-pattern approaches. The regression method uses statistical linear or non-linear relationships between sub-grid scale parameters and coarse resolution predictor variables. Wilby and Wigley (2001) included Artificial Neural Network within the regression-type statistical downscaling. On the other hand, weather-pattern based approaches involve grouping meteorological data according to a given classification scheme. Classification procedures include principal components, canonical correlation analyses, fuzzy rules, correlation-based pattern recognition techniques and analogue procedures; among others (Wilby and Wigley, 2001). Theoretically, dynamical downscaling methods are better than simple statistical methods since they are based on physical laws. However, statistical downscaling method are less computational exigent and can give good results if the relationships between predictand and predictors are stationary (Wilby and Wigley, 2001).

2.1 Weather Generators

Weather generators have been very used in agriculture climate-change impact assessments (Hoogenboom, 2000; Sivakumar, 2001). A weather generator produces synthetic daily time series of climatic variables statistically equivalent to the recorded historical series, as well as daily site-specific climate scenarios that could be based on regional GCM results (Semenov and Jamieson, 2001). The weather generator usually mimics correctly the mean values of the climatic variables, although underestimates their variability (Mavromatis and Jones, 1998; Semenov and Jamieson, 2001; Wilby and Wigley, 2001). Different weather generators are available, but according to Wilby and Wigley (2001), the US-made and the UK-made WGEN and LARS-WG are the most widely used.

LARS-WG is a stochastic weather generator which can be used for the simulation of weather data at a single site (Racsko et al, 1991; Semenov et al, 1998; Semenov and Brooks, 1999; Semenov and Barrow, 2002), under both current and future climate conditions. These data are in the form of daily time-series for a suite of climate variables, namely, precipitation, maximum and minimum temperature and solar radiation.

According to Semenov and Barrow (2002), stochastic weather generators were originally developed for two main purposes:

1. To provide a means of simulating synthetic weather time-series with statistical characteristics corresponding to the observed statistics at a site, but which were long enough to be used in an assessment of risk in hydrological or agricultural applications.
2. To provide a means of extending the simulation of weather time-series to unobserved locations, through the interpolation of the weather generator parameters obtained from running the models at neighbouring sites.

A stochastic weather generator is not a predictive tool, but simply a mean to generate time-series of synthetic weather statistically ‘identical’ to the observations. A stochastic weather generator, however, can serve as a computationally inexpensive tool to produce multiple-year climate change scenarios at the daily time scale which incorporate changes in both mean climate and in climate variability (Semenov and Barrow, 1997).

The LARS-WG weather generator focused to overcome the limitations of the Markov chain model of precipitation occurrence (Richardson and Wright, 1984). This widely used method of modelling precipitation occurrence (which generally considers two precipitation states, wet or dry, and considers conditions on the previous day only) is not always able to correctly simulate the maximum dry spell length. LARS-WG follows a ‘series’ approach, in which the simulation of dry and wet spell length is the first step in the weather generation process.

The most recent version of LARS-WG (version 3.0 for Windows 9x/NT/2000/XP) has undergone a complete redevelopment in order to produce a robust model capable of generating synthetic weather data for a wide range of climates (Semenov and Barrow, 2002). LARS-WG has been compared with another widely-used stochastic weather generator, which uses the Markov chain approach (WGEN; Richardson, 1985; Richardson and Wright, 1984), at a number of sites representing diverse climates and has been shown to perform at least as well as, if not better than, WGEN at each of these sites (Semenov et al, 1998).

3. SIMULATING CROP-GROWTH AND CROP WATER-USE

On the other hand, many crop simulation models have been appeared in the last 20 years. Those models are able to estimate crop water-use and growth under any weather and cop management conditions. Those models, combined with downscaled GCM scenarios, can be a reliable approach to support decision-making under climate change conditions (Hoogenboom, 2000). Despite many models are available, Mechanistic models i.e. those based in the physical laws of the soil-water-plant-atmosphere continuum, are the most suitable to climate-change impact assessments (Eatherall, 1997), since the laws are, in principle, valid for al climatic conditions.

According to Tubiello and Ewert (2002), more than 40 assessments of climate-change impact on agriculture have been published up to now. They pointed out that generally models provided accurate results, compared to actual data. The most used models in such assessments are DSSAT (Jones et al., 2003) and those developed in Wageningen (Van Ittersum et al., 2003).

As pointed out above, modelling tools appeared in the eighties, due to computer availability, aimed to simulate crop growth and final yields. Numerous crop growth models have been developed since them. The models can use weather data input, such as short term weather forecast, a season’s forecasted weather or climate scenarios to estimate potential or actual growth, development or yield. Historical-production records are useful for assessing the impacts of climate variability on crop yields, but cannot reveal crop response under alternative management strategies, which can be done through modelling simulations.

Bastiaansen et al. (2004) provided an update revision of the modelling applications to irrigation assessments. They pointed out the opportunities lying in such modelling approaches to irrigation and drainage assessments, with more than 40 examples. The simulation examples comprises assessing irrigation supply needs, as well as irrigation designing, scheduling, management and performance; salt-affected soils due to irrigation, groundwater recharge and estimating soil losses, among others.

Models have been usually classified as empirical, functional and mechanistics (Connolly, 1998; Bastiaansen et al., 2004). Mechanistic models, i.e. those based in the physical laws of the soil-water-plan-atmosphere are more suitable to assess climate-change effects on agriculture than empirical models (Eatherall, 1997; Hoogenboom, 2000), since the theoretical mechanistic-model backgrounds is still valid under these new conditions. According to

Bastiaansen et al. (2004), concerning suitability to describe irrigation and drainage processes, models can be classified as bucket, pseudo-dynamics, Richards-equation based, SVAT models, multidimensional and crop-production models. However, at the plot and field scale only the bucket, the crop-oriented models and those based on the Richards equation have been significantly used. The Richards equation describes the vertical movement of water within the soil profile and its solutions can, at least theoretically, provide the water distribution under certain initial and border conditions (Kutilek and Nielsen, 1994).

Therefore, concerning irrigation studies at field and plot scales, the most important mechanistic modelling approaches are those mainly aimed to simulate crop-growth and those addressed to physically-based simulation of soil-water movement, through numerical solutions of the Richards equation. These models have been called agrohydrological models, because they combine agricultural and hydrological issues (Van Dam, 2000).

3.1 Crop-Growth Oriented Simulation Models

According to Stockle et al. (2003), the initial crop-growth simulation models, mainly theoretical approaches, appeared in the 1970s (de Wit et al., 1970; Arkin et al., 1976). Applications oriented models appeared during the 1980s (Wilkerson et al., 1983; Swaney et al., 1983). Models such as SUCROS and others associated with the Dutch ‘School of de Wit’ (Bouman et al., 1996); as well as those produced in the US as the CERES (Ritchie, 1998) and CROPGRO (Boote et al., 1998) families of models had a significant impact on the crop modelling community (Stockle et al., 2003). As pointed out by Brisson et al (2003), the rest of the crop-growth simulating models, although different; generally follow similar guidelines than the originally produced models. Alexandrov (2002) provided a complete summary of the crop models that have been used in Europe.

3.1.1 The DSSAT Models and the “Cascade Approach”

The Decision Support System for Agrotechnology Transfer (DSSAT) was originally developed by an international network of scientists, cooperating in the International Benchmark Sites Network for Agrotechnology Transfer project (IBSNAT, 1993; Tsuji et al., 1998; Uehara, 1998; Jones et al., 1998), to facilitate the application of crop models in a systems approach to agronomic research (Jones et al., 2003).

DSSAT is a microcomputer software package that contains crop-soil simulation models, data bases for weather, soil, and crops, and strategy evaluation programs integrated with a ‘shell’ program which is the main user interface (Jones et al., 1998). DSSAT originally comprises the CERES models for maize (Jones and Kiniry, 1986) and wheat (Ritchie and Otter, 1985), as well as the SOYGRO soybean (Wilkerson et al., 1983) and PNUTGRO peanut (Boote et al., 1986) models, among others (Jones et al., 2003).

The decision to make these models compatible led to the design of the DSSAT and the ultimate development of compatible models for additional crops, such as potato, rice, dry beans, sunflower, and sugarcane (Hoogenboom et al., 1994; Jones et al., 1998; Hoogenboom et al., 1999; Jones et al., 2003).

According to Hoogenboom et al. (1999), the DSSAT Cropping System Model (CSM) simulates growth and development of a crop over time, as well as the soil water, carbon and nitrogen processes and management practices. The CSM main components are:

- A main driver program, which controls timing for each simulation,
- A Land unit module, which manages all simulation processes which affect a unit of land
- Primary modules that individually simulate the various processes that affect the land unit including weather, plant growth, soil processes, soil-plant-atmosphere interface and management practices.

Collectively, these components simulate the changes over time in the soil and plants that occur on a single land unit in response to weather and management practices.

DSSAT has a module format. Each module has six operational steps, (run initialization, season initialization, rate calculations, integration, daily output, and summary output). The main program controls the timing of events: the start and stop of simulation, beginning and end of crop season, as well as daily time loops (Hoogenboom et al., 1999).

Ritchie (1998) provided the background of DSSAT models regarding simulation of soil-water movement and crop water-use. The DSSAT simulation of the soil water balance depends on the capability of water from rainfall or irrigation to enter soil through the surface and be stored in the soil reserve.

The “cascading approach” as used in DSSAT is explained by Ritchie (1998). Drainage from a layer takes place only when the soil water content at a given depth is between field saturation and the drained upper limit.

The Priestley-Taylor (1972) equation for potential evapotranspiration is used in DSSAT. Calculation of potential evaporation requires an approximation of daytime temperature and the soil-plant reflection coefficient (albedo) for solar radiation. For the approximation of the daytime temperature a weighted mean of the daily maximum and minimum air temperatures is used. The combined crop and soil albedo is calculated from the model estimate of leaf area index and the input bare soil albedo (Ritchie, 1998).

The root water absorption in DSSAT is calculated using a law of the limiting approach whereby the soil resistance, the root resistance, or the atmospheric demand dominates the flow rate of water into the roots. The flow rates are calculated using assumptions of water movement to a single root and that the roots are uniformly distributed within a layer (Ritchie, 1998).

The potential transpiration and biomass production rates are reduced by multiplying their potential rates by a soil water deficit factor calculated from the ratio of the potential uptake to the potential transpiration. A second water deficit factor is calculated to account for water deficit effects on plant physiological processes that are more sensitive than the stomata controlled processes of transpiration and biomass production (Ritchie, 1998).

The DSSAT models have been indeed the most used simulation tools in agricultural climate-effect assessments (Tubiello and Ewert, 2002) and crop water balance studies (e.g. Eitzinger et al., 2002). They were calibrated and validated at many agricultural regions of the world (Hoogenboom, 2000). DSSAT models have been intensively used also in the framework of the CLIMAG activities aimed to mitigate and estimate agricultural climate-risks (Adiku et al., 2007; Meza, 2007; Singh et al., 2007).

3.1.2 The Wageningen Models

Van Ittersum et al. (2003) provided a complete summary of the family of models made in Wageningen, The Netherlands, during the last 30 years. According to Tubiello and Ewert (2002), these Dutch models have been the most widely used, after DSSAT models, in agricultural climate-risk assessments.

As pointed out by Van Ittersum et al. (2003), the Wageningen group has a long tradition in developing and applying crop models in its agroecological research program, based on the pioneering work of C.T. de Wit. In the 1960s and 1970s the main aim of these modelling activities was to obtain understanding at the crop scale based on the underlying processes. De Wit and co-workers at the Department of Theoretical Production Ecology of Wageningen University, and the DLO Research Institute for Agrobiology and Soil Fertility developed the model BACROS and evaluated components of the model (such as canopy photosynthesis) with especially designed equipment and field experiments (De Wit et al., 1978; Goudriaan, 1977; Van Keulen, 1975; Penning de Vries et al., 1974). These modelling approaches have served as the basis and inspiration for modelling groups around the world (Stockle et al., 2003).

In the 1980s a wide range of scientists in Wageningen became involved in the development and application of crop models. The generic crop model SUCROS for the potential production situation was developed (Van Keulen et al., 1982; Van Laar et al., 1997), which formed the basis of most recent Wageningen crop models such as WOFOST (Van Keulen and Wolf, 1986), MACROS (Penning de Vries et al., 1989), and ORYZA (Bouman et al., 2001). In the 1990s the Wageningen group focused more on applications in research, agronomic practice and policy making (Van Ittersum et al., 2003).

Crop modelling in Wageningen for potential production situations follows the photosynthesis approach in the SUCROS family of models (Van Ittersum et al., 2003). LINTUL (Light INTerception and UtiLisation) models use the linear relationship between biomass production and the amount of radiation intercepted (captured) by the crop canopy (Monteith, 1981), which has been found for many crop species, grown under well-watered conditions and ample nutrient supply, in the absence of pests, diseases and weeds. This relationship sets a finite limit on yield potential (Sinclair, 1994), which thus can be modelled without going into detailed descriptions of the processes of photosynthesis and respiration. Spitters and Schapendonk (1990) developed the model LINTUL with a module for the calculation of crop growth based on the LUE concept.

In the photosynthesis approach in SUCROS (Simple and Universal CROp growth Simulator) models, the daily rate of canopy CO2 assimilation is calculated from daily incoming radiation, temperature and leaf area index (LAI). The model contains a set of subroutines that calculate the daily totals by integrating instantaneous rates of leaf CO2 assimilation (Goudriaan and Van Laar, 1994; Van Laar et al., 1997).

Particularly, the model WOFOST (WOrld FOod STudies) simulates crop production potentials as dictated by environmental conditions (soils, climate), crop characteristics and crop management (irrigation, fertiliser application) (Van Diepen et al., 1989). The model has been continuously modified, and applied for many different purposes (e.g. De Koning and Van Diepen, 1992). WOFOST uses the SUCROS approach for potential production conditions.

WOFOST permits dynamic simulation of phenological development from emergence till maturity on the basis of crop genetic properties and environmental conditions. The cultivar-specific values of thermal time assimilate conversion coefficients, maximum rooting depth, daily root development rate and partitioning fractions are important inputs. Dry matter accumulation is estimated by the rate of gross CO2 assimilation of the canopy. This rate depends on the radiation energy intercepted by the canopy, which is a function of incoming radiation and of crop leaf area. Simulated growth processes and phenological development are regulated by temperature (e.g. the maximum rate of photosynthesis), radiation and atmospheric CO2 content and limited by availability of water. Root extension is computed in a simple way, the initial and the maximum rooting depth as determined by the crop and by the soil and the maximum daily increase in rooting depth being specified prior to the simulation. The daily increase in rooting depth is equal to the maximum daily increase unless maximum rooting depth is reached. The Ritchie (1972) equation is used to separate the evaporation and transpiration terms from the evapotranspiration.

The potential biomass production rate is assumed to decrease in the same proportion as the transpiration so that the actual amount of biomass produced on a given day and consequently during whole season can be calculated.

WOFOST has been used by the European Union’s Joint Research Centre (JRC) to develop a system for regional crop state monitoring and yield forecasting for the whole European Union (Van Ittersum et al., 2003). The system comprises winter wheat, grain maize, barley, rice, sugar beet, potatoes, field beans, soybean, winter oil seed rape and sunflower. This system, called crop growth monitoring system (CGMS), generates region-specific indicators of the agricultural season conditions in the current year, on a semi-real time basis. This has been realised by simulating yields from weather and soil data, which serve as crop production indicators. This model output is qualitative in the sense that it is based on comparison of quantified indicators of the current year with those of the past. It provides information on whether in the current season a given crop deviates from the ‘normal’ growing pattern in terms of biomass and phenological development. These crop indicators are used in combination with regression techniques as a basis for quantitative regional yield prediction for the various crops. The system is operational for the EU and has been installed in various non-EU countries.

According to Van Ittersum et al. (2003), despite that Wageningen has a strong tradition in crop modelling, which has yielded a rich variety in crop modelling approaches and modules; there has not been a strong drive towards integration of research efforts, particularly not for implementation and application purposes.

3.1.3 Other Available Crop-Oriented Models

As pointed out above, besides DSSAT and the Wageningen models, several other models have been developed during the last years, aimed to estimate crop development and yields under different agricultural management conditions. Some of these models have been developed and tested in Europe. Numerous models are now available, with different objectives, and many new models are still appearing. Actually, there is no universal model and it is necessary to adapt system definition, simulated processes and model formalisations to specific environments or to new problems (Van Ittersum et al., 2003). To efficiently manage irrigation systems has been one of the most important issues considered in simulation models since they appear.

Particularly, the European Society of Agronomy (ESA), has a special session dedicated to such modelling tools. Besides, special numbers of the European Journal of Agronomy have been dedicated to promote such models. The CROPSYST model (Stockle et al., 2003), the French model STICS (Brisson et al., 2003) and the Australian model APSIM (Keating et al., 2003) are examples of such other models.

Other available European model is the Czech model PERUN (Dubrovsky et al., 2002, 2003). The model is a computer Windows-based system for probabilistic crop yield forecasting. The system comprises all parts of the process: (1) Preparation of input parameters for crop model simulation, (2) launching the crop model simulation, (3) statistical and graphical analysis of the crop model output, (4) crop yield forecast. The weather data series are calculated by the stochastic weather generator Met&Roll (Dubrovsky, 1999) with parameters that are derived from the observed series. The synthetic weather series coherently extends the available observed series and fit the weather forecast. Wind speed and humidity were added to the standard set of four surface weather characteristics generated by Met& Roll to meet the input data requirements. These two variables are generated separately by nearest neighbours re-sampling. To prepare the weather data for seasonal crop yield forecasting, the weather generator may now generate the synthetic series which coherently follows the observed series at any day of the year.

The crop yield forecast made by PERUN is based on the WOFOST crop model simulations run with weather series consisting of observed series till DAY-1 coherently followed up by synthetic weather series since DAY. The simulation is repeated n times (new synthetic weather series are stochastically generated for each simulation) and the probabilistic forecasts are then issued in terms of the average and standard deviation of the model crop yields obtained in the n simulations. The synthetic part of the weather series is prepared by a two step.

3.2 Agrohydrological Models

Agrohydrological or water-oriented models were significantly developed during the last years (Bastiaansen et al., 2004). The models SWAP (Van Dam et al., 1997), DRAINMOD (Kandil et al., 1995), WAVE (Vanclooster et al., 1994), ISAREG (Teixeira and Pereira, 1992) and HYDRUS (Šimunek et al., 1998) can be considered as agrohydrological models, among others.

The unsaturated zone, i.e. the zone between the soil surface and the groundwater, is a complicated system governed by highly non-linear processes and interactions. Flow processes can alternatively be described by means of physical-mathematical models. According to Bastiaansen et al. (2004), unsaturated-zone models can be used to simulate the timing of irrigations and irrigation depths, drain spacing and drain depth, and system behaviour and response. The models have increased our understanding of irrigation and drainage processes in the context of soil–plant–atmosphere systems. Progress in modelling can be attributed to merging separated theories of infiltration, plant growth, evapotranspiration and flow to drain pipes into a single numerical code (Bastiaansen et al., 2004).

According to Van Ittersum et al. (2003) agrohydrological models are more suitable to irrigation and water-use assessments than crop-growth oriented models, although both approaches have been used.

3.2.1 Constraints of Crop-Oriented Models Regarding the Simulation of Soil Water-Movement and Crop Water-Use

Actually, water moves not only down within the soil, but also lateral and even upward, depending on the potential gradients (Kutilek and Nielsen, 1994). Transport phenomena, as water movement into the soil, are driven by potential gradients that depend on gravity, water extraction by roots and water that enters or leaves the profile from top or bottom, causing different soil water suctions in the different layers.

The cascade approach could be appropriate on sandy soils or if the objective is to calculate the amount of water available to the crop over longer periods of time. However, this approach could fail in soils with significant clay and silt content and if the objective is to calculate daily soil-water profiles, as needed in irrigation assessments. A Richards-based approach might be more appropriate in those cases (Van Ittersum et al., 2003).

Several researchers have pointed out the DSSAT limitations regarding soil-water simulations, due to the use of the cascade approach in such simulations (Gabrielle et al., 1995; Maraux et al., 1998; Mastrorilli et al., 2003). According to Ritchie (1998), there is definitely a need to have better DSSAT simulations of the water balance in very poorly drained conditions where oxygen stresses will impact plant growth. Some attempts to improve DSSAT in that concern have been made already (Yang et al., 2004).

Particularly, since the cascade approach is unable to simulate upward water movement due to capillary rising, DSSAT yield predictions significantly depart from actual yields under heavy rain conditions (Rosenzweig et al., 2002). Particularly, Utset et al. (2006) showed that capillary rising can be an important component of maize water balance, when maize is cropped nearby river and channels, where shallower water tables can be found.

Extreme rainfall conditions will be more frequent in the near future, due to climate change (IPCC, 2007). As pointed out by Rosenzweig et al. (2002), yield loses in the US due to heavy rainfall could be very important in the future and the modelling-based climate-risk assessments should take them into account.

Utset et al. (2006) results also showed that water excess could significantly affect crop production. Figure 3 depicts the maize relative transpiration (ratio between actual and maximum transpiration) as simulated during dry years through SWAP by Utset et al. (2006). RT is depicted in Figure 3 as a function of Total Water Supply (TWS), considering a water table at a 2-m depth. The line shows the obtained regression. As can be seen in the figure, higher TWS gives raise to a reduction in RT rather than to further increments. Since the Feddes et al. (1978) root water-uptake function, included in SWAP, is able to account on water-excess effects on crop water use, the Utset et al. (2006) simulations can estimate the extreme rainfall effect also, whereas other models are unable to evaluate that consequence. Utset et al. (2006) simulation results indicate that precipitation excess could bring a negative effect in flooded irrigated maize, if relatively shallow water tables are found.

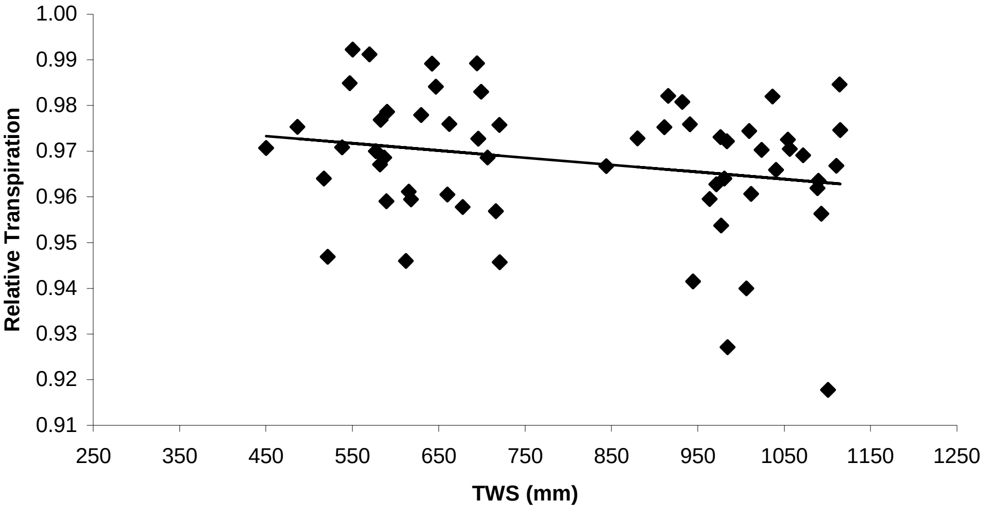

Figure 3: Simulated Maize relative transpirations as a function of Total Water Supply in dry years, considering a shallower water-table at 2-m depth (after Utset et al., 2006).

3.2.2 SWAP Model. Generalities

Feddes et al. (1978) developed the agrohydrological model SWATR (Soil Water Actual Transpiration Rate) to describe transient water flow in cultivated soils with various soil layers and under the influence of groundwater. The model was further developed to accommodate more boundary conditions (Belmans et al., 1983), crop growth (Kabat et al., 1992), shrinkage and swelling of clay soils (Oostindie and Bronswijk, 1992), and salt transport (Van den Broek et al., 1994). More recently, the model SWAP (Van Dam et al., 1997) was released as a result of a combination of SWATR with WOFOST (Van Keulen and Wolf, 1986). Several improved versions of SWAP were released; the most updated includes also the solute-leaching simulation model PEARL (Kroes, 2001).

SWAP is a computer model that simulates transport of water, solutes and heat in variably saturated top soils. The program is designed for integrated modelling of the Soil-Atmosphere-Plant System. Transport processes at field scale level and during whole growing seasons are considered. System boundary conditions at the top are defined by the soil surface with or without a crop and the atmospheric conditions. The lateral boundary simulates the interaction with surface water systems. The bottom boundary is located in the unsaturated zone or in the upper part of the groundwater and describes the interaction with local or regional groundwater.

Van Dam (2000) provides a detail description of the SWAP theoretical background. SWAP solves Richards’s equation numerically, subject to specified initial and boundary conditions and the soil hydraulic functions.

The maximum root water extraction rate, integrated over the rooting depth, is equal to the potential transpiration rate, which is governed by atmospheric conditions. The potential root water extraction rate at a certain depth may be determined by the root length density, at this depth as fraction of the total root length density.

Stresses due to dry or wet conditions and/or high salinity concentrations may reduce The potential root water extraction rate. The water stress in SWAP is described by the function proposed by Feddes et al. (1978), which comprises a coefficient that takes values between zero and one. Under conditions wetter than a certain “anaerobiosis point” (h1) water uptake by roots is zero, as well as the coefficient α. Likewise, under conditions drier than “wilting point” (h4), α is also zero. Water uptake by the roots is assumed to be maximal when the soil water pressure-head is between h2 and h3 and hence α-value is one in that case. The values of α decrease linearly with h for h values lower than h4 but larger than h3. According to Leenhardt et al. (1995), the Feddes et al. (1978) root water-uptake model has the advantage that not only considers the crop transpiration reduction due to lower soil-water contents, but also takes in account the negative effect of water excess in the soil root zone. Utset et al. (2000) showed that the Feddes et al. (1978) model fits better to actual data, obtained in tropical conditions, than the model provided by Van Genuchten et al. (1987). This SWAP feature could be very important, since flooding could be regionally more severe in the future (IPCC, 2000, Rosenzweig et al., 2002; Utset et al., 2006).

For salinity stress the response function of Maas and Hoffman (1977) is used in SWAP (Van Dam, 2000), as this function has been calibrated for many crops.

Besides calculating crop yields through the WOFOST module, a simpler approach to calculate yield reduction as function of growing stage can be used in SWAP (Doorenbos and Kassam, 1979; Smith, 1992). The ratio between actual to potential transpirations is known as “Relative transpiration ratio” (Van Dam, 2000). The relative transpiration reductions can be related to the effects of water stress (De Wit et al., 1978; Van Dam 2000). The relative yield of the entire growing season is calculated as product of the relative yields of each growing stage.

Two different types of irrigation can be specified in SWAP (Kroes et al., 2002). Either a fixed irrigation can be specified, or an irrigation schedule can be calculated for a specific crop according to a number of criteria. A combination of fixed and calculated irrigations is also possible. An example of this is a fixed irrigation (preparation of the seed bed) before planting and calculated irrigations based on soil moisture conditions after planting. Fixed irrigations can be applied the whole year. Irrigation scheduling can only be active during a cropping period. The irrigation type can be specified as a sprinkling or surface irrigation. In case of sprinkling irrigation, interception will be calculated (Kroes et al., 2002).

3.2.3 SWAP Model. The Simple Approach to Estimate Crop Water-Use

Kroes and Van Dam (2003) described the SWAP performance. According to them, the simple SWAP crop-growth approach represents a green canopy that intercepts precipitation, transpires and shades the ground. Leaf area index, crop height and rooting depth must be specified as functions of the development stage. SWAP simulates crop growing on a daily basis. The development stage (DVS) at a given day j depends on the development stage at the previous day and the daily temperature, according to:

$$DVS^{j} = DVS^{j-1} + \frac{T_{eff}}{T_{sum}} \qquad [1.]$$

where T_{sum} is the required temperature sum and T_{eff} is the effective daily temperature, calculated from mean daily air temperature minus a minimum starting temperature (3 ºC). DVS reaches 1 at anthesis and 2 at maturity, according to the temperature sums at these two stages.

Van Dam (2000) provided the theoretical SWAP background. SWAP solves the Richards equation numerically, subject to specified initial and boundary conditions and the hydraulic functions of the soil. The maximum root water extraction rate (S_p) at a depth z, considering a uniform root-length density distribution, can be calculated from:

$$Sp(z) = \frac{T_p}{D_{root}} \qquad [2.]$$

Where D_{root} is the root density fraction, integrated over the rooting length density at this depth and T_p is the potential transpiration rate, which is subject to atmospheric conditions.

Actual root water uptake can be estimated through:

$$Sa(z) = \alpha \; Sp(z) \qquad [3.]$$

The α values range from zero (no root-water uptake) to one (maximum water-uptake, no stress) according to the Feddes et al. (1978) function. These values change according to actual soil water-content, but the function is crop-dependent (Van Dam, 2000). Utset et al. (2000) showed that the original parameters of the Feddes et al. (1978) model can be used to simulate potato water-use in conditions that are very different from those existing where the model was originally applied. Therefore, the parameters applied to sugarbeet in the Netherlands have been used in this assessment.

The potential reference evapotranspiration (ETP) is calculated in SWAP by the Penman-Monteith approach, although the user may introduce other ETP calculations (Van Dam, 2000). In addition, the crop coefficients K_c must be introduced to convert reference ETP on maximum crop evapotranspiration.

SWAP first of all separates the potential plant transpiration rate T_p and potential soil evaporation rate E_p and then calculates the reduction of potential plant transpiration and soil evaporation rates. The soil evaporative component can be separated from the total evapotranspiration calculated by the equation:

$$Ev = ETP \, e^{-m.I} \qquad [4.]$$

where m is a crop-dependent coefficient and I is the Leaf Area Index. The transpirative component is therefore calculated from the difference between the total evapotranspiration and the evaporative component. Ritchie (1972) and Feddes (1978) used $m = 0.39$ for common crops.

Secondly, actual transpiration is calculated considering the root water uptake reduction due to water stress, using equation [2]. Actual soil evaporation can be calculated from the Maximum Darcy flow at the soil surface, which depends on actual soil water content and hydraulic conductivity, although several other options for calculating actual soil evaporation are implemented in SWAP (Van Dam, 2000).

The simple SWAP crop-growth approach does not estimate the crop yield. However, the user can define yield response factors (Doorenbos and Kassam, 1979; Smith, 1992) for various growing stages as functions of the development stage. During each growing stage k, the actual yield $Y_{a,k}$ (kg ha-1) relative to the potential yield $Y_{p,k}$ (kg ha-1) during the said growing stage is calculated by:

$$1-\frac{Y_{a,k}}{Y_{p,k}}=K_{y,k}\left(1-\frac{T_{a,k}}{T_{p,k}}\right) \qquad [5.]$$

where $Y_{a,k}$ and $Y_{p,k}$ are the actual and potential yields for the period k, $T_{a,k}$ and $T_{p,k}$ are the actual and potential crop transpiration, respectively, and $K_{y,k}$ is a coefficient which depends on the crop and on the crop growing period k. Final relative yields, i.e. the ratio between Y_a and Y_p, are calculated as the product of the relative yields of each growing stage k.

In SWAP, irrigations may be prescribed at fixed times or scheduled in accordance with certain criteria. According to Kroes and Van Dam (2003), the irrigation scheduling criteria applied in SWAP are similar to those found in CROPWAT (Smith, 1992), IRSIS (Raes et al., 1988) and others. SWAP can therefore be used to select the irrigation management that maximizes crop yield, minimizes irrigation costs, optimally distributes a limited water supply or optimizes production from a limited irrigation system capacity (Kroes and Van Dam, 2003).

3.2.4 HYDRUS Model

An important modelling approach, aimed to simulate water and solute transport through the soil vadose zone is the model HYDRUS-1D (Šimunek et al., 2005). The model consists of the HYDRUS computer program, and the HYDRUS1D interactive graphics-based user interface. According to Šimunek et al. (2005), the HYDRUS program numerically solves the Richards equation for saturated-unsaturated water flow and convection-dispersion type equations for heat and solute transport. The water flow equation incorporates a sink term to account for water uptake by plant roots, as well as in SWAP (see equation 1). The heat transport equation considers movement by conduction as well as convection with flowing water. Salinity is also considered through the Maas and Hoffman (1977) function and the simulation of crop water uptake follows a similar approach than the SWAP model.

The HYDRUS-1D code may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. The flow region itself may be composed of non-uniform soils (Šimunek et al., 2005). Flow and transport can occur in the vertical, horizontal, or in a generally inclined direction. The water flow part of the model considers prescribed head and flux boundaries, as well as boundaries controlled by atmospheric conditions, free drainage, or flow to horizontal drains (Šimunek et al., 2005).

The source code was developed and tested on a Pentium 4 PC using the Microsoft's Fortran PowerStation compiler. Several extensions of the MS Fortran beyond the ANSI standard were used to enable communication with graphic based user-friendly interface (Šimunek et al., 2005). HYDRUS1D comprises an interactive graphics-based user-friendly interface for the MS Windows environment. The HYDRUS1D interface is directly connected to the HYDRUS computational programs. Besides, the HYDRUS program come with several utility programs that make easier the data input process.

HYDRUS1D can be considered as a one-dimensional version of the HYDRUS-2D code. This updated modelling release is aimed to simulate water, heat and solute movement in two-dimensional variably saturated media (Šimunek et al., 1998), while incorporating various features of earlier related codes such as SUMATRA (van Genuchten, 1978), WORM (Van Genuchten, 1987), HYDRUS 3.0 (Kool and van Genuchten, 1991), SWMI_ST (Šimunek, 1992), and HYDRUS 5.0 (Vogel et al., 1996). Indeed, to be able to simulate soil water-movement and crop water-uptake in two dimensions open new possibilities that perhaps make HYDRUS2D the most important currently available model in this concern (Van Genuchten and Šimunek, 2005).

3.2.5 Agrohydrological Models Constraints

Many models comparisons have pointed out that despite mechanistic model yield more accurate and sounder simulations; they require many input parameters that are not always easy to measure or to estimate (Leenhardt et al., 1995; Connolly, 1998; Bastiaansen et al., 2004). Sensitivity analysis of SWAP outputs showed that the simulated water balance are most sensitive to the crop coefficients used for calculating potential transpiration and to the soil hydraulic properties (Van Dam, 2000). This agrees with other analysis made with similar agrohydrological modelling approaches, based on Richards' equation (Clemente et al., 1994; Leenhardt et al., 1995). Unfortunately, the soil hydraulic properties use to show high spatial variability (Warrick and Nielsen, 1980; Van Genuchten, 1994; Leenhardt et al., 1995). Therefore, the SWAP dependence on these properties can be seen as one of the highest constraints when using such modelling approach (Van Genuchten, 1994; Leenhardt et al., 1995; Van Dam, 2000).

3.2.6 Simple Crop Water-Use Simulation Models. CROPWAT

Very often availability of model input data (especially soil input data) is a serious limitation for applications of complex crop water balance models as to be used for irrigation scheduling. This is especially a problem in poor agricultural regions, where input data generation might be a serious cost factor. The limitation on input data quality can lead to the situation that simple models or methods may perform better than the complex models. That is why for all SIRDEM experimental sites the performance of a simple approach will be tested as an alternative option. The test will result in defining limitations and potentials of both simple and complex approaches.

CROPWAT is a free-distributed code from the Food and Agriculture Organization (FAO) and can be downloaded from the FAO web (http://www.fao.org/landandwater/aglw/cropwat.stm). It is meant as a practical tool to help agro-meteorologists, agronomists and irrigation engineers to carry out standard calculations for evapotranspiration and crop water use studies, and more specifically the design and management of irrigation schemes. CROPWAT allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rainfed conditions or deficit irrigation. It simulates crop water-requirements on a monthly, 10-days period or daily basis with a simplified soil water balance (cascade approach). Actually, the cascade approach can yield same results than the physically-based approach, based on numerical solutions of Richards's equation, as shown by Eitzinger et al. (2004).

3.3 Models Calibration, Validation and Inter-Model Comparisons

Since SWAP simulates the soil-water balance; the model outputs include deep drainage, capillary rising and runoff also. The model itself can provide irrigation recommendations, based on the simulated soil water contents and crop evapotranspiration. All these capabilities can be used at the field level to integrate a general farm water-management, trying to help farmers to control water more efficiently and to improve the environmental and economic performance of irrigation systems. SWAP is specifically oriented to water management, but comprises the WOFOST also, which make SWAP able to simulate crop-growth as well. Nevertheless, SWAP simulation outputs should be compared to other similar modelling approach. As shown by Eitzinger et al. (2004); Tardieu (2005) and others, several model approaches can yield the same results. Particularly, DSSAT models have been used for irrigation and crop water-use assessments in Spain (Guereña et al., 2001; Villalobos and Fereres, 2004) and overseas (Hoogenboom, 2000). Therefore, a prior model comparison should be made before selecting the model that can be used to irrigation decision-making. Such comparison should include, at least, some internationally used model as those of DSSAT, based on the "Cascade approach"; as well as an agrohydrological model.

4. APPLYING CLIMATE AND CROP-GROWTH SIMULATION TOOLS TO SUPPORT AGRICULTURAL DECISION-MAKING

Despite the manifold papers addressed to estimate climate-change and climate-variability effects on agriculture, appeared in the last years, few cases can be referred where such tools have been effectively used to provide recommendations to farmers and stakeholders. Some of the current actions regarding such applications are outlined below.

4.1 Previous Experience

Probably, the most important contributions to the use of the available simulation tools to support agricultural decision-making are CLIMAG (Climate Prediction and Agriculture) activities. The CLIMAG workshops were held in Geneva 1999 and 2005, sponsored by WMO and IRI (Sivakumar, 2001; Sivakumar and Hansen, 2007). The CLIMAG proceedings remain as significant guidelines for using such tools in future studies. However, the assessments of climate-impacts on agriculture made in the framework of CLIMAG were only specially-funding applications. The CLIMAG assessments did not yield to sustainable applications of the simulation tools in the targeted countries.

One of the most important successful applications of climate information, combined to crop-growth simulation models, have been made in Australia (Meinke et al, 2001; Hammer et al., 2001; Meinke et al., 2006). Rainfall and many other meteorological variables strongly depend on El Niño behaviour. Since ENSO occurrence can be forecasted several months in advance, this information can be used to support agricultural decision-making, through crop-growth modelling exercises (Hammer et al., 2001). A “participatory process” (Meinke et al., 2001) comprising researchers, stakeholders and extension facilities has been pointed out as a way to provide sustainable and sounder support to Australian agriculture.

Another important application of climate information and crop-growth models can be found in the South East Climate Consortium (SECC), as described by Hoogenboom (2007). Seasonal forecasts at the county level, using ENSO phases, are combined with DSSAT modelling results in order to provide estimations of final yields, water and fertilizer requirements and several other outputs very useful to farmers. The forecast and the whole system are only reliable in El Niño years, although current researches aim to enlarge the system reliability to other years (Baigorria, 2007).

El Niño signal is not very strong over Europe, which limits the applicability of ENSO-based forecasts. Marletto et al. (2005) showed that WOFOST simulations of winter wheat yields, based on the available seasonal forecasts, departed significantly from the recorded data. However, using spatial and temporal aggregated data, as usually done by JRC when providing recommendations to the EU Commission of Agriculture, might be not the right approach to capture the relationships between weather variables and crop growing.

Hansen et al. (2006) provided an insight view of current advances and challenges while translating climate forecasts into reliable agricultural decision-making. They describe several methods used up to now to spatially and temporal downscale the forecasts, recommending methods comparisons and evaluations at local scales. Likewise, Alexandrov (2007) provided an update revision of current state on applying climate scenarios and seasonal forecasts to support agricultural decision-making. Alexandrov (2007) points out that improved climate prediction techniques are growing faster and finding more applications; hence close contacts between climate forecasters, agrometeorologists, agricultural research and extension agencies in developing appropriate products for the user community are needed. Furthermore, feedbacks from end users are essential identifying the opportunities for agricultural applications (Alexandrov, 2007).

4.2 The Role of Local Agricultural Research and Extension Services

As pointed out above, negative climate-variability impacts could be reduced by following adaptation options, which can be obtained from crop-model simulations combined with climate scenarios. The usefulness of such simulation tools has been proved in manifold papers, usually produced in Universities or similar centres. However, despite of the considerable public concern about climate change, European stakeholders and farmers are not yet using these scientific results for agricultural decision-making. Actually, the most reliable climate-change mitigation options depend on each specific situation.

While experts and researchers at high-level centres in Europe and other places (“developers”) have established significant Know-How and produced relevant of the above-cited tools for such climate-impacts studies; practical experts at local agricultural-research or extension centres as well as agricultural advisers (“users”), those who should apply these tools for agricultural decision-making, are often not aware about the available tools or their access to such tools is quite limited due to several reasons, as financial issues or lack of user-friendly design of tools.

A connection is needed between the “developers” and “users”, to improve decision making by better implementing the climate and crop-growth simulation model tools. Furthermore, feedback from low end-users to the tool-provider researchers is a prerequisite for improving these tools for their practical use e.g. by providing background information, setting up the actual input data needs, fitting time and spatial scales as required by specific applications and other similar issues.

In that context AGRIDEMA, a Specific Support Action (SSA), has been funded by the EU Sixth Framework Program from January 2005 to June 2007. The SSA aims to promote a research network, linking European modelling tool-providers and developers with the potential users of their research results (Utset et al., 2007a). AGRIDEMA general objective is to establish initial contacts and to conduct primary collaborations between “developers” and potential “users”, basically researchers and experts at agricultural services.

4.3 The AGRIDEMA Proposal. General Description

AGRIDEMA comprises the following specific objectives:

1. To identify European human resources that developed, improved and tested simulating tools such as GCM, seasonal forecasts, regional downscaling techniques and agricultural-impact simulation models; inviting them to participate in the SSA proposal activities for implementing their tools and Know-How.
2. To identify and to invite attending the SSA activities to potential users of the European-provided modelling tools.
3. To conduct short courses, where the invited “developers” will present the particularities of their developed or validated tools to the invited “users”.
4. To perform pilot collaborations between “developers” and “users”.
5. To disseminate the obtained results and to build up a wider consortium, comprising both, the “developers” of the simulating tools and the potential “users” of such tools (e.g. experts from regional agricultural-oriented research centres, advisers and farmers).

According to these objectives, several tasks or “work packages” were scheduled. The tasks can be seen in Figure 1. Following the AGRIDEMA timetable, three Workpackages were finished during the 1st period, i.e. “Identifying and Contacting developers”, “Identifying and contacting users” and “Courses on climate and crop-growth modelling tools”.

4.3.1 Identifying and Contacting Developers

The AGRIDEMA consortium created an initial list of which developers should be contacted. The list was based mainly the partners experience and previous contact. The use of European-made simulation tools was encouraged.

The following Table shows the simulation tools that were contacted by the AGRIDEMA consortium, as well as the corresponding European institution and relevant person.

Table 2: Models, institutions and “developers” included in the AGRIDEMA activities.

Model	***Institution***	***Contact***
REGCM3	ICTP, Italy	J. Pal
LARS-WG, SIRIUS	Rothamsted Experimental Station, UK	M. Semenov
Met&Roll	Inst. Atmos. Physics, Czech Republic	M. Dubrovsky
Statistical downscaling	BOKU, Austria	H. Formayer
DEMETER	ECMWF, UK	F. Doblas-Reyes
LAPS	Agrometeorological Institute Novi Sad, Serbia	D. Michailovic
SWAP	Wageningen Agricultural University, The Netherlands	J. Kroes
WOFOST	Wageningen Agricultural University, The Netherlands	K. Van Diepen
PERUN	Mendel University Brno, Czech Republic	M. Trnka
ROIMPEL	Romanian Foundation on Global Change, Romania	C. Simota
CROPSYST	ISCI, Italy	M. Donatelli
STICS	INRA, France	F. Ruget
DSSAT	University of Madrid, Spain	A. Iglesias

Several work agreements were achieved between the AGRIDEMA consortium and most of the contacted “developers”, pointing out the “developers” participation in the AGRIDEMA courses, as well as their future support of the “Pilot Assessments” to be conducted by the “users” in the framework of AGRIDEMA.

4.3.2 Identifying and Contacting Users

Mediterranean countries could face the highest negative consequences of global warming within Europe, through water-shortage and crop-water requirements increments. Besides, since climate-change and extreme events effects could be more serious in countries with less-developed agriculture, the EU associated countries from Central and Eastern Europe, with relative reduced technological capacities, would be more affected than Northern-European countries. Therefore, AGRIDEMA focuses on “users” coming from Southern, Central and Eastern Europe, as well as from the countries of the Mediterranean area.

The members of the AGRIDEMA consortium released a call to “users” applicants since April 2005. Relevant institutions were contacted, according to AGRIDEMA partner’s experience, as well as official centres depending on the Countries’ Ministries of Agriculture or similar institutions.

The call was published also using all the available means, including email lists and internet facilities. As pointed out by the three AGRIDEMA partners during their first meeting, the basic criteria for selecting the “users” institutions to be involved in the proposal were:

i. To be able to communicate in English and to be able to work with data management software (Windows, Excel, etc.).
ii. To be involved with local agricultural decision-making, advising and farming.

iii. To be aware about the potential benefits of agricultural decision modelling tools, being able to identify which agricultural management options should be change and how to optimise management and reduce climate risk of local agricultural production.
iv. To have available data for the training course and for the potential conducting the SSA pilot assessments (crop growth and yields, meteorological variables, soil properties, irrigation and crop management scheduling, etc).

Additionally, users conducting PhD studies in the same subjects of AGRIDEMA activities will be especially considered for invitation.

4.3.3 The AGRIDEMA Courses on Climate and Crop-Growth Simulation Tools

The Courses were held in Vienna in November-December 2005, as scheduled in the proposal. Since many applications to the AGRIDEMA courses were received from “users” out of the targeted countries, the AGRIDEMA partners decided to include these applicants also without any course fee, if they were able to support their trips and lodging expenses. Finally, 44 “users” were present in total, from more than 15 different countries. Sixteen “users” were fully supported by AGRIDEMA and other eight were partially supported by the SSA. A picture showing all the participants in the AGRIDEMA courses is depicted in Figure 2.

Institutions from several countries decided to support additional participants in AGRIDEMA courses. Particularly, the participation of five Spanish researchers was supported by the INIA AC05-008 complementary action. Besides, several students and researchers from BOKU, Austria, were in the courses too.

The AGRIDEMA web page (www.agridema.com) shows all the details of Courses held in Vienna; as the lectures program, time schedule, invited developers, participant users, etc. The courses on Climate tools comprise lectures on climate change scenarios, dynamical and statistical downscaling, as well as weather generators. The details and work-performance of quite known crop-growth models as SIRIUS, DSSAT, CROPSYST and WOFOST; among others, were shown too.

4.3.4 The Agridema Pilot Assessments

The AGRIDEMA pilot assessments were basically applications conducted by some of the “users” that attended the AGRIDEMA courses on climate and crop-growth simulation tools that were held in Vienna ending 2005. Assessments were made using existing data and were addressed to relevant issues concerning climate risks and agricultural decision-making in their respective countries and institutions.

The following issues were considered in the Assessments propositions:

- Local modelling comparisons and validations using available data will be encouraged as the agreement subjects.
- All the collaborations must identify clearly the potential benefits of these modelling applications for local agricultural decision-making. Particularly, those applications which include farmers from regional medium and small enterprises, as potential users of the tested tools, will be better considered for funding.

- Educational outputs, such as Ph. D. studies connected to the work agreements are highly desirable.
- Only original and different propositions can be supported.

The selection of the pilot assessments was based on the propositions that the “users” made at the end of the AGRIDEMA courses. The selection was geographically made. The AGRIDEMA consortium partners considered the available budget and the agreements among them during their first meeting.

Eight assessments were selected in the Mediterranean area, although only six were funded (those not leaded by ITACyL). Five assessments were conducted in Central Europe and three in Eastern Europe. The SSA coordinator gave priority to cooperation and exchange among the Mediterranean “users”, as well as funding dissemination activities, rather than to support ITACyL researches that have other funding possibilities. Furthermore, ITACyL received additional funds from the Spanish government to strength the cooperation with the Spanish institutions working in AGRIDEMA Pilot Assessments (Complementary Action CGL2006-26211-E) as well as with the Mediterranean countries involved (International Complementary Action PCI2005-A7-0105).

The Pilot assessments were conducted from March to October 2006. The AGRIDEMA support was based on agreements to be signed between each “user” conducting Pilot assessments and the corresponding partner of the AGRIDEMA consortium. The Pilot assessments information can be seen in the AGRIDEMA web page: www.agridema.org.

The complete lists of the funded AGRIDEMA Pilot assessments can be seen below.

Table 3: Pilot Assessments conducted in the framework of AGRIDEMA Mediterranean area (under the responsibility of the Spanish partner)

Title	***Presenter Name***	***Institution***
Full irrigation estimates and palliative measurements for coping with climate change in vineyard and peach orchards in Spain: a past tendency towards a future perspective	Jordi Marsal	IRTA, Spain
Optimizing irrigation water management on the global change context in a Mediterranean region	Jose A. Rodriguez*	DAP, Andalusia, Spain
Estimating climate-change effects on Sugarbeet irrigation efficiency in the Spanish Northern Plateau	Blanca del Rio	ITACyL, Spain
Adaptations of irrigated cropping systems of Southern Italy as affected by climate change at field/farm scale	Domenico Ventrella	CRA-ISA, Italy
Assessment of the Impact of Climate Change on Water Productivity in Rainfed Wheat Systems in the Mediterranean region	Fatema Mosseddaq	IAV Hassan II, Morocco
Assessment of the Impact of Climate Change on Water Productivity in Irrigated potatoes in the Southern Mediterranean region	Mahmoud Medany	CLAC, Egypt
Estimation of water availability for annual crops at Tree – Crop ecosystems	Dimos Anastasiou	NAGREF, FDA, Greece

*Conducting a Ph D in this issue

Central Europe (under the responsibility of the Austrian partner)

Title	*Presenter Name*	*Institution*
Modelling of the maize production and the impact of climate change on maize yields in Croatia	Visnja Vucetic	Meteorological Service of Croatia
Irrigation in different Climate conditions using crop models	Blaz Kurnik	EARS (Met. Office, Slovenia)
Introducing crop modeling tools into a Serbian crop production	Branislava Lalić	University of Novi Sad, Novi Sad, Serbia and Montenegro
Determination of the water demand and use of various crops in the region Lake Neusiedl and Seewinkel	Ildikó Dobi Gerhard Kubu	Hungarian Meteorological Service; Univ. of Natural Resources and Appl. Life Sciences, BOKU
Modelling of crop yields in the present and future climatic conditions in WIELKOPOLSKA REGION (POLAND) with and without irrigation management practices	Jacek Leśny	Agricultural University of Poznań

Eastern Europe (under the responsibility of the Bulgarian partner)

Title	*Presenter Name*	*Institution*
Impact of climate factors on grain yield of spring barley in Latvia	Jelena Korolova*	Latvia University of Agriculture (LUA)
Climate variability and change over the Balkan peninsula and related impacts on crops	Stanislava Radeva	NIMH, Bulgaria
Complex assessment the efficiency of adaptation of agricultural ecosystems to climate change in the European part of Russia based on integration with European crop models	Vladimir Romanenkov	All-Russian Institute for Agrochemistry

*Conducting a Ph D in this issue

The reports of the AGRIDEMA Pilot assessments, which can be downloaded from the AGRIDEMA web, comprise an excellent collection of many different applications from several European and Mediterranean countries, all of them addressed to local potential climate-risks. The strategic AGRIDEMA goal, which aims to promote a research network, linking European modelling tool-providers and developers with the potential users of their research results, has been already partially fulfilled.

4.4 The Agridema Pilot-Assessments Results

According to the AGRIDEMA goals, the Pilot assessments should comprise the two following tasks:

1. Downscaling the provided GCM-outputs and/or seasonal-forecasts.
2. Simulating impacts (such as crop growth and yield, drought stress level etc.) under the locally-obtained climate scenarios, evaluating several management options, which might mitigate the probable climate impact.

Scientific quality of the assessments is quite variable, which can be expected from the wide irregularity of AGRIDEMA applicants. Furthermore, the applicability of the obtained results varies among the assessments as well. Generally, those assessments conducted by researchers located in agricultural stations are closer to stakeholder goals, but unclear regarding climate analysis. Objectives were too ambitious sometimes and could not be fulfilled with a simple application. Moreover, the use of the climate and crop modelling tools shown in the AGRIDEMA courses was mainly related to the user' previous experience and not to the tool reliability for the expected goal. Comparisons between modelling tools were not conducted in most of the cases. In spite of all the above, the AGRIDEMA results constitutes perhaps the most important collection of independent climate-change agricultural assessments that have been made in Europe.

The following table shows the climate and crop-growth simulation tools that have been used in the AGRIDEMA pilot assessments. The downscaling method is clearly identified in all the reports. However, the GCM data source is not always pointed out. In some cases, the assessment was very simple due to the lack of data or relevant knowledge on the crop model.

Table 4: Climate and crop-growth tools used in the AGRIDEMA Pilot assessments

Assessment Conductor	***Institution***	***CLIMATE***	***CROP***
Jordi Marsal	IRTA, Spain	CCMA -LARS	CROPSYST
Jose A. Rodriguez	DAP, Andalusia, Spain	CCMA -LARS	DSSAT
Blanca del Río	ITACyL, Spain	CCMA -LARS	SWAP
Domenico Ventrella	CRA-ISA, Italy	CGM-LARS	SWAP
Fatema Mosseddaq	IAV Hassan II, Morocco		DSSAT
Mahmoud Medany	CLAC, Egypt	MAGICC	DSSAT
Dimos Anastasiou	NAGREF, FDA, Greece	CCMA -LARS	SWAP
Visnja Vucetic	Meteorological Service of Croatia	ECHAM4-CSIRO-HADCM3-M&R	DSSAT
Blaz Kurnik	EARS (Met. Office, Slovenia)	REGCM3-LARS	CROPSYST

Table 4: Continued

Assessment Conductor	***Institution***	***CLIMATE***	***CROP***
Branislava Lali	University of Novi Sad, Novi Sad, Serbia and Montenegro	M&R-LARS	SIRIUS-PERUN(W)
Ildikó Dobi	Hungarian Meteorological Service	LARS-WG	PERUN(W)
Jacek Lezny	Agricultural University of Poznan	M&R	PERUN(W)
Jelena Korolova	Latvia University of Agriculture (LUA)		
Stanislava Radeva	NIMH, Bulgaria	HADCM3-REGCM3	ROIMPEL
Vladimir Romanenkov	All-Russian Institute for Agrochemistry	HADCM3-CLIMGEN	CSY+CROPSYST-ROIMPEL

As can be concluded from the above Table, the most used GCM outputs were the Canadian CCCMa (4 times) and HADCM3 (3 times). The ECHAM and CSIRO GCM outputs were used in one assessment, where a GCM output comparison was performed. The LARS-WG appeared in 8 of the AGRIDEMA pilot assessment, which makes this weather generator as the most frequently used climate-tool in the framework of AGRIDEMA. According to Wilby and Wigley (2001), LARS-WG is one of the most used weather generators. The AGRIDEMA results confirm this conclusion. The Met&Roll weather generator was found in 3 assessments, including one comparison with LARS-WG. The Regional ReGCM3 model was used in 2 assessments and the MAGICC model in one.

Regarding the crop models considered in the Pilot assessments, the Wageningen model WOFOST was the most used, but in its SWAP (3 times) and PERUN (3 times) versions. DSSAT models were employed in 4 Pilot Assessments, while CROPSYST was used 3 times, ROIMPEL was considered 2 times and SIRIUS was used in one assessment, which performed a model comparison with PERUN. The frequency of using crop models in the AGRIDEMA Pilot assessments is similar to that found in climate-change impact assessments all over the world, reported by Tubiello and Ewert (2002) as well as in Europe, as pointed out by Alexandrov (2002).

An important AGRIDEMA conclusion is that DSSAT, SWAP-WOFOST and CROPSYST are the most relevant crop-growth simulation models that are being used in Europe for climate-change risk assessments. Furthermore, SWAP has been the most used agrohydrological model within the AGRIDEMA Pilot assessments.

4.5 A Pilot Assessment Example: Managing Sugarbeet Irrigation in the Spanish Northern Plateau under Present and Future Climate Conditions

Castilla y Leon, with 94 000 km^2, is the largest Spanish Autonomic Community and one of the major administrative regions of Europe. Castilla y Leon is basically a large plateau, with an important agricultural production. The region involves more than 20% of the cultivated area of Spain, 22.7% of grassland area and 31.9% of the cereals-cropping area. Even though Castilla and Leon comprises only 6% of Spanish population, they mean about 12% of the reported farm-workers in Spain, almost twice the country mean (7.7%) and higher than the European mean (9.0%).

Castilla y León is, after Andalusia, the Spanish Autonomic Community with higher irrigation surface. According to the last Ministry of Agriculture report (MAPA, 2004), Castilla y León irrigated-agriculture produces 57% of Sugarbeet, 38% of maize and 30% of potatoes of the whole country. The investment in irrigation infrastructures in Castilla y León is the second highest in Spain. However, such investment must be joined to applied researches aimed to improve water-management efficiency, particularly in eventual prices diminishing or severe droughts.

The recent reform of the European Sugar Market (EC Council Regulation 318/2006) will bring important reductions on the Sugarbeet prices. Irrigation means about 35% of the total Sugarbeet production costs in Northern Spain. Sugarbeet water requirements will be higher in the future, according to Climate-Change predictions, while water availability will diminish in the Castilla y León zone. Furthermore, EU Water Framework Directive (EC Directive 2000/60), through its “recovering costs” principle, will very probably increment the water prices. The combination of all these factors could yield that Sugarbeet becomes an unaffordable crop in Castilla y León in the near future.

According to the above, an AGRIDEMA Pilot assessment was conducted in order to calibrate and validate the SWAP model for Sugarbeet water-use simulations, as well as to estimate Climate Change effects on water use efficiency, considering a typical irrigation management. Utset et al. (2007b) provided the calibration and validation of the SWAP model. The assessment was conducted at Valladolid, Northern Spain (41º39’N, 4º43’W). The regional climate is Mediterranean Semiarid with an annual average precipitation of 531 mm. According to the local soil map (JCYL, 1987), Sugarbeet is cropped mainly in Cambisols and Fluvisols.

4.5.1 SWAP Calibration and Validation. The Assessment Data

The SWAP calibration comprised data of experiments addressed to study water-shortage effects on sugarbeet growth, made during 1992, 1993, 1994 and 1995 in a clayey Fluvisol and in a Cambisol (Velicia, 1998). The water-stress effect on sugarbeet yields depends on the growing period (Brown et al., 1987; Groves and Bailey, 1994; Fabeiro et al., 2003). Accordingly, water shortages were applied at the beginning and end of sugarbeet development. Four irrigation start and end dates were considered (Velicia, 1998), based on non-restrictive irrigation management with typical considerations (Morillo, 1993; Allen et al., 1998), which provides all the sugarbeet water requirements from seeding to harvest. Four plots were dedicated to each irrigation design at each soil type. The plots were separated from each other by at least 20 m in other to avoid water redistribution among them.

Sugarbeet roots can reach up to 2 m in length (Brown et al., 1987; Velicia, 1998). The root distribution in depth depends on soil and moisture conditions. However, according to Velicia (1998), about 60% of the roots is usually found in the first 30 cm, whereas 90% could be found at depths shallower than 90 cm. Therefore, a non-linear root distribution was assumed.

Potential evapotranspiration was calculated by the Penman-Monteith approach, using meteorological data available from stations at distances of 1.2 and 2.3 km from the plots. Maximum crop evapotranspiration was calculated considering the Kc coefficients estimated for the zone (Morillo, 1993). Daily temperature values were also recorded. The SWAP FCS stage was considered as the date when sugarbeet covers soil completely under non-restrictive irrigation water-management conditions (Velicia, 1998). The maturity date was assumed as the harvest.

The sugarbeet (Ramona cultivar) germination date was May 15 and the average harvest date was October 15. The said dates were considered for computing the temperature sums at FCS and maturity and can be considered as typical dates for spring-sown sugarbeet (Morillo, 1993). The irrigation water applied at each plot was measured weekly. Final sugarbeet yields were measured at each plot.

The leaf area index (LAI) was measured monthly at each plot. The length and width of all the green leaves on each plant in 1-m rows were measured. LAI was indirectly estimated according to a regression equation obtained from previous studies (Velicia, 1998). Root lengths and weights were also measured (Velicia, 1998) from three randomly selected plants, removed entirely from the ground at each plot on a monthly basis. Soil water content was measured weekly by a neutron probe (Velicia, 1998). The actual crop evapotranspiration was estimated by water balance (Allen et al., 1998).

The actual crop transpiration was separated from total evapotranspiration considering the experimentally-measured LAI values (Ritchie, 1998). Final yields were measured and total crop transpiration was computed as the cumulative sum; the Ky coefficients (Doorenbos and Kassam, 1979; Kroes and Van Dam, 2003) were then calculated. The hydraulic properties of the soil were estimated from the physical soil data taken at each plot (Velicia, 1998) through a pedotransfer function (Shaap et al., 2001). SWAP simulations were performed at each plot, considering the parameters obtained in the calibration and free drainage at the bottom of the 1-m soil layer. A regression between relative yields and actual yields was conducted in order to find which maximum yield adapted better to the experimental conditions.

An independent data set was used for SWAP validations. Two sugarbeet plots, corresponding to a Cambisol (Plot Z) and a Fluvisol (Plot A), were selected in the Valladolid area. The plots were separated from each other by a distance of approximately 15 km.

Sugarbeet was seeded in the two plots in March 2005. Emergence dates were April 5 (A) and April 25 (Z). Undisturbed soil samples were taken at 20-40 cm depth in ten randomly-selected sites within each plot. The soil water retention curves were determined at each sample through a sand-kaolin box and a Richard membrane (Klute, 1986). The saturated hydraulic conductivity of each sample of soil was measured in a laboratory permeameter. The soil field capacity and the wilting point were considered as the water contents at 33 and 1500 kPa, respectively. The parameters of the Van Genuchten model for the soil-water characteristic curve were estimated through the RETC code (Van Genuchten et al., 1991).

Access tubes were placed at the same places where soil samples were taken at each plot. Soil water contents were measured weekly during July and August 2005 at 0-20, 20-40 and

40-60 cm depths by a Trime TDR [IMKO Micromodultechnick GmbH]. Actual crop evapotranspiration was computed using the balance method from the measured water contents and neglecting any possible capillary rising, runoff and/or percolation. Daily precipitation, global radiation, maximum and minimum temperature, wind speed and relative humidity values were recorded at two agrometeorological stations located near the selected plots.

Irrigation was applied traditionally in a way similar to that used by farmers to manage sugarbeet water applications at each plot. The irrigation water supply at each plot was measured through a water counter. Sixteen irrigations were applied on the Z Plot from June to August, comprising a total water application of 508 mm. Likewise, 556 mm of water were applied by irrigation on the A plot in the same period over eighteen irrigations. Precipitations are scarce in the Mediterranean summer. Accordingly, the total rainfall recorded was 41 mm on the Z Plot and 25 mm on the A Plot during the 2005 sugarbeet cropping season.

Actual SWAP simulations were conducted using the measured soil and meteorological data and considering the model calibration performed. Free drainage at the bottom of the 1-m simulated soil layer was considered, which is consistent with the soil descriptions (JCYL, 1987). Correlation and determination coefficients between simulated and estimated actual evapotranspirations were calculated, as well as the same coefficients between the SWAP-simulated actual evapotranspirations and the sugarbeet water requirements, calculated from Penman-Monteith computations of the reference evapotranspiration and the sugarbeet coefficients in use, as provided by Morillo (1993). Furthermore, Root Mean Square Errors (RMSE) were calculated between the simulated ETC and the water-balance estimated ETC, as well as between the simulated ETC and the maximum ETC, estimated from weather data. The RMSE has been considered as the most effective method of comparing simulated and actual values in evaluation model performance (Willmott et al., 1985; Timsina and Humphreys, 2006). The normalized RMSEn is used to compare modelling performances and can be calculated as:

$$RMSEn = \frac{\left[n^{-1} \sum_{i=1}^{n} \left(P_i - O_i \right)^2 \right]^{0.5}}{n^{-1} \sum_{i=1}^{n} O_i} \qquad [6.]$$

where P_i and O_i are the predicted and observed values, respectively, and n is the number of observations.

4.5.2 SWAP Calibration. The Results

Table 5 summarizes the calibration results; comparing the experimentally-obtained temperature sums at FCS and maturity, as well as the LAI and K_y values at several development stages with the corresponding values of the original SWAP calibration for Northern Europe.

Average FCS, i.e. maximum foliar development, corresponds to 71 days after germination in the irrigation managements that provide all the sugarbeet water requirements (Velicia, 1998). Therefore, development stage (DVS) reaches one at that date. The temperature sum at this development stage is 1141 ºC, which is much higher than the 365 ºC originally considered in SWAP. Indeed, average temperatures in Southern Europe after May are higher than the temperatures usually recorded in the Netherlands and other sites of Northern Europe, where SWAP has been previously calibrated. However, temperature sums from germination to FCS similar to those shown in Table 5 for Mediterranean conditions have been found in France (Durr and Mary, 1998) and the UK (Werker and Jaggard, 1997). Furthermore, the difference between the temperature sums at FCS and maturity is lower under Mediterranean conditions than in Northern Europe, which indicates a faster growing rate during summer. Estrada (2001) pointed out the influence of direct sun radiation on sugarbeet growing while cropped under Mediterranean conditions with unlimited water supply. Such direct radiation influence could determine that the temperature sums needed for sugarbeet maturation under Mediterranean conditions is lower than that required in Northern Europe.

Table 5: Average temperature sums, Leaf Area Index, Root Lengths and Root Length Densities; as well as K_C and K_y coefficients as function of development stages (DVS) under Mediterranean conditions and those values originally considered in the SWAP calibration provided for Northern Europe (after Utset et al., 2007b).

Function		*Locally-obtained*		*SWAP original*	
Temperature Sum (ºC)	Anthesis	1141		365	
	Maturity	2008		1622	
Leaf Area Index LAI		**DVS**	**LAI**	**DVS**	**LAI**
		0.55	0.4	0.56	0.13
		0.75	0.6	0.74	0.44
		0.77	0.6	1.00	1.47
		0.80	0.9	1.27	4.48
		0.89	1.2	1.52	5.04
		0.92	1.6	1.76	4.69
		0.98	2.1		
		1.00	1.7		
		1.01	2.1		
		1.02	3.1		
		1.02	2.4		
		1.08	3.2		
		1.10	2.7		
		1.15	3.3		
		1.16	3.2		
		1.17	2.5		
		1.22	2.3		
		1.28	5.5		
		1.79	3.8		
		1.85	4.9		
		1.88	3.5		

Table 5: Continued

Function	*Locally-obtained*		*SWAP original*	
Root Length (cm) RL	**DVS**	**RL**	**DVS**	**RL**
	0.55	46	0.56	58
	0.75	71	0.74	70
	0.77	81	1.00	87
	0.80	77	1.27	118
	0.89	81	1.52	120
	0.92	72	1.76	120
	0.98	115		
	1.00	95		
	1.01	81		
	1.02	104		
	1.02	107		
	1.08	112		
	1.10	125		
	1.15	118		
	1.16	107		
	1.17	129		
	1.22	131		
	1.28	125		
	1.79	123		
	1.85	135		
	1.88	126		
Root Length Density (RLD) as a function of Relative Root Length (RRL)	**RRL**	**RLD**	**RRL**	**RLD**
	0.25	0.60	0.0	1.0
	0.70	0.90	1.0	1.0
	1.00	1.00		
Crop Coefficients K_C	**DVS**	**K_C**	**DVS**	**K_C**
	0.40	0.4	0.0	1.0
	0.50	0.5	2.0	1.0
	0.60	0.7		
	0.80	1.0		
	1.80	1.1		
	2.00	0.9		
Yield response factors K_y	**DVS**	**K_y**	**DVS**	**K_y**
	0.33	1.00	0.0	1.0
	0.80	1.50	2.0	1.0
	1.00	1.50		
	1.50	1.00		
	2.00	0.90		

The experimentally-measured Leaf Area Indexes are also shown in Figure 4 as a function of the DVS calculated from the temperature sums shown in Table 5. The original SWAP values are included in the figure as a continuous line. Furthermore, Figure 4 also shows the measured and SWAP-original sugarbeet root-lengths as functions of the crop DVS. As the figure shows, the sugarbeet LAI development under Mediterranean conditions follows a pattern similar to that measured in Northern Europe. Therefore, the original function included in SWAP could be considered as still valid in a warmer environment.

The sugarbeet leaf area and root lengths show faster growing rates and higher averages in Mediterranean conditions than those anticipated in the original SWAP functions, particularly before FCS. This is in accordance with the temperature sum differences shown in Table 5.

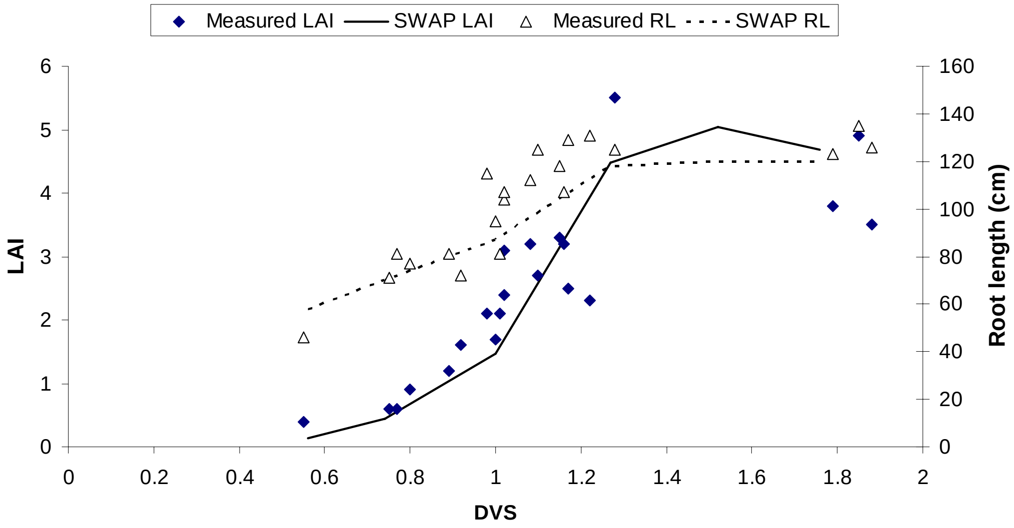

Figure 4: Measured sugarbeet Leaf Area Indexes (LAI) and Root Lengths (RL), as functions of the crop development stages (DVS). The continuous and dashed line shows the respective SWAP original functions (after Utset et al. 2007b).

Figure 5 compares the experimentally-measured sugarbeet root-lengths with those originally considered in SWAP as functions of the crop development stages. The SWAP function might slightly underestimate the sugarbeet root development as grown under Mediterranean conditions. However, the measured values behave in a way that is similar to the original SWAP function. Furthermore, there is a considerable dispersion of the measured values, which can be due to the different soil types considered.

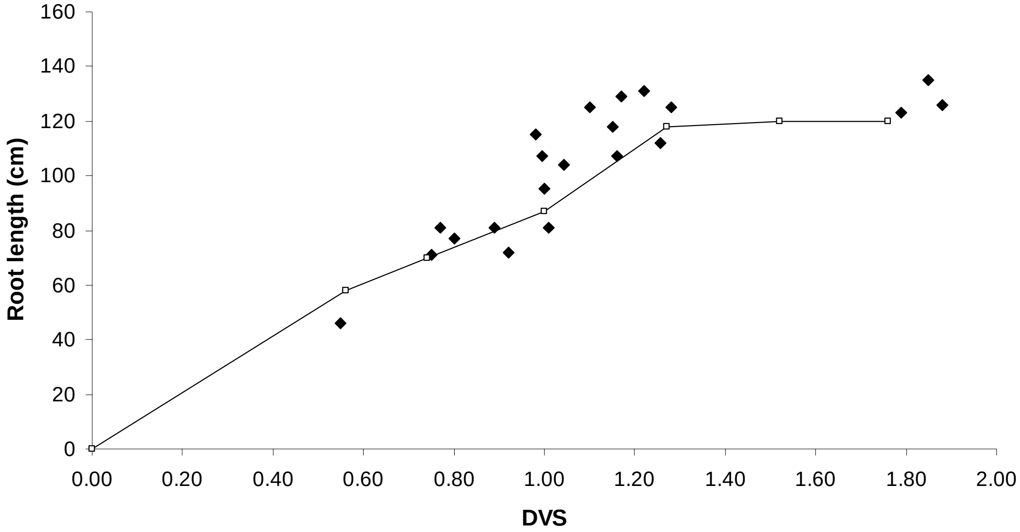

Figure 5. Measured Sugarbeet root lengths under several water managements as function of the crop development stages (DVS). The continuous line shows the SWAP original function (after Utset et al. 2007b).

Likewise, Figure 6 depicts the Mediterranean-considered and the SWAP-original K_C and K_y coefficients as functions of the development stages. Unlike the original SWAP value, which sets the same K_C coefficient for all the sugarbeet crop development, we consider a variable K_C. Velicia (1998) showed that sugarbeet water requirements are lower than the maximum reference evapotranspiration during the initial growing period. However, sugarbeet water needs increase significantly after completing foliar development and starting the root-growing period (Velicia, 1998), which might be considered for a DVS of around 0.8. Crop water needs are reduced close to maturity. Furthermore, the relationships between sugarbeet transpiration and root yield should not be considered as linear, as originally in SWAP. A reduction of actual sugarbeet transpiration regarding its potential transpiration may imply no serious yield reduction during initial leaf development, but such a reduction has significant consequences on final yields at the beginning of the root growing period (Velicia, 1998). The K_y coefficient, as well as the relative importance of water shortage in Mediterranean sugarbeet yields, can be linearly reduced after the initial root-growing period (Velicia, 1998).

Figure 7 depicts the relationship between the measured yields and the simulated relative yields, as well as the corresponding regression line. The data in Figure 10 comprise all the pairs of simulated-actual yields, regardless of water managements or soil types. As shown in Figure 7, lower actual yields start notably at the 1:1 line, while yields of above 50 t/ha generally correlate well with the simulated relative yields. Indeed, SWAP only takes into account the yield reductions due to water shortage. However, final yields rely on many other issues besides water availability, such as weed infections, diseases or nutrient deficiency. Furthermore, relative yields are always estimated as one if irrigation water is sufficient, whereas actual yields are variable. That is why the dispersion shown in Figure 10 is higher around the highest simulated relative yields.

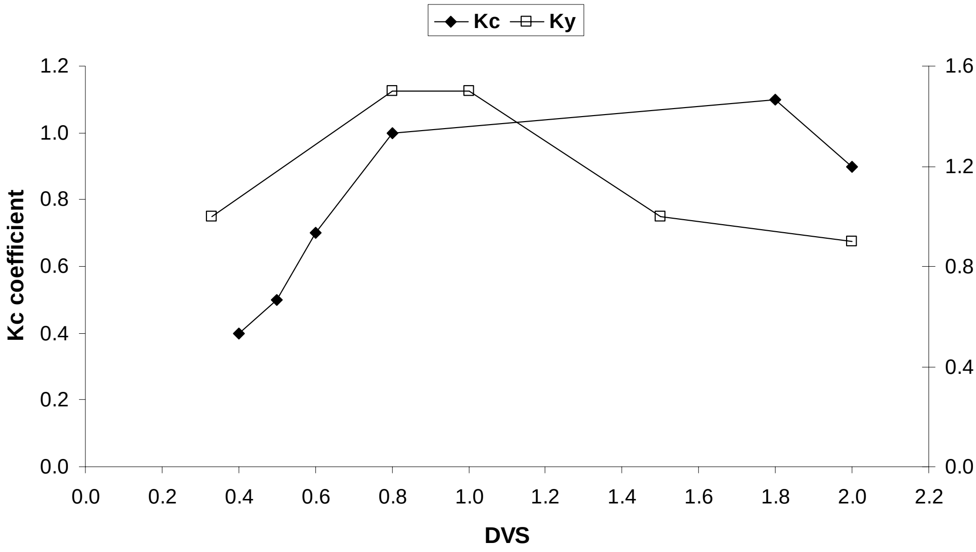

Figure 6: Sugarbeet Crop (KC) and yield factor (Ky) coefficients considered for SWAP simulations under Mediterranean conditions, as functions of the crop development stages (DVS) (after Utset et al. 2007b).

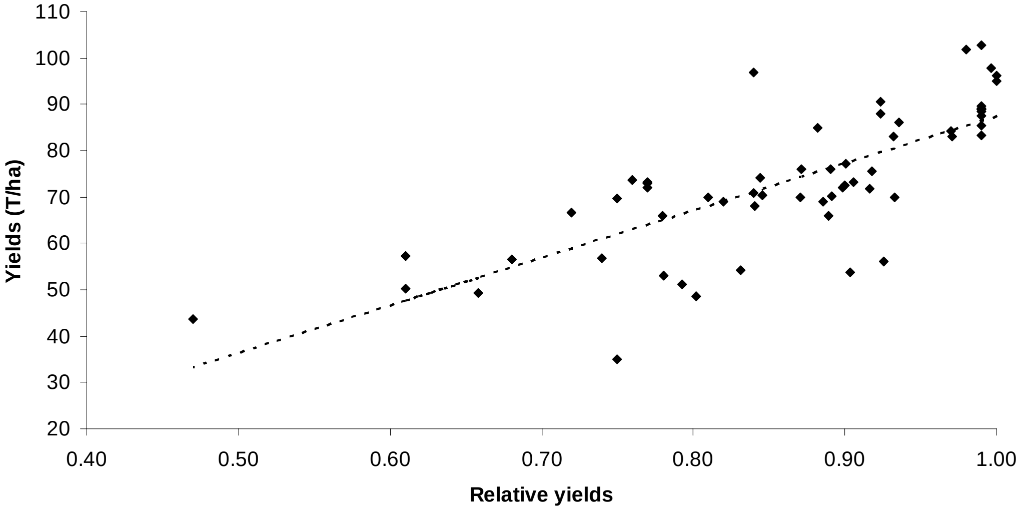

Figure 7: Experimentally obtained sugarbeet yields vs. SWAP simulated relative yields. The dashed and the solid lines show the regressions considering all the data and fitting-reduced data, respectively (after Utset et al., 2007b).

The correlation coefficient between simulated relative yields and the actual sugarbeet yields was 0.71. According to the regression obtained, the average maximum yield to be used in equation [5] should be 87.5 t/ha. The regression is statistically significant at the 99% probability level and explains more than 50% of the yield variability. However, the simulated relative yields are not normally distributed, since they are skewed to their highest value. Therefore, statistical comparisons between simulated relative yields and actual yields are limited. Despite this, the relatively high correlation coefficient and the level of statistical regression confidence would allow this simple SWAP approach to simulate water management effects on sugarbeet yields.

The average sugarbeet yield corresponding to simulated relative yields higher than 0.95 was 90.8 t/ha. Taking into account both results, a potential maximum yield for sugarbeet of around 89 t/ha can be used in SWAP simulations to estimate the effects of water availability on the final yields during crop seasons.

4.5.3 SWAP Validation. The Results

The soil water contents at the average depth of 0-60 cm in the Cambisol and Fluvisol plots, measured during the sugarbeet irrigation season, are shown in Figure 8. The water contents are generally close to the field capacity, shown in the figure by a dashed line. Water contents much higher than the field capacity would indicate an excess of water in the root zone and eventual water percolation. Furthermore, water contents much lower than the field capacity would indicate potential water excess and inefficient irrigation management. The results shown in Figure 8 indicate that, despite their non-technical approach, farmers usually know how to manage irrigation in an acceptable way (Utset et al., 2006).

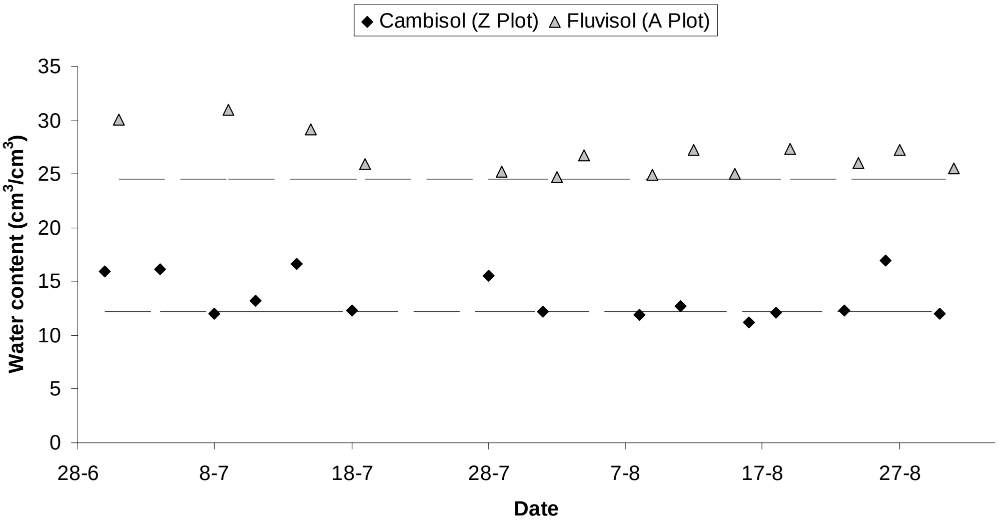

Figure 8: Average soil-water contents at the 0-60 cm depth in the Cambisol and Fluvisol plots during the 2005 Sugarbeet irrigation season. The dashed lines show the corresponding Field Capacities (after Utset et al., 2007b).

However, water contents are higher than the field capacity at the earlier stages of sugarbeet development, when the sugarbeet roots are not long enough and crop water use is lower. The results suggest that water application might be excessive at this stage. The difference between the measured soil water contents and the field capacity is higher in the Fluvisol, where clay contents are higher and water moves slowly across the soil profile.

Figure 9 shows the actual SWAP-simulated sugarbeet evapotranspiration, the maximum sugarbeet evapotranspiration, calculated using the Penman-Monteith reference evapotranspiration and the K_C coefficients shown in Table 5, as well as the actual crop evapotranspiration estimated from water balance and the water content measurements shown in Figure 8. The evapotranspiration values given in Figure 9 comprise both the Cambisol and the Fluvisol data and were calculated on a weekly basis.

As shown in the figure, simulations can follow the temporal changes of both measured ET_C values and those computed from reference evapotranspirations. The measured ET_C values are higher than the simulated and maximum rates computed from weather data at the beginning of the irrigation season. The water balance was calculated neglecting the percolation and capillary rising components of the balance. However, at these earlier sugarbeet stages, irrigation excess might yield to significant water loss by percolation, which is in accordance with the water contents being higher than the field capacity for the same period, as shown in Figure 8. The simulated evapotranspirations are lower than the maximum, as expected.

All the computed evapotranspirations indicate that sugarbeet water use at the end of the cropping season is lower than at the beginning of the root growing period, as pointed out by Velicia (1998).

The correlation coefficient between the actual SWAP-simulated evapotranspiration and the maximum weather-dependent sugarbeet evapotranspiration was 0.81; whereas the correlation coefficient between the simulated and actual estimated water-balance evapotranspirations was 0.75.

Figure 9 also shows that simulated ET_C values correlate better with the maximum evapotranspiration than with the measured ET_C. In practice, irrigation management at both plots was able to keep soil water contents above field capacity throughout the sugarbeet growing season. Therefore, actual crop evapotranspiration must be close to the highest possible maximum, since water requirements were mainly satisfied. This can explain the good ratios between the SWAP simulations and the weather-based maximum ET_C.

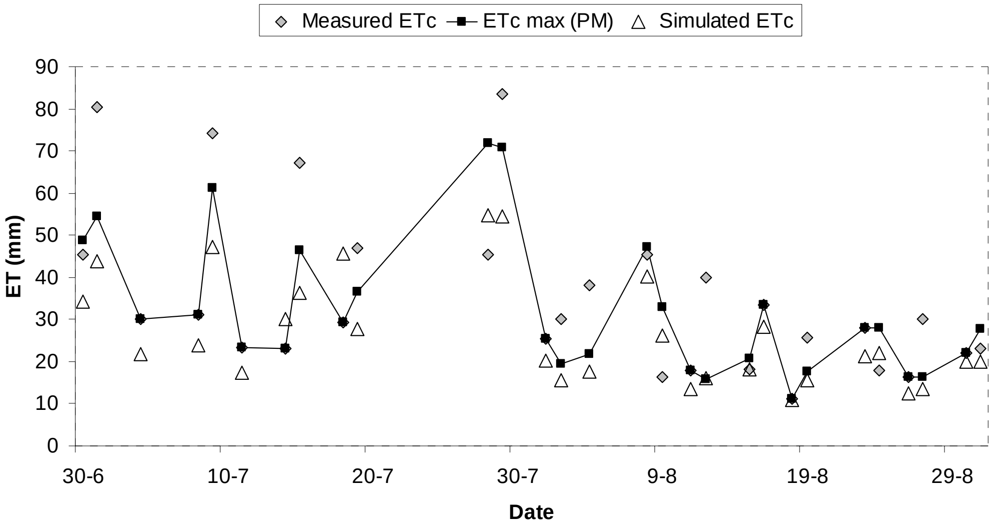

Figure 9: SWAP-simulated sugarbeet actual evapotranspiration (Simulated ETc), sugarbeet maximum evapotranspiration calculated from the Penman-Monteith reference evapotranspiration (ETc Penman-Monteith) and actual evapotranspiration estimated by water balance from the measured soil water contents (after Utset et al., 2007b).

However, ET_C calculations by water balance were made ignoring any eventual percolation. However, water loss by percolation seems to be significant at the beginning of the irrigation season, since the water contents measured during the said period were higher than the field capacity, as shown in Figure 8. SWAP estimates that all the components of the water balance and the simulated evapotranspirations do not comprise percolation. This could explain the relatively lower correlation between SWAP-estimated and measured ET_C.

Figure 10A shows the ratios between sugarbeet evapotranspirations estimated by water balance and the SWAP-simulated evapotranspirations.

As the figure shows, simulated and field-measured evapotranspirations are close to the 1:1 line, particularly for the lower rates of the measured ETc. As indicated below, sugarbeet ET_C could be overestimated by water-balance estimations. Figure 10B shows the absolute differences between ET_C values simulated by SWAP and the ET_C estimated by water balance. Absolute differences depend on the measured ET_C values. Differences are much higher for the water-balance measured ET_C that is higher than 30 mm. This value is higher than the Readily Available Water usually computed for sugarbeet (Morillo, 1993). Therefore, actual sugarbeet evapotranspiration could hardly reach such high values (Allen et al., 1998).

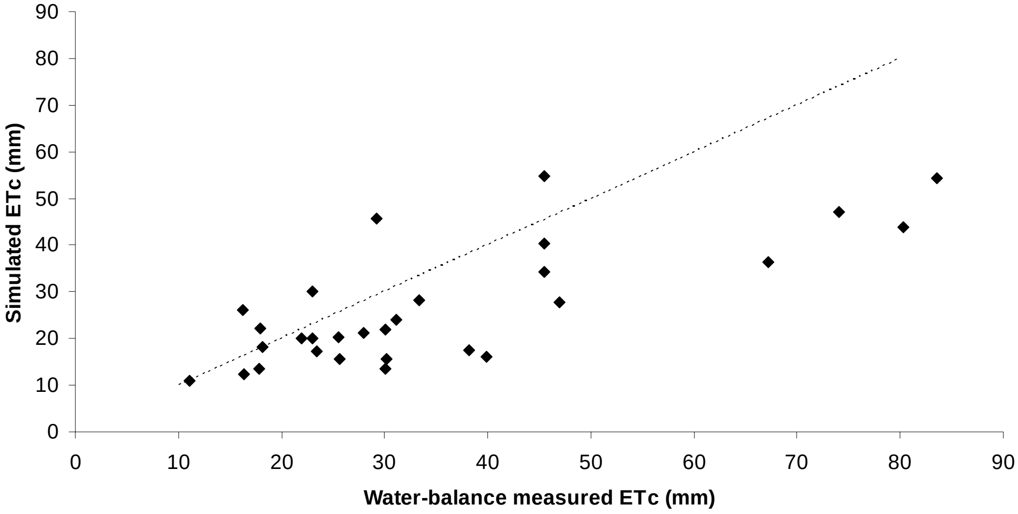

Figure 10A: Simulated and water-balance measured ETc. The dashed line shows the 1:1 relationships.

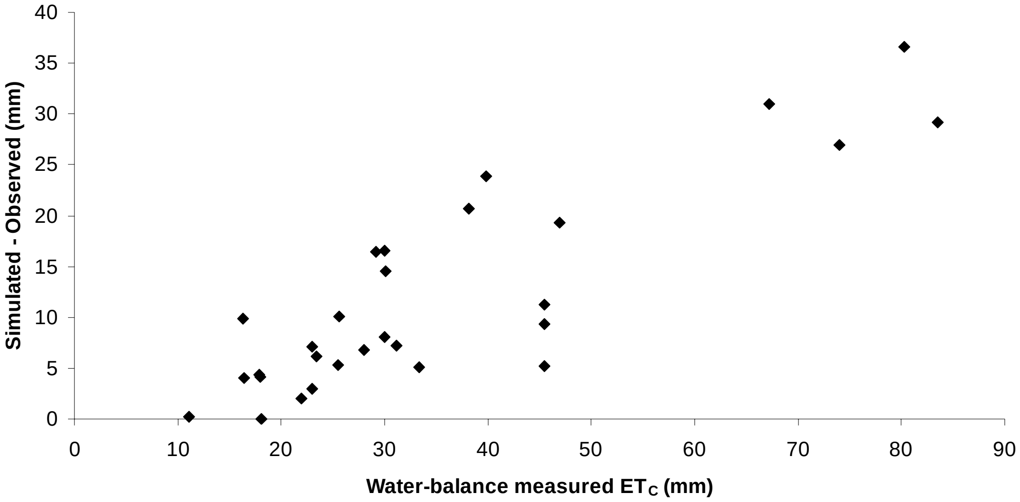

Figure 10B: Absolute differences vs. Water-balance measured ETc

Figure 10: Comparison between water-balance measured and SWAP-simulated ETc (A) as well as absolute differences between water-balance measured and SWAP-simulated as functions of water-balance measured evapotranspirations (B) (after Utset et al., 2007b).

Despite these differences, the regression line between simulated and water-balance measured ETc has a gradient of 1.14. The regression is statistically significant at the 99% confidence level. Simulated ETc values can explain up to 56.8% of the variability of water-balance ETc estimates. Furthermore, Table 6 shows the summary statistics of the water-balance measured ETc, the SWAP simulated ETc and the paired differences. As shown in the Table, both ETc data can be considered as distributed normally. According to a t-test for difference between means, considering non-equal variances, there is no statistical difference between the water-balance measured and the SWAP simulated sugarbeet ETc at the 95% confidence level. The same result was achieved by comparing the probability distributions of the water-balance measured and the SWAP simulated ETc values through a Kolmogorov-Smirnov test. However, according to a variance-comparison F-test, the water-balance measured ETc is significantly more variable than the SWAP simulated ETc at the 95% confidence level.

Table 6: Summary statistics of the water-balance measured and SWAP simulated sugarbeet evapotranspirations (after Utset et al., 2007b).

	Water-balance ETc	**Simulated ETc**	**Difference**
Mean	35.1	26.5	11.9
Standard deviation	19.4	12.8	9.9
Minimum	11.1	10.9	0.0
Maximum	83.5	54.8	36.6
Skewness	1.311	0.937	1.035
Kurtosis	1.015	-0.192	0.163

Calculations of normalized RMSE, as computed by equation [6], yielded 1.8 and 2.3 when comparing SWAP-simulated ET_C with weather-based maximum ET_C and water-balance based ET_C. According to Timsina and Humphreys (2006), the values for normalized RMSE can be considered as relatively high, indicating unreliable modelling performance. Considering only simulated and observed pairs with the water-balance measured ET_C below 30 mm yields a normalised RMSE of 0.9, almost three times lower than considering the higher ET_C values.

According to the simulations, actual sugarbeet evapotranspiration was close to maximum evapotranspiration throughout the crop season. Furthermore, the irrigation managements at both plots were enough to keep the soil water content above the field capacity, as pointed out above. Accordingly, the simulated relative yields were 0.98 at the A plot and 0.92 at the Z plot. This means that the yields obtained with the said irrigation managements are close to the maximum, i.e. 87 and 82 t/ha on the A and Z plots, respectively. However, the simulated water loss due to percolation was relatively high: approximately 10% of the irrigation water applied. This over-irrigation could be useful in the case of saline soils. However, soil salinisation is not a main concern in the Duero basin (JCYL, 1987). The results indicate that sugarbeet irrigation management can still be improved in the area, as pointed out by Playan and Mateos (2005) and many others.

4.5.4 Simulating Current and Future Sugarbeet Water-Use

The baseline 1960-1990 and the 2010-2040 Climate Change scenarios were taken from the CGCM2 model outputs, provided by the Canadian Centre for Climate Modelling and Analysis (Flato et al., 2000; Flato and Boer, 2001). The IPCC SRES A2 scenario for greenhouse gases emissions (IPCC, 2001) was considered. Despite other global circulation models, CGCM2 provides free internet access to daily simulation data in a text format. Hence, this model is more suitable for simple agricultural applications anywhere. According to Merrit et al (2006), results considering CGCM2 are similar than those obtained through other general circulation models.

A historical meteorological series of Valladolid (41.7º N, 4.85º W), comprising daily data from 1970 to 2005 of maximum and minimum temperatures, sunshine hours and precipitation; was used in combination with the LARS-WG weather generator (Semenov and Barrow, 2002) to generate 100 realizations of local weather corresponding to 2025, approximately.

The weather generator realizations were perturbed according to the CGCM2 results corresponding to the study site, i.e., Northeast of Iberian Peninsula. The relative change in wet and dry series lengths, as affected by global change, was done following the approach recommended by Semenov and Barrow (2002), based on the daily CGCM2 outputs for each ten-year range. The relative changes in temperature standard deviations, as well as relative changes in mean temperature, precipitation amount and solar radiation were obtained from the CGCM2 daily estimations, as suggested by Semenov and Barrow (2002).

Besides, 100 realizations were also obtained, without perturbing the weather generators. Such data was representative of current climate conditions, for the 1970-2005 period. The Priestley and Taylor (1972) equation for computing the maximum evapotranspiration was used instead of the recommended Penman-Monteith approach. Penman-Monteith computations involve meteorological variables that are not included in GCM and downscaling assessments. The Priestely and Taylor approach, however, needs only maximum and minimum temperatures, as well as global radiation. Those variables can be obtained from GCM and are usually considered in the available weather generators. Besides, many crop-growths oriented models, as DSSAT, uses this approach to compute evapotranspiration (Ritchie, 1998) and most of the studies addressed to estimate climate-change effects on Spanish agriculture (Guereña et al., 2001; Minguez et al., 2005). Furthermore, according to Utset et al. (2004), both approaches are statistically equivalent when considered to simulate water managements through SWAP.

Both climate data, representing current and 2025 climate conditions, were used as input in the SWAP model, considering the sugarbeet calibration parameters described above and shown by Utset et al. (2007b). A typical irrigation management, as conducted by farmers in the zone (Utset et al., 2007b) was considered. The soil hydraulic properties estimated for a Cambisol at Valladolid province were used in SWAP simulations.

Figure 11 depicts the average components of the simulated water balance in the sugarbeet plot, according to the irrigation management considered, for the current and the 2025 climate conditions.

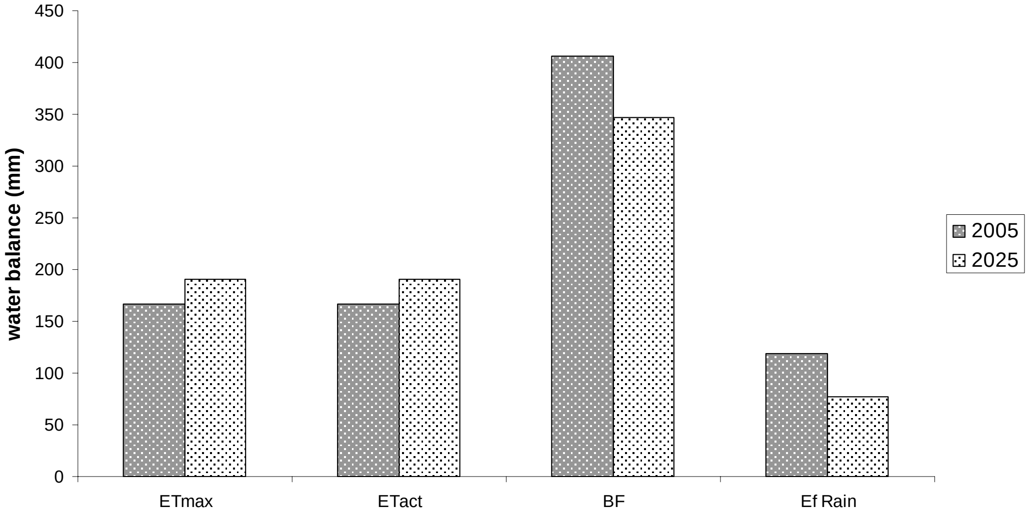

Figure 11: Water balance components in a sugarbeet irrigated plot at current and 2025 climate conditions.

The water balance analysis comprises the Priestley and Taylor maximum evapotranspiration, as well as the simulated sugarbeet actual evapotranspiration, the simulated bottom flux under the 1-m soil layer considered for simulations and the effective rain.

As can be seen in the figure, the considered irrigation management is able to cover the sugarbeet irrigation management at current conditions, since the crop actual evapotranspiration is almost equal to the maximum evapotranspiration. The irrigation water-management was correct from the crop water-use point of view, since soil water contents were over or close to field capacity as can be seen in Figure 8. However, water use efficiency is low, since the simulated bottom flux is very large. The considered irrigation management could still be improved, changing the irrigation frequency and the water depth in order to minimize water looses keeping soil water contents close to filed capacity. Playan and Mateos

(2005) pointed out also that despite irrigation managements in Spain are generally able to fulfil crop water requirements; water use efficiency can still be largely improved.

The maximum evapotranspiration in 2025 is higher and the effective rain is lower than in current conditions, which agrees with the Climate Change assessments. However, the considered irrigation management is still able to fulfil the sugarbeet water requirements, in average. Accordingly, the water use efficiency is higher since the water looses by percolation are lower.

Besides the average results shown in Figure 11, Figure 12 depicts the simulated actual sugarbeet evapotranspiration under the irrigation period for the current and the 2025 climate conditions.

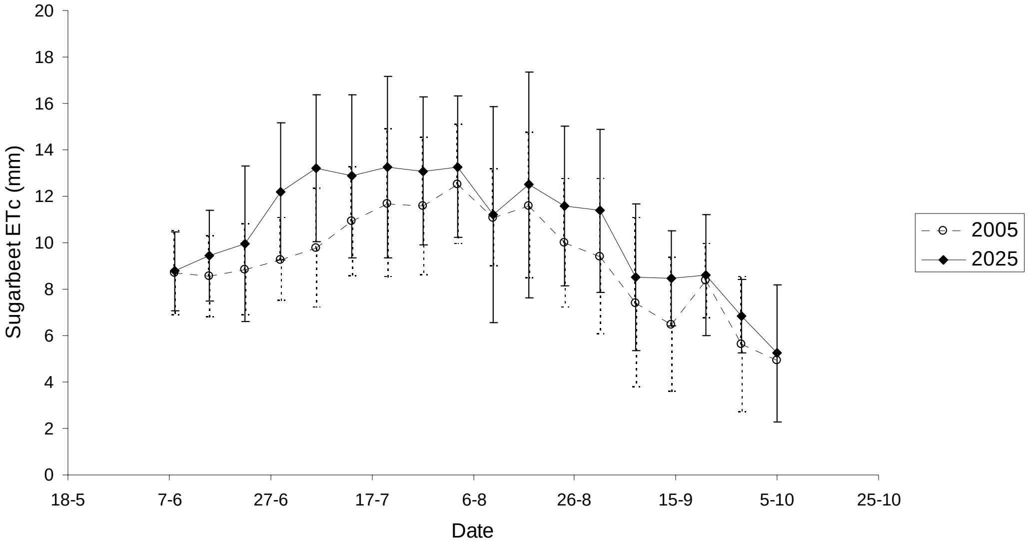

Figure 12: Sugarbeet actual evapotranspiration (ETc) during the crop irrigation period at current and 2025 climate conditions. Vertical bars indicate ETc variability.

The sugarbeet actual evapotranspirations in 2025 are higher, or at least similar, than the corresponding evapotranspiration in the current climate conditions, as expected. Furthermore, the variability of actual evapotranspiration is also very high in 2025. It means that the considered water management might be not enough to satisfy the sugarbeet water requirements in several years around 2025. The success probability of the considered water management is much higher under current conditions. Weather variability has been internationally estimated as the most important climate-change risk in agriculture (Katz and Brown, 1992; Mearns et al., 1996; Riha et al., 1996; Rosenzweig et al., 2002). The European approach and the Spanish assessments agree also with these estimates (Minguez et al., 2005; EC, 2007). Our results indicated also that the enhancement of weather variability around 2025, associated to Climate Change, could significantly affect the reliability of the currently considered sugarbeet irrigation-management.

Furthermore, Figure 13 shows the simulated water flux (positive downwards) under the whole irrigation campaign.

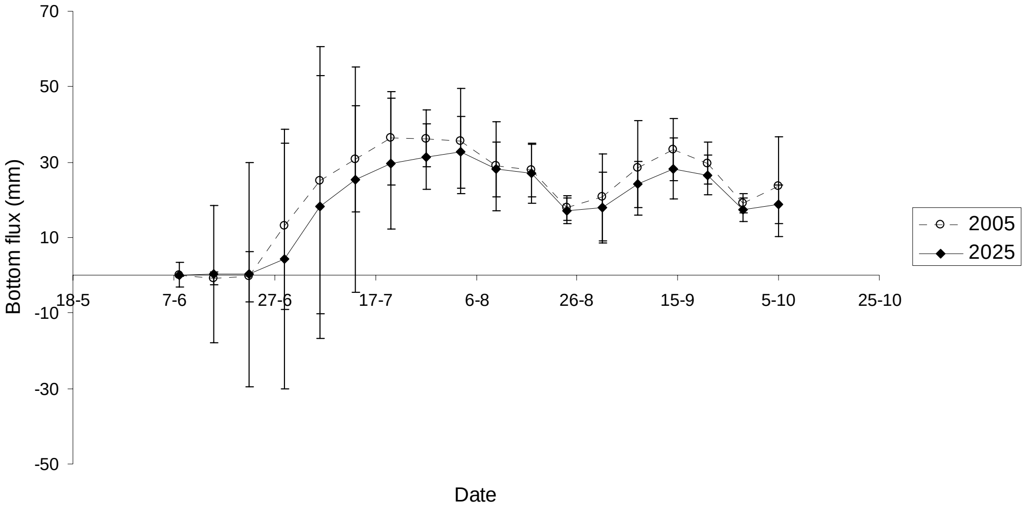

Figure 13: Bottom water flux (positive downwards) during the crop irrigation period at current and 2025 climate conditions. Vertical bars indicate ETc variability.

As shown in Figure 11, average water looses in 2025 are lower than in current conditions. Sugarbeet maximum evapotranspirations will be higher in the future and hence the crop will use some of the water that is currently percolating. This relative increment of the water-use efficiency of the current irrigation management would be more evident during the first crop growing stages, as well as during the tuber formation period.

However, in the same way than the actual evapotranspiration shown in Figure 12, the water loosing variability will be much higher in the future. The variability is extremely large during the first crop-growing phases. Rainfall variability and temperature extremes are expected one of the most important consequences of Climate Change for the first half of the XXI century (IPCC, 2007; EC, 2007). It would have a significant effect in the water-use efficiency of the currently considered irrigation water managements.

Introducing Climate and Crop-Growth Simulation Tool to Support Agricultural Decision-Making: The "Users" Point of View

"Users" and "Developers" were invited to the final AGRIDEMA workshop, which was held in Valladolid, Spain, middle 2007. The results of the assessments report were presented, focusing on the "users" points of view regarding the limitations of the available climate and crop-growth modeling tools. Hence, the "developers" received a feedback on how to improve the corresponding tools. Furthermore, the "developers" also pointed out the current development of the tools. Some representatives of farmer organizations, insurance companies and policy makers were also present.

AGRIDEMA interactions between "Users" and "developers" yielded some interesting results. Regarding the GCM outputs, "users" complained on the data format and the time scale. Only the Canadian CCCMa model provides daily data in an easily-converted format, through a Web service. This became such model as the most used in the AGRIDEMA framework. Besides, “Users” request to the national meteorological services to provide statistical (and/or) dynamical downscaled data of the most relevant GCM and emission scenarios. Such data can be used at each country in climate-change agricultural applications. Some of the “Users” and particularly the farmer representatives argue about the utility of RCM data, since the 2070-2100 seems to be extremely far for practical medium-term assessments. Farmers are mainly interested on seasonal or short-term applications. Furthermore, market prices, CAP, WFD and European or national policies can significantly influence farmer decision, besides of climate conditions. Particularly, CAP cross-compliance and the rural development funds can be an important instrument to introduce and evaluate climate-change adaptation measures in the European agriculture.

Concerning the weather generators, “Users” from the Mediterranean region pointed out that the main current approach, based on generating the variables needed for Priestly and Taylor evapotranspiration approach might not be useful. The Penman-Monteith approach has been largely recognized as the most adequate in dry conditions. “Users” took note about the facilities provided through the EU proposal ENSEMBLES. The availability of downscaled data from seasonal forecast and decadal scenarios could be an important encouragement for climate-risk agricultural assessments.

According to the AGRIDEMA results, DSSAT, WOFOST and CROPSYST are the most relevant crop-growth simulation models that are being used in Europe for climate-change risk assessments. The utility of crop models to support agricultural decision-making has been recognized. However, the “cascade approach” considered in many models to simulate soil water balance might be not adequate. This approach ignores capillary rising, which might be important in rainfed or deficit irrigation crop systems.

The AGRIDEMA participants strongly encouraged Universities and Educational politicians to held courses of current climate and crop-growth simulation tools. These tools are still unknown by most of their potential “Users”, which has been considered as the main current limitation to introduce them in practice. Besides, they encourage also conducting demonstration proposals, addressed to calibrate and validate the simulation tools in several farm conditions. FP7 cooperation program aims to increase private investment rates in R+D in Europe. The demonstration proposals, funded by FP7, could count on farmers and agribusiness since they are interested in adopting reliable measures in order to reduce climate risks. The participation of agricultural applied-research or extension services in those proposals is crucial.

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Chapter 2

AGRICULTURAL WATER MANAGEMENT IN CASTILLA-LA MANCHA (SPAIN)

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ABSTRACT

Castilla-La Mancha is located in the middle of the Iberian Peninsula. Due to its location, the water resources of this area are essential to the development of the neighbouring coastal regions. These areas have one of the most competitive agricultural systems in the European Union, an important industrial sector and tourism industry, and a high percentage of the Spanish population. For these reasons, the volume of water assigned to cover the demands of Castilla-La Mancha is approximately one third of the generated water resources.

The agricultural sector is the main water consumer in the region (more than 90%), which plays an important economic and social role. The transformation of large rainfed areas into irrigated lands during the last 30 years has limited the emigration of rural populations to cities or other industrialized regions of Spain. The water used for this transformation is mainly groundwater. Due to the lack of previous studies about the natural recharge of the aquifers and to an obsolete legislation, the three main irrigated areas of the region (08.29 Mancha Oriental: 8,500 km^2 and 100,000 ha of irrigated land; 04.04 Mancha Occidental: 5,000 km^2 and 153,000 ha of irrigated land; and 04.06 Campo de Montiel: 2,500 km^2 and 7,000 ha of irrigated land), suffer groundwater overexploitation.

In Castilla-La Mancha there are several institutions that try to optimize the use of water for agriculture and to improve the competitiveness of this sector to achieve sustainable development. In general, all these institutions work together with farmers in carrying out an integral and integrated management of the water resources.

CREA is the only institution that works in the entire region. In consequence, the irrigated areas experience different levels of advisory. In addition, it is necessary to emphasize that, water resources in Castilla-La Mancha are managed by seven different

public authorities. This situation, together with the characteristics of each basin, causes a high variability in management methodology.

This paper attempts to elucidate the research, management, and dissemination actions carried out in Castilla-La Mancha, where agriculture is an essential sector with problems of water scarcity due to both semiarid climatic conditions, and the importance of the resources generated in Castilla-La Mancha for the development of other regions.

1. INTRODUCTION

Castilla-La Mancha (CLM) is one of 17 regions in Spain, being the third largest in surface area (79,463 km^2) and more sizeable than some countries of the European Union (EU), such as Belgium, Denmark, and Ireland. However, the population density is one of the lowest i.e. 22.9 habitants/km^2. This situation is best explained by the particular distribution of the Spanish population, which tends, with the exception of Madrid, to be concentrated in coastal regions. The interior regions of Spain have traditionally supported agricultural production while industry and tourism are more commonly established in coastal areas. The water demand of coastal regions restricts the availability of water resources in interior regions. CLM generates an important volume of both surface water and groundwater resources. Nevertheless, more than 70% of these resources are appropriated to uses outside of the region. This aspect would not be relevant if the water demands of CLM were covered, however, in spite of being the allocating river basin, the region is experiencing critical water shortages. These water shortages impede economic growth, and fail to insure water availability to some populations.

Most of the territory of CLM experiences a semi-arid climate, with cold winters and warm summers. The distribution of precipitation is irregular and scarce throughout the year, with frequent periods of drought. In the regional southeast of CLM, desertification processes are on the rise. This encroachment advances from the provinces of Murcia and Almeria, which are the two most affected in Spain (CES, 2006).

The agricultural area of CLM consists of approximately 3,400,000 ha, 450,000 ha of which are irrigated land (PNR, 2000). In spite of being a low percentage (13.2%), lower than the national average of 20.9%, irrigated land plays an important social and economic role in the region. It enlarges the profit value of farms and contributes a greater degree of economic security to farmers. More than 90% of the regional water consumption is attributed to irrigated lands, which provides insight into the importance of implementing efficient water use in this sector (MAPA, 2006).

The main irrigable areas of CLM are intentionally situated close to groundwater sources, given that the greatest part of the surface water resources are appropriated to other uses in the regions of Comunidad Valenciana, Región de Murcia, Extremadura, Andalucia and Madrid. The aquifers included in the Hydrogeological Units (HU) 04.04 Mancha Occidental, 04.06 Campo de Montiel and 08.29 Mancha Oriental, are the main sources of water for more than half of the irrigated land area in the region. The rapid conversion of great areas into irrigated land during the last 30 years, along with a lack of planning and obsolete legislation, has permitted for the volume of water of extraction to exceed the volume which can be naturally replenished. As a result, two out of three aquifers have been declared overexploited and the third aquifer is on the brink of a similar plight.

This situation could be solved if CLM had a great enough water volume to supply its demands, or would reduce demands by more efficient irrigation. The second option would negatively affect the social and economic structure of the region, especially in the countryside, where a high percentage of the population would be forced to emigrate. An increase in water availability is needed for CLM. However, this outcome is not favored by neighboring regions, as from their points of view this would imply a reduction in the water that would be available for their uses.

The prospect of greater water resource shortages, greater dependency of regional agriculture on irrigated land, the overexploitation of natural resources, and the proliferation of land desertification has resulted in the establishment of several institutions, in CLM, that try to collectively solve problems. In an effort to integrate the management of water resource problems, the following agencies participate: public agencies, research centers, private companies and irrigation associations.

Through the Regional Water Research Centre (*Centro Regional de Estudios del Agua,* CREA), the University of Castilla-La Mancha (UCLM) is the institution that designates the greatest number of technical and human resources to resolving water resource problems. The principle objective of researchers of CREA is to achieve sustainability and to obtain the maximum efficiency in water use in the region.

The aim of this study is to show the methods introduced to try to solve the problems of a region of semiarid climate with limited legal availability of water resources to cover demand. The latest technologies are being applied to obtain the maximum efficiency in the sustainable use of water for irrigation. This process includes up to studies directed to quantify the availability of water in the future, due to the effect of climatic change, down to the evaluation of the irrigation systems in plots, to verify optimum operation and appropiate use by farmers.

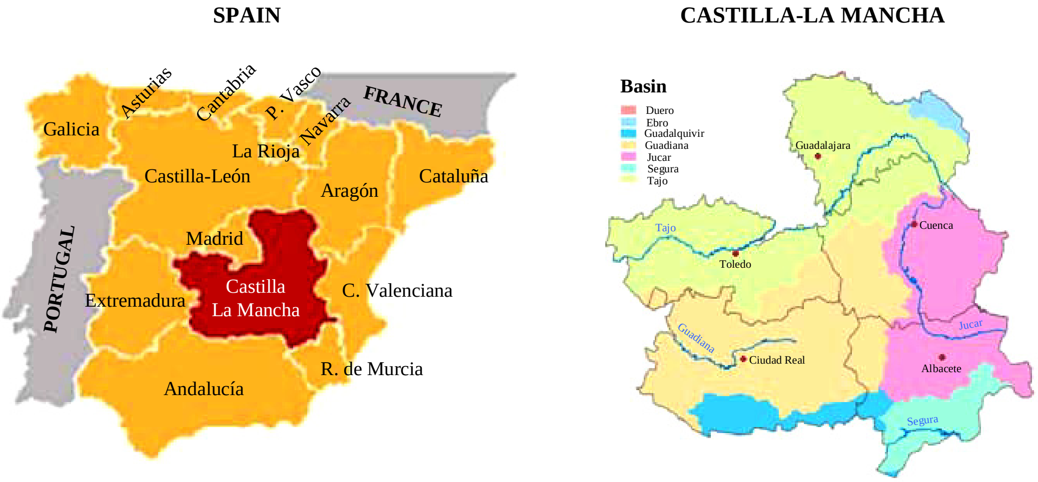
2. WATER RESOURCES ISSUES IN CASTILLA-LA MANCHA

2.1 General Characteristics

2.1.1 Edafoclimatic Conditions and Water Resources

Due to CLM being situated in the center of the Iberian Peninsula the sources of important rivers are located within this region, such as the Tajo and Guadiana, of the Atlantic side, the Júcar and the Segura of the Mediterranean, as well as, some tributaries of the Duero, Ebro and Guadalquivir (CES, 2006). Since not one of the aforementioned rivers is completely included within the territory of CLM, this denotes that hydrological planning is a national government competency. Therefore, administratively CLM belongs to 7 hydrographic authorities (Figure 1).

In Spain, all of the hydrographic river basins that are shared by two or more regions are managed by the Environmental Ministry through the Hydrographic Confederations. Only the intra-communitarian river basins can be managed directly by the regions, although they can cede its management to a national government agency. The Hydrographic Confederations are in charge of the elaboration of the Hydrological Plans of the river basin. These documents collect, among other information, what the volume of water generated inside the river basin is, and what the demands and the quantity of dedicated resources to cover such demands will be. The last Hydrological Plans were elaborated in 1998 and will be updated in 2008.


SPAIN

CASTILLA-LA MANCHA

Figure 1: Spain’s regions and hydrographic river basins in Castilla-La Mancha.

Table 1 compiles the water resources generated in CLM territory.

Table 1: Water resources in natural flow regime in Castilla-La Mancha by hydrographic river basins (CES, 2006)

River Basin	**Area of the river basin in the region**		**Total water resources (hm^3 $year^{-1}$)**			
	km^2	**%**	**Superficial**	**Groundwater**	**Totals**	**%**
Tajo	26,699	33	3,204	1,108	4,312	46.5
Júcar	15,736	73	1,161	1,011	2,172	23.5
Segura	4,721	25	509	254	763	8.2
Guadiana	26,431	37	1,189	625	1,814	19.6
Guadalquivir	4,428	8	45	25	70	0.8
Ebro	1,063	1	50	68	118	1.3
Duero	48	<1	Without values	9	>9	0.1
TOTAL	**79,226**		**6,158**	**3,100**	**9,258**	**100**

CLM has considerable water resources. The annual average precipitation oscillates between 300 and 600 mm. The volume of the average annual precipitation constitutes 41,000 hm^3, which is equivalent to an average isoyet line of 510 mm (IGME, 1985). As a result of evapotranspiration, and water exchange to and from neighboring regions, the total available water resources, on average in CLM, approximate 9,258 hm^3 $year^{-1}$.

The distribution of resources in the region is not uniform. In the Tajo river basin, which occupies a third of the regional territory, 46.5% of the resources are concentrated, whereas in the Guadiana, which is comparable in surface area, only 19.6% of the total is found. In terms of the total water run-off in CLM, 67% remains surface water and the 33% remainder circulates subterraneously, giving insight into the importance of groundwater sources.

Among the existing geologic formations in CLM, practically only the limestone, dolomites, sands, gravels and clays can contain groundwater in sufficient amounts to constitute aquifers of interest at the regional level. These are located in geologic units from the Mesozoic, Jurassic and Cretaceous (CES, 2006).

The natural water contributions are distributed in a non-concordant form in time and with demand patterns. In order to achieve balance between water that is available and demand, it is necessary to have adequate regulation. For this reason, the construction of reservoirs for storing surface water and the sustainable management of groundwater resources is necessary (Table 2).

Table 2: Storage capacity and regulated resources in Castilla-La Mancha (CES, 2006)

River Basin	Storage Capacity (hm^3 $year^{-1}$)		Regulated resources (renewable) (hm^3 $year^{-1}$)		
	Superficial	Groundwater	Superficial	Groundwater	Total
Tajo	3,395	15,000	1,643	1,108	2,751
Júcar	2,016	23,000	811	1,011	1,822
Segura	760	9,000	356	254	610
Guadiana	420	17,000	392	625	1,017
Guadalquivir	150	Without values	28	25	53
Ebro	0	1,000	0	68	68
Duero	0	Without values	0	9	9
TOTAL	**6,741**	**65,000**	**3,230**	**3,100**	**6,330**

In CLM there are more than 90 reservoirs, with a total capacity in excess of 6,741 hm^3, with approximately 60 of them having a very limited capacity i.e. less than 5 hm^3. Among the reservoirs, emphasized are those of “Entepeñas and Buendía”, in the Tajo river basin, which can store more than 2,440 hm^3. These reservoirs are well known, as from them originates the Tajo-Segura Aqueduct (*Acueducto Tajo-Segura*, ATS). Other important reservoirs are those of Alarcón and Contreras, in the river basin of the Júcar, with capacities of 1,112 and 884 hm^3 respectively. The reservoir of the Cenajo in the Segura river basin has a capacity of 437 hm^3.

In relation to the number of Hydrogeological Units (HU) in the region, 55 HU are recorded, less than half belonging to the Júcar and Segura river basins. The total surface area occupied by the CLM aquifer systems is 50,807 km^2 (CES, 2006), with reserves around 65,000 hm^3 (Table 2). The aquifers with greater water volume and greater operation level are: the 08.29 Mancha Oriental of the Júcar river basin with renewable resources around 377 hm^3 $year^{-1}$ (CHJ, 2004a), the 04.04 Mancha Occidental and 04.06 Campo de Montiel of the Guadiana river basin, with renewable resources around 329 and 86 $hm^3 year^{-1}$ respectively (CHG, 1999 and 2004). It is in these aquifers where problems related to overexploitation are most pressing; between them, they support more than 50% of irrigable area according to the National Irrigation Plan (*Plan Nacional de Regadíos*; PNR, 2000) (Figure 2).

Figure 2: Distribution of the irrigated lands in Castilla-La Mancha (PNR, 2000).

Although the regulated surface and groundwater resources, that average 6,330 hm^3 $year^{-1}$ for CLM, would satisfy demands amply, this is not the case because:

- Parts of the resource are generated at the boundary with other regions, as is the case of the Tajo and Guadiana. Resources are also available at the boundary with Extremadura, which prevents its possibility of use in this region.
- A great part of the regulated water in CLM is "committed" for use in other territories. This occurs at the source of the Tajo, its resources are used in some provinces of Andalucía, Región de Murcia and Comunidad Valenciana by the ATS. The water resources of the high river basin of Segura are mainly designated for use in Murcia, and the resources of the Júcar river basin are appropriated in great extent to uses in the Comunidad Valenciana (Figure 1).
- There is no physical or administrative agreement between the existence of resources and the location of the demands.

2.1.2 The Water Demand and Allocation of Resources by the Hydrographic Confederations

The population of CLM is estimated to be approximately 1,850,000 (INE, 2004) to which must be added another 500,000 transitory inhabitants. Of the 915 municipalities that constitute this region, 69% have less than 1,000 inhabitants registered, which is 11% of the population. On the other hand, although the percentage of municipalities greater than 5,000 inhabitants represents 7% of the total, within them 60% of the population is found.

The nuclear power plants of "José Cabrera" and "Trillo", and the thermal power stations of "Aceca" and "Puertollano", use an important percentage of the total water assigned to the region; they constitute the second sector in importance after agriculture. However, the consumptive use of water resources due to these activities is reduced, by approximately 5% (EEA, 2003), as a great part of the used water is returned to the environment after purification processes.

The agricultural sector utilizes and consumes the greatest volume of water in CLM. The transformation of great zones of the region into irrigated land, mainly during the decades of the 70's and 80's, has permitted an increase in the level of income of the population and has allowed for a large percentage of the population to remain in the countryside.

Table 3 illustrates the assigned volumes by the different Hydrological Plans (HP) to cover the previous demands.

Table 3: Established allocations in the Hydrological Plans of river basin for water use in CLM grouped by sectors (CES, 2006)

River Basin	**Supplying (hm^3 $year^{-1}$)**	**Irrigated land (hm^3 $year^{-1}$)**	**Industry & energy (hm^3 $year^{-1}$)**	**Total (hm^3 $year^{-1}$)**
Tajo	116.65	63.75	813.92	1,569.32
Júcar	43.00	400.00	-	443.00
Segura	5.62	132.28	-	137.90
Guadiana	49.81	491.20	10.17	551.18
Guadalquivir	9.19	0.06	18.14	27.39
Ebro	-	194	-	1.94
Total	**224.27**	**1,664.23**	**842.23**	**2,730.73**

The main allocation of water in the region is for agricultural use (61.0%), followed by industrial use (30.8%) (of which 97.0% is for the generation of energy), and the remainder (8.2%) is dedicated to urban supply. It is important to indicate that, within urban supply, water destined for industries situated in the interior of the population are included.

The National Statistical Institute (*Instituto Nacional de Estadística*, INE) annually processes the data necessary to understand the demand patterns by sectors in different regions (Figure 2.3).

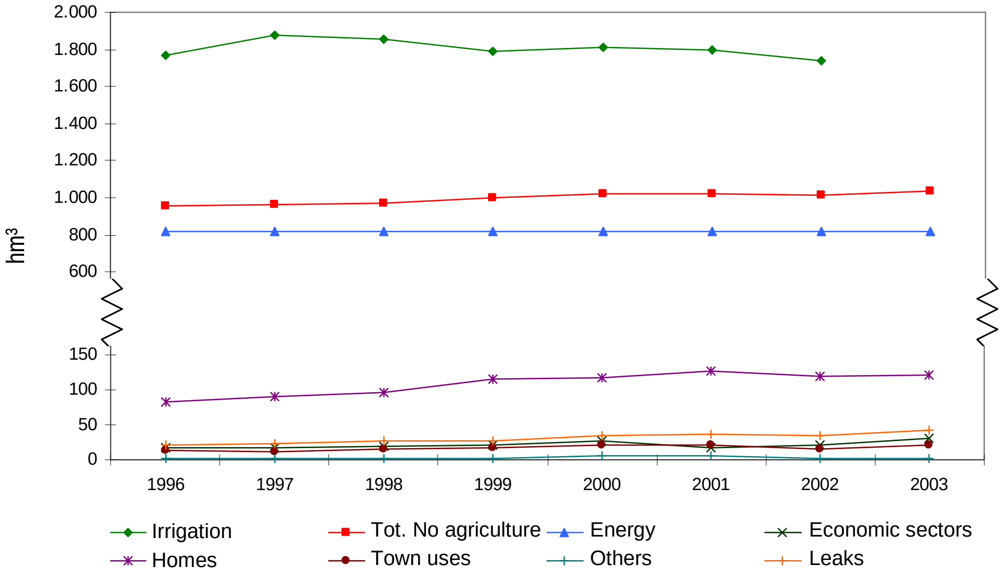


Figure 3: Water demand pattern by sectors in Castilla-La Mancha (INE, 2003).

In Figure 4 the urban demand by inhabitant is represented, as well as, the agricultural demand by unit of area. Consumption by inhabitant in CLM (around 100 m^3 by inhabitant per year) shows an increasing tendency from 1996, with a small reduction in 2002. These values are lower than the average consumption by inhabitant of the European countries of the Mediterranean river basin that approximate 130 m^3 per inhabitant per year. (EEA, 2003).

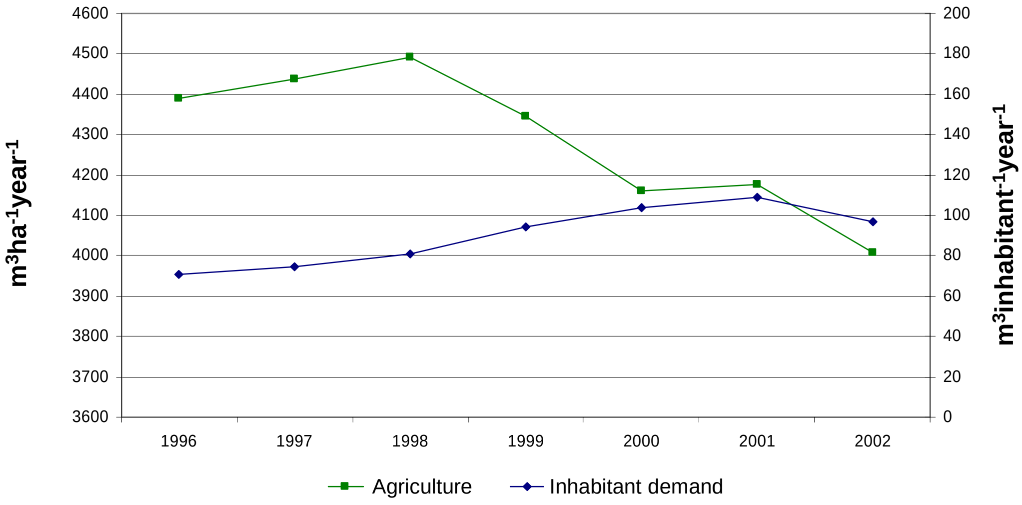


Figure 4: Progression of water demand in agriculture (m^3 ha^{-1} $year^{-1}$) and urban uses (m^3 $inhabitant^{-1}$ $year^{-1}$).

At the moment, the excess of agricultural demand is covered via greater utilization of groundwater. This practice has caused the Aquifers of 04.04 and 04.06 to be declared overexploited and with others at risk of being similarly declared. Although CLM has sufficient surface resources to cover the excess of agricultural demand and to avoid the exploitation of aquifers, they are devoted to use in bordering regions, as is the case of the Júcar river basin and to a lesser extent that of the Segura.

Although the resources used by agriculture are over the allocations established in the Hydrological Plans, the average water volume applied by hectare of irrigated land is low, about 4,500 m^3 ha^{-1} $year^{-1}$ (INE, 2003), whereas the average endowment established by the Hydrological Plans is 3,700 m^3 ha^{-1} $year^{-1}$. The same study of the INE (2003) indicated that the average volume of water for irrigation by hectare applied in CLM is lower than the national average (5,200 m^3 ha^{-1} $year^{-1}$) (Figure 5).

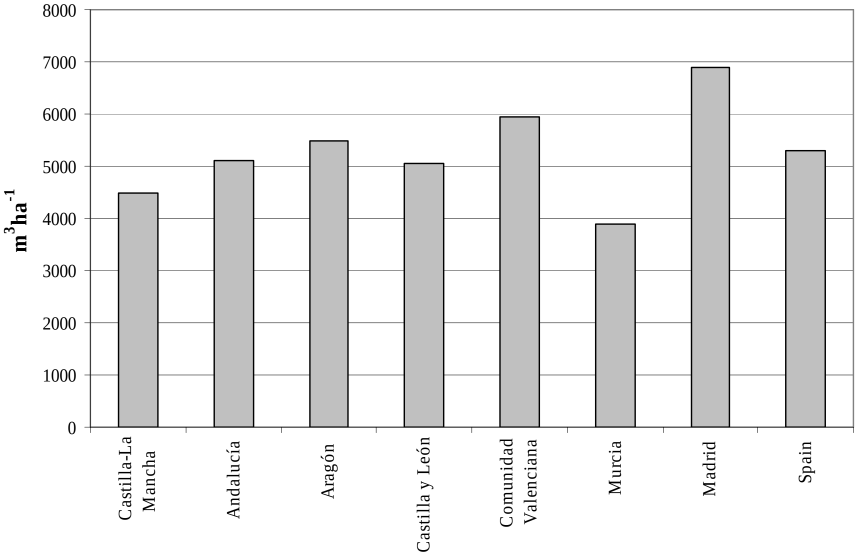


Figure 5: Average annual water volume applied by hectare in several regions of Spain (INE, 2003).

This situation is not only due to the fact that a high percentage of the irrigation systems used in CLM are modern and highly efficient, compared with other regions of Spain (Fig. 6), but also that a great part of the irrigable lands of CLM are infra-equipped and are supplied by aquifers declared overexploited (like Mancha Occidental, to which the water exploitation plan assigns approximately 1,500 m^3 ha^{-1} $year^{-1}$), or in risk of overexploitation (like Mancha Oriental, with a water exploitation plan that assigns around 4,500 m^3 ha^{-1} $year^{-1}$).

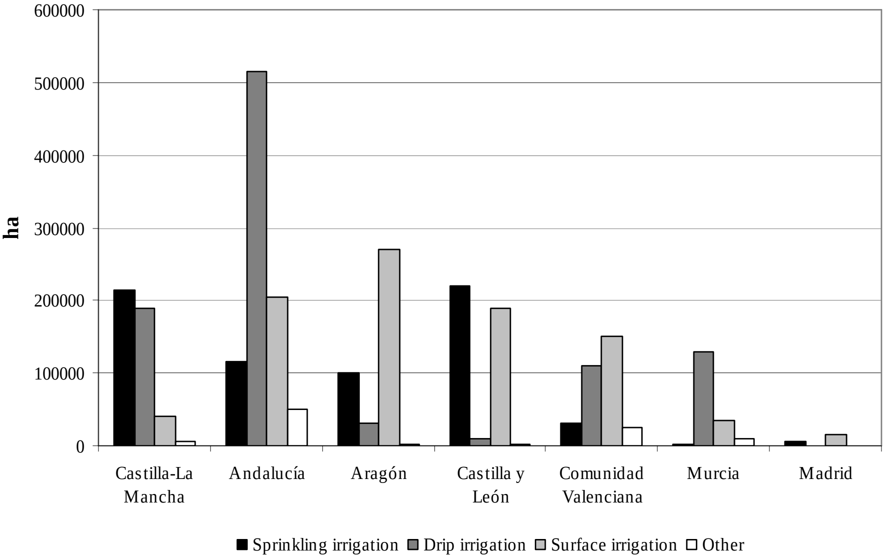


Figure 6: Irrigated area according to irrigation systems in different regions (INE, 2003).

Finally, the last use of water which the water resources of CLM must satisfy, although no less important, are environmental requirements. In order to cover these necessities, ecological volumes have been established by the Hydrographic Confederations.

The established ecological flows for the main rivers of the region are indicated:

- Tajo River: 10 m^3 s^{-1} when flowing by the town of Toledo. This volume is not sufficient to counteract the high pollution level of the river, as it receives a great part of the sewage from Madrid.
- Júcar River: 2 m^3 s^{-1} downstream of the reservoir of Alarcón. This volume diminishes as a result of its infiltration into the aquifer 08.29 Mancha Oriental, as the river crosses the province of Albacete.
- Segura River: 4 m^3 s^{-1}, it has not generally reached this value, except for particular moments of water transport towards irrigable areas.
- Guadiana River basin: at least 1% of the total of water gathered in its reservoirs will be drained annually for ecological uses.

It is necessary to indicate that in CLM numerous wetlands exist with special importance to migratory birds. These wetlands are typically supplied with underground water that has risen to the surface; the wetlands are very sensitive to the reduction of piezometric levels. Of them, the National Park of the Tablas de Daimiel (PNTD), belonging to the basin of the Guadiana, and situated on the HU 04.04 Mancha Occidental, is the one of greatest importance (CES, 2006).

The Geologic and Mining Institute of Spain (*Instituto Geológico y Minero de España*, IGME) developed a study using the historical progression of a piezometer network, since 1974, distributed in the surroundings of the PNTD. According to this study, reductions are registered of the piezometers with, in some cases, differences of more than 15 m since the first data was collected (IGME, 2005). This situation stems from the rapid transformation of large areas, into irrigated land, in the surroundings areas of the PNTD. In order to solve the problem, numerous measures have been executed such as the Income Compensation Plan (*Plan de Compensación de Rentas,* PCR), that will be discussed later in greater depth, and that in broad strokes gave a bonus to the farmers who voluntarily reduced the volume of water applied to agriculture. For times of great water shortage, it is possible to transfer water from the river basin of the Tajo to the PNTD by taking advantage of the infrastructures of the ATS (CES, 2006).

2.1.3 Production Systems

The agrarian systems are defined as ecosystems composed of living beings that are settled in a determined place. These living beings are involved in a process of symbiotic interactions with each other and the surrounding vegetation. In addition, they are affected by the human intervention by means of their cultivation techniques (Urbano and Moro, 1991).

The agrarian systems are derived from the influence on agrarian activity, of a series of factors that are systematically grouped into five large blocks (Lamo de Espinosa and Bahamonde, 1992): Climatic and edafological factors; Biological factors; Economic factors; Social factors; and Political and institutional factors.

The combination of these factors configures an agrarian system (Lamo de Espinosa, 1998). Any agrarian system can be constructed to fulfill different objectives at different moments, at different sites and by different people. Consequently, throughout the history of agriculture, diverse agrarian systems have been developed (Spedding, 1975).

- Forest systems. The vegetative cover is formed by ligneous species.
- Agro-silvicultural systems. Attempt to achieve a balance between forest systems and agriculture.
- Meadows and pasture lands systems. The vegetative cover is formed by permanent meadows and pasturelands (natural meadows of semiarid and dry climates).
- Agricultural systems with habitual farming of the land covered by vegetation. These systems include, in addition to herbaceous and tree crops, set-aside lands.

In the case of semi-arid zones, assuring a high degree of permanent vegetative land cover is essential to avoid water and wind erosion. This positive effect is compatible with the exploitation of the vegetation. The vegetation produces other beneficial environmental effects such as: CO_2 absorption and generation of O_2, regulation of the water regime, and creation of an ecosystem that insures biodiversity.

In agricultural farms, where herbaceous species are cultivated during a great part of the year, the land remains bare. However, tree crops and forest farms maintain a high percentage of ground cover throughout the year. In CLM, agriculture is the sector that makes the greatest use of land, occupying around 49% of the 7,931,000 ha of area of the region. Forest land occupying 26% and pasturelands occupying 10% are second in importance (Fig. 7). Nevertheless, although the rate of vegetative cover may seem high, the seasonal nature of the herbaceous crops, the high percentage of fallow land (set-aside), as well as the low degree of cover of tree crops, considerably reduces its value.

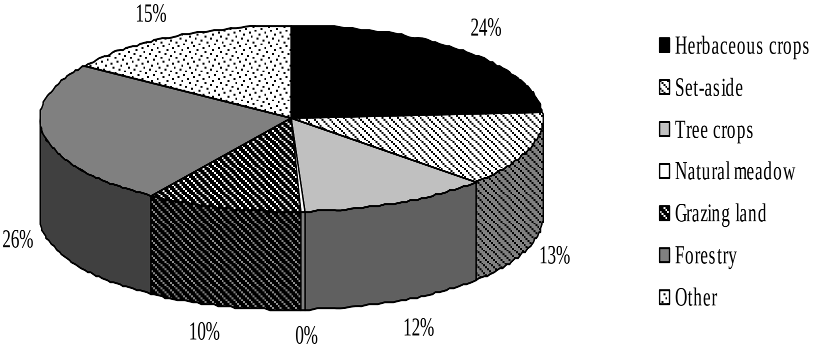


Figure 7: Land use distribution in Castilla-La Mancha for 2005 (MAPA, 2006).

In general, the variety of land use in the region demonstrates stability, as the rate of vegetative cover has evolved favorably in recent years (Fig. 8). Forest area and tree crops have increased, whereas the area devoted to herbaceous crops has been reduced. Consequently, at present more vegetation remains on the ground throughout the year. This fact is conditioned by aid directed at reforestation of agricultural lands. In addition, there are different lines of action that promote the forestation of the land, like the obligation to reforest a part of the land in which any type of construction in rustic land has been undertaken.

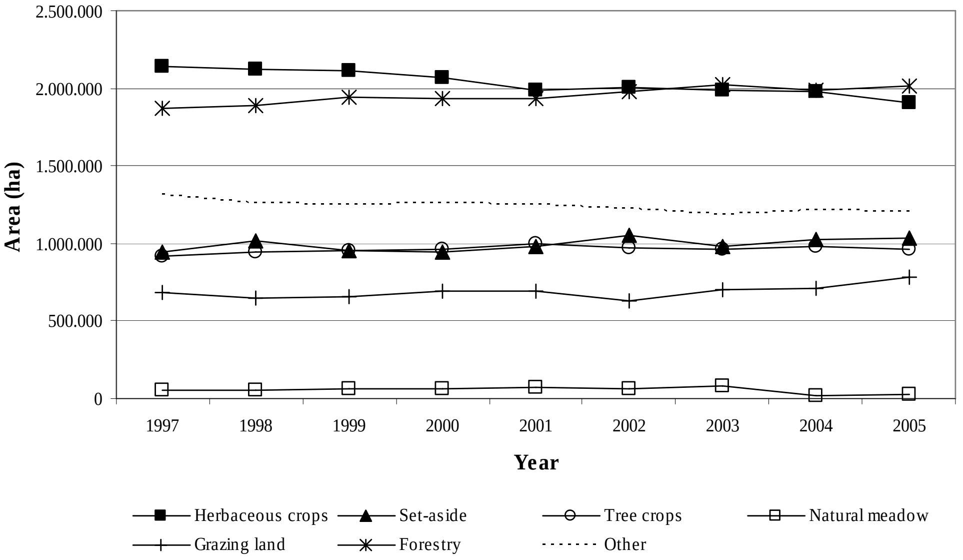


Figure 8: Evolution of land use in Castilla-La Mancha (MAPA).

Finally, CLM is the region of Spain with the greatest crop area, representing 21.8% of the total. Nevertheless, the correlation between irrigated land and dry land area is lower than the national average (Table 4). This difference is due to the low proportion of irrigated land in the provinces of Cuenca, Guadalajara and, to a lesser extent, Toledo. The first two provinces experience more humid climatic conditions than the rest of the region. On the other hand, Albacete and Ciudad Real represent a proportion of irrigated land near the national average. However, these irrigable lands are infra-equipped and depend to a great extent on insufficient groundwater resources, which are causing the exploitation of the aquifers associated with these irrigations.

Table 4: Distribution of rainfed area and irrigated land in Castilla-La Mancha for 2005 (MAPA, 2006)

	Rainfed land	Irrigated land	Irrigation	Total arable land
	(ha)	(ha)	(%)	(ha)
Albacete	609,306	155,029	20.3	764,335
Ciudad Real	846,321	208,678	19.8	1,054,999
Cuenca	761,694	40,689	5.1	802,383
Guadalajara	302,215	16,834	5.3	319,049
Toledo	861,533	92,883	9.7	954,416
CLM	**3,381,068**	**514,113**	**13.2**	**3,895,181**
Spain	**14,117,022**	**3,727,170**	**20.9**	**17,844,192**

During the decade of the 1990's, CLM was the region in Spain with greatest production of wine, garlic and some legumes; second in cereal production and third in industrial crops. Nevertheless, the shortage of water resources and the low gross margin of cereals are causing a change in the percentage of the area dedicated to each crop group. In addition to the increase in the area dedicated to tree crops, the extensive horticultural crops also receive greater importance. Among the crops, garlic and the onion utilize the greatest proportion of area; also important are the potato, the melon, the tomato, the pepper and lettuce.

2.1.4 Evolution of the Irrigated Crop Area

The size of irrigated land in CLM has been multiplied by four in terms of its original size from 1960 to present, increasing from 128,000 to 510,000 ha (JCCM, 2001; MAPA, 2006). This irrigated land progession has caused an increase of the water demands that have been covered mostly by groundwater resources. Initially, cultivations of high water requirements and with high gross margins were opted for. However, in the decade of the 1990's, problems of water resource overexploitation became obvious.

The beginning of directed actions to reduce the agricultural demand of water, along with changes that modified the Common Agricultural Policy (CAP) of 1992, caused an increase in crop diversification.

The main reforms undertaken by public administration, i.e. the Hydrographic Confederations, and irrigators, to try to regulate water use in irrigated land agriculture were: the Water Exploitation Plans, and the creation of irrigators associations (Martín de Santa Olalla *et al.*, 2005). These measures are discussed in more detail in the following sections.

In 1985, Spain entered the EU. Spanish agriculture was then regulated by the CAP. The Common Market Organizations (CMO) was the main tool used by the EU to fulfill agrarian policy. The objective of the CAP was to guarantee the minimum prices of crop productions to farmers, and to promote exports to other countries. In order to achieve this, an interventionist policy was established that protected the European market by regulating internal demand, by means of the purchase and storage of European agricultural products, and by limiting imports via tariffs. CLM was in the midst of the transformation of land for the purposes of irrigation. Consequently, farmers cultivated the products most subsidized by the EU, generally intense water consumers, like maize, alfalfa and sugar beet.

Due to the international pressures on the CAP, which accused it of noncompliance with free trade of agricultural products, the EU had to modify its agricultural policy. The CAP reform of 1992 led to a change in the crop distribution of irrigated land in the region. The main modifications from the previous CAP were:

- To reduce the amount of guaranteed prices.
- To offer farmers compensatory aids related to production, and independent of production.
- To establish a set-aside area for crops that received subsidies.

The last reform of the CAP-2003 had as objectives: a reduction in the CAP expenses, to guarantee the health and quality of agro-alimentary products, and to protect the environment, as well as, to improve the quality of life of livestock. In order to achieve this, the following modifications have been proposed:

- To completely separate economic aid from agricultural production. Farmers receive economic aids based on the amount received in the past, and not based on current production. In this manner, the farmer attempts to achieve optimal and not maximum production. This will be performed in an effort to increase the competitiveness of farmers and to adapt their crops to market demands.
- In order to receive aid, farmers would have to comply with standard regulations of acceptable agricultural practices for the protection of the environment and life conditions of livestock i.e. cattle.

The consequences of these modifications are summarized herein:

- Within the crops that receive subsidies from the CAP, there is a decrease in summer cultivation and an increase in those of winter (Figure 9).

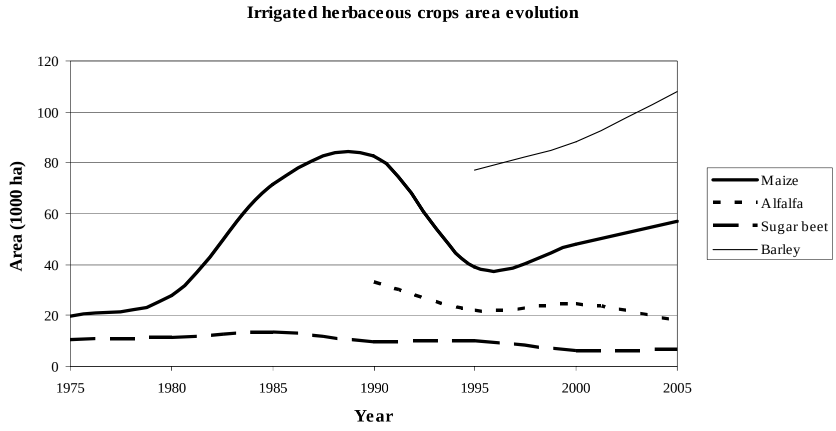


Figure 9: Area progression of: maize, alfalfa, sugar beet and barley in Castilla-La Mancha.

- In this set of the crops, there is a decrease in those that receive subsidies from the CAP and an increase in those that do not receive one. Within the latter crops, there is a significant increase in the area of tree crops (Figure 10).

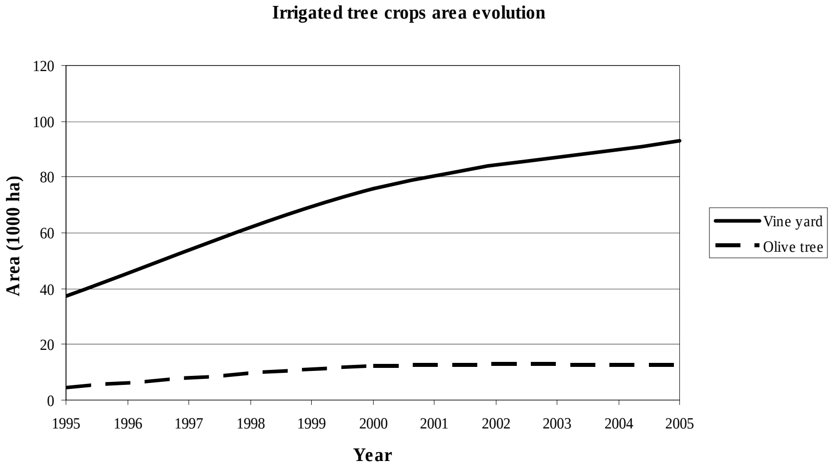


Figure 10: Area progression of tree crops in Castilla-La Mancha.

- The last reform of the CAP, is causing an increase in the area of horticultural crops like onion, melon and garlic; varieties of vineyard are being replaced with those more suitable within market demand (i.e. Cabernet-Sauvignon, Syrah, Merlot, etc.); the cultivation of the sugar beet has ceased, however, this is also due to the last modifications made to the sugar CMO.

Diversification of crops has permitted a final reduction in water demand utilized for irrigation (Fig. 4). In general, irrigated winter crops consume approximately 2,500 m^3 ha^{-1}, whereas irrigated summer crops consume approximately 7,000 m^3 ha^{-1} (Calera *et al.*, 1999).

The current distribution of irrigated land crops (Table 5) and the progression in the proportion of different groups of crops in the HU 08.29 Mancha Oriental (Table 6) are illustrated.

The increase in the area of irrigation of tree and horticultural crops is due to the higher gross margins that are capable of generating these types of crops. It is necessary to indicate that the volume of water that can be applied to tree crops (vines and olive trees, among others) is limited. Only a support irrigation that helps to guarantee production is allowed. The seasonal volume of irrigation for these crops has been established at 1,000 m^3 ha^{-1}.

CLM is the main wine producing region in the world. For this reason, vineyard protection is of special importance to the region. Irrigated crops are 7 times more productive than rainfed land, and in the case of horticultural and tree crops, the proportion is even greater. This has led to the replacement of traditionally cultivated varieties of rainfed vineyards, into the more productive ones of irrigated land.

Another important aspect of tree crops is their environmental role. Tree crops protect ground soil from erosion and maintain an elevated index of vegetative cover throughout the year. This circumstance is important in a region such as CLM, where set-aside land in irrigated farms, due to its area occupied, is the third agricultural activity in importance.

Table 5: Distribution and water demand of irrigated crops in the HU 08.29 Mancha Oriental in 2005 (ITAP, 2006)

Crops (2005)	Area (ha)	Irrigation requirements (m^3 ha^{-1})	Mancha Oriental (hm^3)
Wheat	15,942	4,170	66.5
Garlic	4,801	3,700	17.8
Rape	45	3,680	0.2
Poppy	3,362	3,200	10.8
Oat and other winter crops	1,077	3,250	3.5
Barley	16,986	3,300	56.1
Pea	1,419	3,250	4.6
Green pea	1,685	3,040	5.1
Set-aside	11,930	0	0
Total winter crops	**57,248**		**164**
Alfalfa	8,008	9,011	72.2
Sugar beet	3,388	7,770	26.3
Potato	1,086	6,300	6.8
Maize	18,641	7,061	131.6
Onion	6,239	5,990	37.4
Sweet maize	941	5,006	4.7
Kenaf	0	-	-
Sunflower	1,154	4,310	5.0
Bean	628	2,510	1.6
Other	5,118	3,600	18.4
Total summer crops	**45,203**		**304**
Vineyard	7,450	1,500	11.2
Olive	582	1,500	0.9
Almond	329	1,500	0.5
Other tree crops	367	2,000	0.7
Total tree crops	**8727**		**13**
TOTAL CROPS	**111,178**		**482**

Table 6: Evolution of the crop groups in the HU 08.29 Mancha Oriental (Calera *et al.*, 1999; ITAP, 2006)

	1985	1996	2005
Summer crops (%)	88.7	69.9	55.9
Winter crops (%)	11.3	30.1	44.1

2.1.5 Technical-Economic Indices

One of the main challenges of current agriculture in developed nations is to increase competitiveness within an increasingly global market. This increase in competitiveness is essential in disadvantaged regions, where agrarian activity conserves economic and social importance.

The management of crops is determined by technical itineraries, which show the cultivation techniques required to carry out the entire phase of crop development. The cost analysis of these activities permits the optimization of the production process, mainly as a decision support tool in the election of the raw materials, the amount to produce that favors cost reduction, and a reduction in environmental impact, while obtaining products of quality and of sufficient edibility.

In 2000, with the purpose of characterizing the systems of production of CLM, CREA devised the technical itineraries for the main crops of the region (de Juan *et al*., 2003). In all, 163 technical itineraries for 20 rainfed herbaceous crops, 31 irrigated herbaceous crops, and 4 tree crops were developed. As an example, a maize crop irrigated by means of a system pivot, is illustrated (Table 7).

Table 7: Technical itinerary for maize in a farm with vast irrigated area

Technical itinerary: Grain Maize (*Zea mays* L.) **Productive scene: Vast irrigated area**				**Province: Albacete** **System of irrigation: Sprinkling, center pivot.**			
Month	**Nº**	**Labours**	**Equipment**	**Labour**	**Yield (h/ha)**		**Raw material**
					Equipment	***Labour***	**(ud/ha)**
January	1	Deep	Tractor 110	Driver	1.67	1.67	
		ploughing	CV				
February	2		Chisel, 2m	Driver	0.53	0.53	
		Stone	Tractor 75	Laborer		1.06	
	3	removing	CV	Driver	0.60	0.60	
			Trailer, 12t				
April	4	Harrowing	Tractor 75	Driver	0.21	0.21	800 kg (8-
			CV	Laborer		0.42	15-15)
		Seeding	Grada de				64 UF N,
	5	fertilization	discos	Driver	0.52	0.52	120 UF
			Tractor 75				P_2O_5, 120
	6		CV	Laborer		0.50	UF K_2O
		Fertilizer	Trailer, 12t				
	7	inserting		Driver	0.15	0.15	
			Tractor 75				
	8	Irrigation	CV	Laborer	0.29	0.02	
		system	Cultivator,				6 kg
	9	mantaining	3.4m	Driver	0.62	0.62	Alachlor,
		Herbicide	Center	Laborer		1.24	35% +
		application	pivot				Atrazine,
	10			Driver	0.48	0.48	20%
		Preseeding	Tractor 50				93.75 m^3
June	11	irrigation	CV	Driver	0.18	0.18	water
			Atomizer,	Laborer		0.36	
		Seeding	1,500 l				85,000 seeds
	12	and soil	Center	Driver	0.98	0.98	híbrido
		disinfection	pivot				(0,70x0,17m)

Table 7: Continued

July August September October November	13 14 15 16 17 18 19 20 21 22 23	Roller Top dressing Ploughing Irrigation Top dressing Irrigation Pesticide application Irrigation Pesticide Irrigation Irrigation Harvesting Drying Land clearing (twice)	Tractor 75 CV Trailer, 12t Seed trill Tractor 50 CV Straight roller, 4m Tractor 75 CV Trailer, 12t Fertilizer drill Tractor 50 CV Cultivator, 2.1m Center pivot Center pivot Center pivot Center pivot Center pivot Center pivot Center pivot Center pivot Harvester Truck, 15t Truck, 15t Tractor 75 CV Land clearer, 1.95m	Laborer Laborer Laborer Laborer Laborer Laborer Laborer Laborer Driver Driver Laborer Driver Driver	3.68 8.64 9.02 4.23 1.60 1.06 1.06 1.34 1.34	0.22 0.06 0.52 0.06 0.54 0.06 0.25 0.10 1.06 1.06 1.06 1.34 2.74	12 kg Chlorpyrifos, 5% 375 kg Ammonium nitrate 126 UF N 1,067.5 m^3 water 275 l Nitrate solution, 88 UF N 2,550 m^3 water 1.5 l Tiodicarb, 37.5% 2,675 m^3 water 3 kg Clorpirifos, 25% + 0.75 l Naled, 93% 1,186.25 m^3 water 447.5 m^3 water 15,000 kg seeds (24% humidity) 15,000 kg seeds (24% humidity)

Tables 8 and 9 show the results obtained for a selection of rainfed and irrigated crops.

Table 8: Technical-economic indices of the main rainfed crops in Castilla-La Mancha (de Juan *et al*., 2003)

	Wheat	**Sunflower**	**Rape**	**Vine yard**	**Olive**
Total costs (TC) (€/ha)	449.52	372.48	349.87	2169.67	4529.57
Labour (€/ha)	64.67	62.98	36.59	1190.87	2276.55
Machinery (€/ha)	149.43	176.22	92.64	263.33	912.5
Raw material (€/ha)	154.61	71.89	150.67	339.15	670.01
Other (€/ha)	80.81	61.39	69.97	376.32	670.51
Gross Margin (GM) (€/ha)	205.73	2.55	223.85	223.11	1561.39
Ratio					
Labour/TC (%)	7.0	3.4	2.0	25.7	38.6
Machinery/TC (%)	16.1	9.4	5.0	5.7	15.5
Raw material/TC (%)	16.7	3.8	8.2	7.3	11.4

The results of Table 8 indicate the relatively low profit value of rainfed crops in CLM. However, due to the large size of the farms, and that they often rely on irrigated land or another source of income such as livestock, it is possible for them to obtain a level of net income sufficient to maintain agricultural activity.

Table 9: Technical-economic indices of the main irrigated land crops in Castilla-La Mancha (de Juan *et al*., 2003)

	Barley	***Maize***	**Alfalfa**	**Vine yard**	**Garlic**
Total costs (TC) (€/ha)	927.05	1867.36	1837.66	4641.88	5895.06
Labour (€/ha)	108.26	82.43	248.71	2131.17	3366.05
Machinery (€/ha)	394.18	505.32	952.13	592.65	454.42
Raw material (€/ha)	141.27	483.97	192.32	1042.89	1520.77
Water & application (€/ha)	186.10	337.42	366.45	79.63	207.89
Other (€/ha)	97.24	458.22	78.05	795.54	345.93
Gross Margin (GM) (€/ha)	374.69	623.48	542.34	4012.70	2782.05
Ratio					
Labour/TC (%)	11.7	4.4	13.5	45.9	57.1
Machinery/TC (%)	42.5	27.1	51.8	12.8	7.7
Raw material/TC (%)	15.2	25.9	10.5	22.5	25.8
Water & application/TC (%)	20.1	18.1	19.9	1.7	3.5

Irrigated crops generate a net level of income sufficiently greater than rainfed crops. However, previous results show that greater water consumption does not necessarily imply a greater gross margin. Therefore, crops such as vineyards or garlic can achieve better results than maize or alfalfa. The drawback of these crops is a greater amount of farm labor. This is the main attraction of such crops to the Regional Administration, because they increase the number of full-time farmers in the zone. Crops like barley and maize, are easy to manage as they permit farmers to arrange their agricultural activity with other activities such as construction and industry. Therefore, in many cases there are individuals who work part-time as farmers.

The continuous decrease in the countryside population and the shortage of water resources are causing the transition towards tree and extensive horticultural crops. This fact is due in part, to young farmers being better trained and full-time.

2.2 Main Irrigable Areas of Castilla-La Mancha (Uhs 08.29, 04.04 and 04.06)

2.2.1 Current Situation

CLM is a region with a limited tradition in irrigation, crops having been previously restricted to fertile valleys of rivers and to small zones watered with wells. The progression of surface irrigating in the region appears in table 2.10.

Table 10: Progression of irrigable area in Castilla-La Mancha (10^3 ha) (JCCM, 2005; MAPA, 2006)

Province	**1960**	**1970**	**1980**	**1985**	**1990**	**1996**	**2002**	**2004**
Albacete	29	33	58	82	99	135	148	154
Ciudad Real	32	42	97	116	125	173	186	195
Cuenca	12	12	22	28	25	32	39	48
Guadalajara	18	19	19	20	20	20	20	21
Toledo	38	53	61	70	69	94	107	114
Total CLM (JCCM)	**128**	**159**	**258**	**316**	**338**	**454**	**500**	**532**
% of arable land	3.0	3.8	6.1	7.4	8.0	10.8	12.4	12.8
Total España (MAPA)	**1,810**	**2,155**	**2,779**	**2,960**	**3,403**	**3,426**	**3,354**	**3,322**
% of arable land	8.9	10.7	13.8	14.7	16.9	18.4	18.7	18.9

Although the irrigated land surface constitutes only 13% of regional arable land area, this activity generates 40% of the regional agrarian income (JCCM, 2000). This elucidates the role of irrigation as a catalyst to development, and provides an idea of the limited economic profit value of rainfed in the zone. It should not be forgotten that the average precipitation in agricultural areas of CLM is around 500 mm/year, while the reference values of evapotranspiration surpass 1,100 mm, characterizing the agricultural area as semi-arid (Fig. 11).

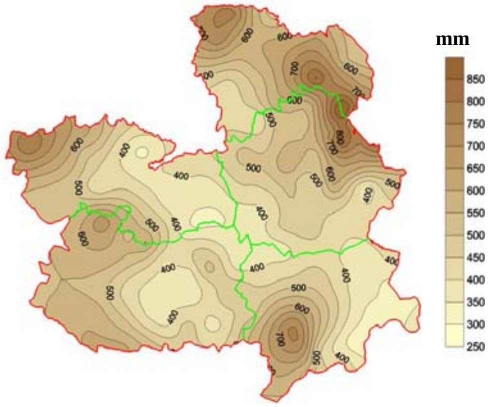


Figure 11: Map of average precipitation in Castilla-La Mancha.

As was previously mentioned, the principal irrigated areas are associated with aquifers that are overexploited or are at risk of being so. The uncoordinated exploitation of groundwater has resulted in the continuous degradation of certain areas, with the following results:

- Decrease in the piezometric levels, and an increase in the pumping costs and drying of wetlands.
- Deterioration of groundwater quality, of which a high percentage of the population centres are supplied.
- Natural spaces of special ecological value have undergone alterations that can be irreversible.

Subsequently, the situation of the three main Hydrological Units of the region are detailed, which as a whole, constitute more than 50% of the irrigated land area.

The Hydrogeological Unit 08.29 Mancha Oriental

The HU 08.29 Mancha Oriental is managed by the Hydrographic Confederation of the Júcar (*Confederación Hidrográfica del Júcar*, CHJ). The HU 08.29 includes the set of surface as well as groundwater resources, located in the geographic area that is shown in Fig. 2. Of these resources, the Júcar River and the groundwater of aquifer 08.29 have special importance.

The 08.29 aquifer has a surface area of approximately 8,500 km^2 and constitutes one of the most important underground water reserves in Spain. One study estimates its total reserves at 100,000 hm^3 and those available at 20,000 hm^3 (IGME, 1980). After the intense process of exploitation that has progressed since the decade of the 1970’s, in great excess of natural recharge, useful reserves of the aquifer are considered to be lower than that previously specified (Martín de Santa Olalla and de Juan, 2001). The natural recharge of the aquifer is estimated at 377 hm^3/year (CHJ, 2004). The volume assigned by the CHJ to the irrigable areas of UH 08.29, for the purposes of guaranteeing sustainability, is 320 hm^3/year (CHJ, 1998).

The extension in the area of irrigation from 1975 until the end of the 1990’s has been notable, constituting an important source of development. This development has resulted in a pronounced increase in water consumption (Figure 12).

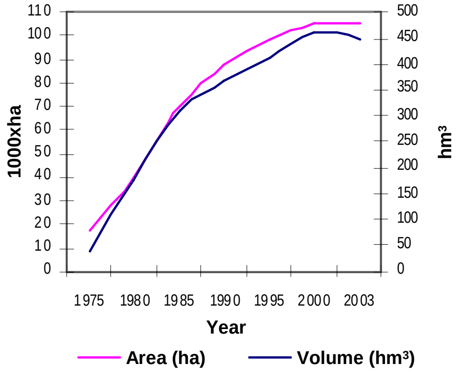


Figure 12: Irrigated area and volume for irrigation demand evolution of HU 08.29 Mancha Oriental (ITAP, 2004).

Water consumption in the last fifteen years has been in excess of natural recharge, which has caused an average reduction of the piezometric levels by 1.5 m/year (López Fuster, 2000). During this period, demand has increased from less than 300 hm^3, to surpass 480 hm^3 in 2005, due to the conditions of drought that year. It is necessary to indicate that the total volume of water utilized in the irrigation of the zone does not proceed entirely from the 08.29 aquifer. The total employed surface water used has increased to 70 hm^3 $year^{-1}$ (45 hm^3 $year^{-1}$ of traditional irrigated lands and 25 hm^3 $year^{-1}$ of groundwater replacement), which means an average volume of groundwater extraction from the aquifer around 390 hm^3 $year^{-1}$ (Domínguez, 2004).

In order to achieve sustainability of the aquifer, the Hydrological Plan of the Júcar river basin established the construction of necessary infrastructure to substitute groundwater dedicated to irrigation, by surface waters, of up to 80 hm^3 $year^{-1}$. Currently, the total volume that it is able to replenish is lower than 40 hm^3 $year^{-1}$. Due to situations of drought, the volume is even lower due to a lack of surface water resources. Thus, in 2006 only 23 hm^3 were replaced (JCRMO, 2007). The absence of guaranteed water supply for irrigation, greater control by the Hydrographic Confederation, and the lack of knowledge of farmers in terms of water costs in the future, is the main reasons that the measure is not heartily accepted by farmers.

In 2005, the entire 111,178 ha of UH 08.29, were irrigated with approximate consumption of 482 hm^3; 89% of this area utilized groundwater. The main crops of this zone are cereals. Maize, barley and wheat constitute almost 50% of the total of the area of irrigated land. Other important crops are garlic and onion, which do not require great amounts of water, but generate a high level of income for farmers. Set-aside land, approximating 12,000 ha, is voluntary on the part of farmers and is compulsory to the obtainment of aids from the CAP (ITAP, 2006).

The Hydrogeological Units 04.04 Mancha Occidental and 04.06 Campo de Montiel

Of the different zones that the Guadiana river basin is divided into, the upstream river basin is the one of greatest interest to CLM. This territory equates to 25% of the area of CLM, with 19,147 km^2, and boasts a population of 500,000 inhabitants. Agricultural activity is the main source of income, with farmers having made important efforts in recent years to modernize farms and adjust crops to market demands.

This area is constituted of a central plain, where the aquifer of 04.04 Mancha Occidental is located. It has a surface area of 5,126 km^2, and acts as a geologic drain to the Guadiana River. Into this plain spills the waters of the drainage network of the Campo de Montiel through to the Lagunas de Ruidera and waters from other rivers of lesser importance. A great proportion of the contributions infiltrate into the aquifer of Mancha Occidental, which also discharge into wetlands, of greatest importance being the Tablas de Daimiel, declared a National Park in 1973. In the decade of the 1960’s, this wetland maintained 6,000 flooded hectares, however, at the onset of the 1990’s this figure was reduced to less than 1,000 ha. Also important are the Lagunas de Ruidera, which accumulate the water of the aquifer 04.06. Since 1980, these lagoons have been protected as a Natural Park (R.D. 13/7/79). These wetlands were designated as a Biosphere Reserve by UNESCO in 1981.

Vineyards, cereals (chiefly barley and wheat), and lesser water consuming horticultural cultivations, such as melon, garlic, and pepper, and with a high impact in labor, are the current trend. This tendency arranges traditional agriculture of rainfed land with irrigated land, being a key element that helps the economic viability of the farms. This new agriculture is displacing that which was established in the decades of the 1970’s and 1980’s, which boasted crops of high water consumption such as maize, and alfalfa, etc.

In the Manchega Plain, a supply of groundwater for agricultural uses has traditionally existed. It is estimated that at the beginning of the 1960’s, in the Aquifer 04.04 Mancha Occidental, 20,000 ha of irrigation existed with water-wheels, that extracted between 50 and 100 hm^3 of water annually. From different agricultural development plans, irrigated land area has increased remarkably, from 30,000 ha in 1974 to more than 125,000 ha in 1987. Similarly, extractions have reached 550 hm^3 year^{-1}. This amount greatly exceeds the renewable resources of the aquifer, considered to be 320 hm^3 year^{-1} (PHG, 1999). As a result, the aquifer of Mancha Occidental was declared overexploited in December of 1994 by the Hydrographic Confederation of the Guadiana (*Confederación Hidrográfica del Guadiana*, CHG).

In June of 1989, the aquifer of 04.06 Campo de Montiel was declared overexploited, due to the fact that the irrigated area reached 8,000 ha. The overexploitation of this aquifer became evident when water from the aquifer no longer reached the Lagunas de Ruidera, also affecting other traditional irrigated lands of the area, and the urban supplying of some villages (CES, 2006).

According to the data collected in Table 11, the HU 04.04 and HU 04.06 are obviously overexploited. Not only do they consume their own resources but they also use the transfer that is produced from a peripheral HU. HU 04.06 is an aquifer with a pronounced flow and discharge to adjacent aquifers, where the decrease of piezometric levels produces a drying in the highest lagoons of the Lagunas de Ruidera, being an aquifer with limited capacity of permanent water storage and highly dependent on rain.

Table 11: Description of the hydrological planning in the Hydrogeological Units of the CHG

Hydrogeological Unit	*Legalized Irrigated Land area (ha)*				*Legalized Demands (hm^3 $year^{-1}$)*	*Nº Wells*		*Replenishment hm^3 $year^{-1}$*
	Herb.	*Vine yard*	*Other*	*Total*	*Total*	*Legal*	*Inventory*	
04.04 Mancha Occidental	***139,645***	***13,378***	***159***	***153,183***	***624.5***	***16,719***	***39,636***	***329***
04.06 Campo de Montiel	***6,805***	***158***	***21***	***6,983***	***29.5***	***468***	***2,693***	***86***
TOTAL HU Guadiana in CLM	*165,891*	*16,257*	*452*	*182,600*	*743.1*	*26,786*	*87,845*	*608*

Evidence exists that the extractions in this river basin are over that authorized, via different methods of monitoring carried out by the CHG (by means of remote sensing, 226,855 ha are considered to have been irrigated in 2003). Declarations of the CAP and estimations of consumption by the Junta de Comunidades de Castilla-La Mancha (JCCM) have also indicated this.

The interests that struggle for control of water in this territory are varied i.e. its uses, organizing structures, areas affected, and social perceptions in terms of how the water should be used. This diversity in complication is not quite as problematic as the non-existence of an adequate forum for the debate of these interests; this does not permit for an agreement to be reached that would foster the most sustainable use of existing water resources.

Consequently, the socioeconomic development of this zone, with difficult viable economic alternatives to those of the agricultural sector, makes necessary and urgent a plan that considers all of the mitigating factors and limitations of the area. The Special Plan of the Alto Guadiana is currently in the editing phase.

2.2.2 Water Exploitation and Income Compensation Plans

The CHJ and the CHG have taken different routes in an effort to solve the problem of overexploitation of their aquifers. In the case of the Júcar river basin, the Water Exploitation Plan (*Plan de Explotación*, PE) has been opted for, whereas in the Guadiana river basin, due to the limited success of the aforementioned, the agricultural Income Compensation Plan (*Plan de Compensación de Rentas*, PCR) has been utilized.

The Water Exploitation Plan of the HU 08.29 Mancha Oriental

The objective of the PE of the HU 08.29 is to annually limit the water consumption of each farm in order to achieve the sustainable management of the aquifer. It is a self-regulation measure that irrigators are offered and is approved at the annual assembly, which takes place before the beginning of each season.

The first step to devise a PE is to know what the available water volume is. Periodically, monitoring of the progression of the network of the piezometers of the aquifer is performed.

Second, it is necessary to know which are the irrigated land farms and to assign each farmer a certain volume of water. The distribution is not made equitably among them, as it is based on the time at which the farm converted to irrigation and the volume of water that was historically used. A study of the area of irrigated land and the types of crops that have existed in the area was completed for three different periods (Fig. 13): before 1986, when the Water Law came into effect; the period of 1986-1997, which includes the time elapsed between the approval of the Spanish Water Law and that of the Hydrological Plan of the Júcar; and finally, those areas where irrigation was established after 1997. To each of the areas a volume of water per hectare has been assigned. The areas of irrigation that were established after 1997 can only be maintained as long as they utilize a portion of the water designated to land that has been previously irrigated. In this case, the area is considered as newly irrigated land and is not assigned a volume of water for irrigation. The tools necessary for the development of these tasks have been the Inventory of Irrigated lands and Digitized Rural land Registry and of particular interest, the data collected by remote sensing on crops that were irrigated in each period.

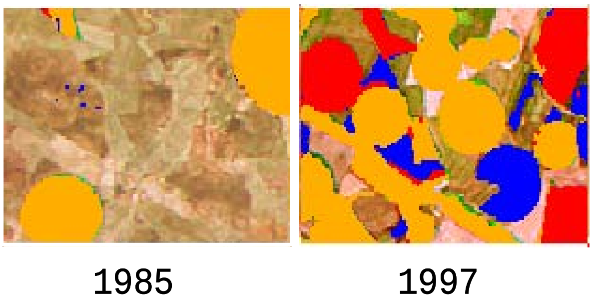


Figure 13: Example of irrigated land progression via remote sensing techniques (JCRMO).

The third step consists of assigning each crop an average water requirement for irrigation. The Irrigation Advisory Service (IAS), belonging to the Provincial Technical Institute of Agriculture in Albacete (*Instituto Técnico Agronómico Provincial de Albacete*, ITAP), has been the agency that traditionally calculates the water requirements for irrigation of crops in the territorial environment of HU 08.29 (Table 12).

Table 12: Irrigation requirements of crops, according to the Water Exploitation Plan of 2007 of the HU 08.29 Mancha Oriental

Crops	**Irrigation (m^3 ha^{-1})**	**Crops**	**Irrigation (m^3 ha^{-1})**
Sugar beet	7,650	Barley	2,700
Alfalfa	7,650	Colza	2,600
Ray-grass	6,950	Bean	2,550
Maize 700	6,550	Lettuce, spinach, broccoli...	2,500
Potato	6,400	Melon	2,500
Maize 400	6,400	Poppy	2,500
Forage maize	5,700	Chinese Garlic	2,250
Onion	5,600	Pea	2,200
Forage sorghum	5,600	Green pea	2,200
Tomato, pepper…	5,500	Forage turnip	2,000
Permanent meadow	5,000	Vetch forage	2,000
Sweet maize	4,900	Winter cereal like forage	1,700
Sunflower may	4,450	Almond, olive, vineyard	1,500
Mulberry garlic	3,350	Grain vetch	1,500
Wheat	3,250	Lentil	1,500
White garlic	3,200	Yeros	1,500
Ray-grass (October-May)	2,900	Saffron	1,000

Finally, the farmer should draft a document in which he indicates the proximate distribution of cultivations in plots of his farm. This document must be approved by technicians of the farmers association (*Junta Central de Regantes de la Mancha Oriental*, JCRMO) before the start of the irrigation season. The technicians must verify that the total volume of potentially usable water by the farmer is equal to or lower than the volume assigned for that season.

The PE would not have any validity if adequate mechanisms of control could not be established to insure the correct use of the resource. This task is quite complicated given that the JCRMO must monitor more than 105,000 ha of irrigated land in an area of 8,500 km^2. Since 2001, the JCRMO has utilized information gathered by remote sensing, in real time, provided by the Remote Sensing Section of the Institute of Regional Development (*Instituto de Desarrollo Regional*, IDR). The IDR supplies images to the JCRMO that have been classified by crop group, before they have been harvested. This situation permits the verification of what was agreed upon in the PE, presented by the irrigator, and what he has actually cultivated. Likewise, it permits the detection of irrigable lands in plots that are not permitted to use water for irrigation.

For the cases in which a possible irregularity between the images of remote sensing and the PE is detected, the technicians of the JCRMO make a visit to the farm before harvesting. If the infraction is corroborated, sanctioning is initiated by the Irrigation Jury or the CHJ. It is helpful to indicate that, currently, the number of violators detected annually is low, being less than 10%. Figure 14 shows an example of how this inspection is performed in the field.

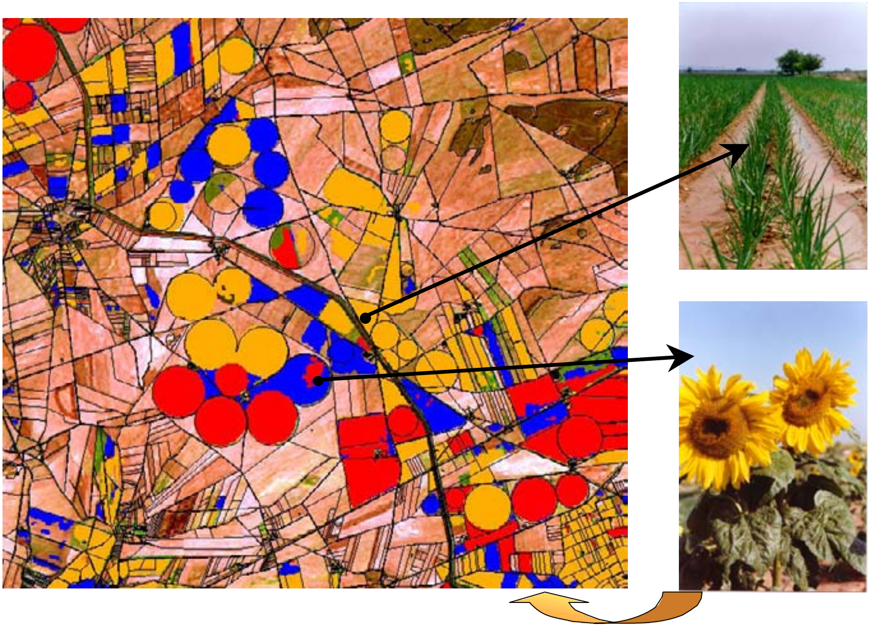


Figure 14: Verification of the data obtained by remote sensing (JCRMO).

The Income Compensation Plan in HU 04.04 And 04.06

As in the case of HU 08.29, the CHG established a PE for HUs 04.04 and 04.06 of the Guadiana river basin. Contrary to the PE of HU 08.29, this measure was rejected by most of the farmers of these HU due to the reduction in income that it entailed.

In order to encourage acceptance of the PE by irrigators, in 1992 the PCR was approved for HUs 04.04 and 04.06. The plan established economic aid to farmers for a period of 10 years. The objective was to reduce the volume of water dedicated to irrigation, through the replacement of crops of greatest water requirements by those of lower water consumption. In this manner, they attempted to balance agriculture of irrigated land with the conservation of wetlands.

From a global view point, the application of the PCR has appeared to be a temporary solution. Nevertheless, this action has contributed to the disappearance of some of the crops of greatest water requirements. The farmers have partially modified their crop alternatives by incorporating those, normally of a horticultural nature, that generate high income with less water consumption.

Figure 15 compares the annual progression of the volume of water extracted from HU 04.04 with the area that received aid from the PCR since 1992. In the period from 1996 to 1999, the combination of the PCR, along with the imposed restrictions of the PE, and favorable precipitation, improved the adverse situation. Throughout these years, extractions were reduced to 250 hm^3 $year^{-1}$, with an average recovery of the piezométric levels of 2.52 m $year^{-1}$. However, the onset of a new period of drought, and the end of economic aid in 2001, has again prompted the reduction in piezométric levels.

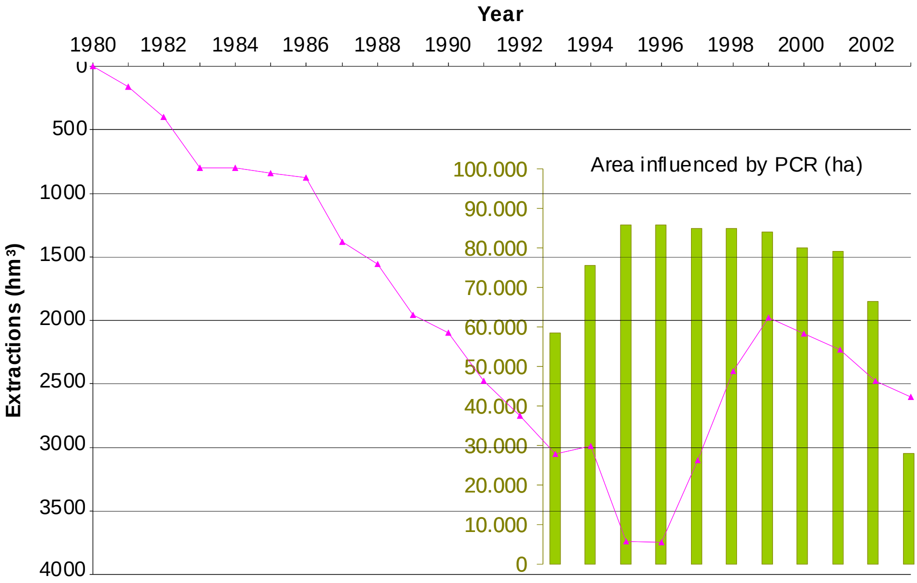


Figure 15: Estimation of the reserves drained from Aquifer 04.04 since 1980 (IGME, 2004) and the area received in the Income Compensation Plan (PCR) according to the Regional Department of Agriculture of CLM (*Consejería de Agricultura de la Junta de Comunidades de Castilla-La Mancha*).

In 2004, the PE established the following distribution of the 329 hm^3 year^{-1} of renewable water resources in the HU of 04.04: 60 hm^3 year^{-1} for the recovery of the aquifer, 30 hm^3 year^{-1} for urban supplying, and the remaining 230 hm^3 year^{-1} for irrigation. In this manner, the average endowment for any cultivation in the zone was 1,995 m^3 ha^{-1} per year. Exceptionally, only 1,000 m^3 ha^{-1} could be applied to vineyards. The PE of 2005, reduced extractions to 170 hm^3 year^{-1} for agricultural activities. This led to pronounced backlash on the part of agrarian associations and farmers who eventually forced the CHG to authorize a greater volume of extraction for irrigation.

2.2.3 The Associations of Irrigators

Irrigators, of the three irrigable areas previously mentioned, are associated with respective associations. The Junta Central de Regantes de la Mancha Oriental (JCRMO) deserves the most attention due to its high level of involvement at all levels in the management of the UH 08.29. It is an example of true integral management of water resources, because farmers use 80% and consume 95% of the total of the water in the area.

La Junta Central de Regantes de La Mancha Oriental (JCRMO)

In 1995 the JCRMO was founded, and is legally defined as a Corporation of Public Right, adhering to the CHJ. All users of groundwater of the HU 08.29 are obligated to belong to the JCRMO.

The objectives of the JCRMO are essentially two: to manage water use, in collaboration with the CHJ, so that a sustainable use of the resources is achieved, and second, to represent and to defend the interests of its associates before the public and private authorities in terms of the way in which water is used. These tasks are structured in four large groups (Martín de Santa Olalla, 2001):

- To elaborate the Inventory of irrigated lands. The objective is to know what the water uses are in HU 08.29.
- To devise, along with the CHJ, the annual PE, to approve documents presented by farmers, and to carry out the tasks of control and monitoring of compliance.
- To define Units of Water Management (*Unidades de Gestión Hídrica*, UGH). In these units there is only one origin point of water supply for the irrigation of several plots (Fig. 16). For that reason, PE affects all of the area of the UGH, independently of the number of proprietors. On the other hand, one person can be included in several UGH.
- To determine along with the CHJ, the zones in which to implement the construction of infrastructure necessary for the replacement of groundwater by surface water. The PHJ anticipates that the replacement reaches 80 hm^3 in all of the Aquifer. It is possible to increase this volume with part of the 65 hm^3 planned to increase the volume for existing irrigated lands with scarce water availability and the establishment of new irrigated areas (PHJ, 1999). Of this volume, it is estimated that 32 hm^3 can be designated to groundwater replacement (CHJ, 2004b).

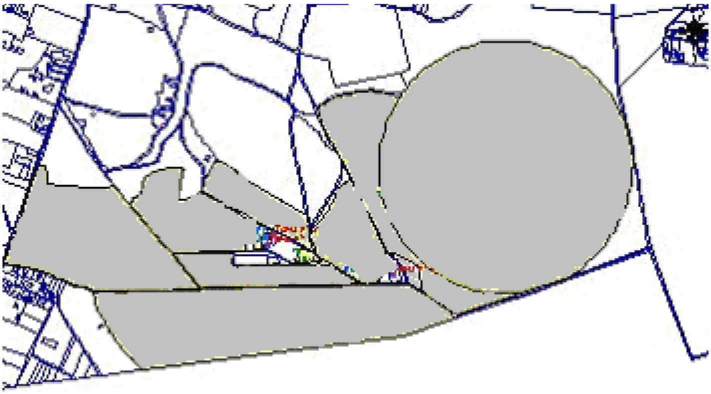


Figure 16: Example of a Unit of Water Management (UGH) (JCRMO).

3. LINES OF RESEARCH

3.1. Modernization of Irrigation

In Spain there were 1,810,000 ha of irrigated land prior to 1960. The current 735,000 ha of irrigable land, in which water is mainly distributed by ground irrigation channels, experience high water loss. In addition, 392,000 ha, over the 1,295,000 ha that distribute water by means of concrete canals, experience serious issues of conservation and maintenance. These irrigations were designed according to existing technology, utilizing surface irrigation (1,981,000 ha), a great part of which (1,635,000 ha) with irrigation in shifts. The lack of efficiency in conductions through the course the time and the modification of crop alternatives have created a situation in which 1,129,000 ha have severe problems of water supply and 694,000 ha have mild problems of water supply. In consequence, the Spanish Ministry of Agriculture, Fishering and Food (*Ministerio de Agricultura Pesca y Alimentación,* MAPA) developed a program of consolidation and improvement of the existing irrigable lands, with the purpose of increasing the efficient use of water, an improvement of the profit value of the farms and the standard of living of the farmers (PNR, 2000).

Prior to the end of 2008, the PNR anticipates to act on 120,835 ha of irrigated land in CLM in the following manner: creation of 28,910 ha of new irrigable lands; consolidation of 32,072 ha; necessary actions to increase the availability of water for irrigation, given that irrigations have problems of water supply; and improvement and modernization of infrastructures and systems of irrigation in 59,853 ha, with the purpose of increasing the saving and efficiency in the use of water for irritation. A total investment of 408 million € (PNR, 2000).

The completion of contemplated actions in the PNR is being carried out through the State Societies of Agrarian Infrastructure (*Sociedades Estatales de Infraestructuras Agrarias,* SEIASAS). The SEIASA de la Meseta Sur includes in their scope of duties the irrigable areas belonging to the regions of Extremadura, Madrid, Castilla-La Mancha and Comunidad Valenciana (Figure 17).

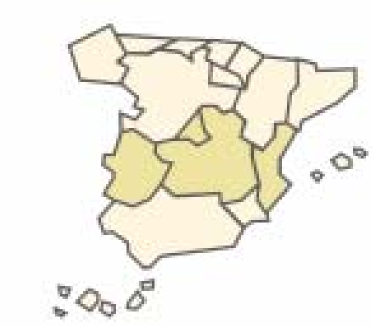


Figure 17: Scope of action of the SEIASA de la Meseta Sur.

The modernization and consolidation of irrigations of general interest that the SEIASA de la Meseta Sur has developed in CLM until now appear in Table 13. It is necessary to indicate that, currently, they have only accomplished the objective in the irrigable area of El Salobral (Albacete).

The delay in the approval and commencement of the PNR, given the importance of agriculture to CLM, boosted the Department of Agriculture, of the JCCM, to develop its own plans of action for the establishment of new irrigable areas of public initiative, as well as the improvement and modernization of existing irrigations of private initiative. In the period between 1994 and 1999, it was modernized more than 195,000 ha of irrigated land with a cost of 85.1 million € (JCCM, 2000). Part of the money utilized in the financing of the previous accomplishments originated from the *Programa Marco de Apoyo 1994-1999,* of the EU, in improvement of agrarian infrastructure and the countryside, *FEOGA Direction*.

Table 13: Works of improvement and consolidation of irrigations developed by the SEIASA de la Meseta Sur (SEIASA, 2007)

Province	Irrigable area	Area (ha)	Budget (10^6 €)
Albacete	El Salobral	323	1.2
	Balazote-La Herrera	5,349	32.7
Ciudad Real	Torre de Abraham, Margen Izquierdo	5,135	8.0
Cuenca	Priego	300	1.8
Guadalajara	-	-	-
Toledo	Valdepusa, Sector IV	1,000	3.0
	Canal bajo del Alberche	3,000	18.0
Total		**15,107**	**64.7**

Subsequent to the approval of the PNR, the JCCM has developed two new plans of action in the improvement and transformation of new irrigations in CLM. Both plans appear in the *Decreto 95/2000* and in the *Orden 28-07-2004*.

The irrigable policy adhered to by the JCCM in the second period is the following:

- Improvement and consolidation of existing irrigations by means of the modernization of infrastructure.
- Optimization of the management of water resources by directly involving users.
- The creation of new irrigations that fulfill the following requirements: to have resources assigned in the corresponding Hydrological Plan; to adhere to the regional proposal of the PNR; edafoclimatic conditions of the zone must be adequate; and they are oriented towards traditional tree and herbaceous crops of low water consumption, within the guidelines of the CAP.

In this manner, the JCCM determines the priority of the different irrigable areas in the region that are capable of entering into the program of transformation, improvement and irrigation modernization.

3.2 Irrigation Water Management

3.2.1 The Irrigation Advisory Services

IAS services can play an important role in assisting users in adopting new techniques and technologies to increase productivity (economic or social), minimizing environmental risks and contributing to the sustainability of the agrarian sector (Smith and Muñoz, 2002). Such services can be provided by private companies, public or co-operative agencies. Financial sustainability is the critical point in the promotion of irrigation advisory services.

In CLM, two IAS exist for the irrigators. The first in operation was the Servicio de Asesoramiento al Regante (SAR) (1987), coordinated by the ITAP and directed by the Delegation of Albacete. Consequently, its application scope is provincial, and mainly advises the irrigators of HU 08.29. In 1999, the Servicio Integral de Asesoramiento al Regante (SIAR) was put into effect for the rest of the territorial scope of CLM, because of the importance a service such as this contributes to the region. SIAR is coordinated by the CREA of the UCLM and directed by the Regional Department of Agriculture, which is in charge of the general guidelines, promoting contact with farmers and providing meteorological data. Both services have similar theoretical foundations and their schemes of operation are similar. For this reason, only the SIAR is described.

The Irrigation Advisory Service of Castilla-La Mancha (El Servicio Integral de Asesoramiento al Regante de Castilla-La Mancha, SIAR)

The overall SIAR objective is to help farmers to achieve an efficient use of their tools of production, especially water, fertilizers and energy. Appropriate scientific and technical support is provided to farmers in order to optimize management, making agriculture a sustainable activity compatible with the environment.

SIAR acts in coordination with the farmers, having them participate in the suggestion of solutions to problems and providing useful feed-back. SIAR contributes as much as possible to farmers' capacity building, so that they can develop the tools required to make business-oriented decisions in the management of their farms. This initiative aims to channel technology to irrigated agriculture, bearing in mind the relevance of local experience, and also considering the divergence between research results and farmers' practices.

Some of SIAR's key activities for achieving an efficient and economic use of water for irrigation (English *et al.*, 1990; Ortega *et al.*, 1997; Tarjuelo and de Juan, 1999; English, 2002; and Ortega *et al.*, 2004a) are as follows:

- *Irrigation scheduling*. The timing and volume of irrigation must be specified according to standard scheduling criteria.
- *Distribution network and on-farm irrigation systems*. Both levels must be correctly designed, maintained and managed to achieve high-irrigation performance.
- *Crop rotations to maximize the gross margin*. Since agriculture is an economic activity, it is important to maximize water profitability. Water management plans must include deficit irrigation strategies, searching for maximum gross margin instead of maximum yield.

The following sections describe these activities in depth.

In order to develop these tasks, a multidisciplinary scientific team is available (agricultural engineers, hydrogeologists, electronic engineers, computer specialists, and economists). Together with researchers, a field engineer's team is in charge of collecting field data, providing information to farmers, and performing irrigation system evaluations.

The areas where SIAR operates are presented in Figure 18. These areas represent the main irrigated production systems in the region. The areas are strategically distributed to achieve a demonstration effect of the SIAR in the entire CLM region. All the pilot areas of SIAR are water-limited, except for those in Toledo and Guadalajara.

Figure 18: Pilot areas of SIAR.

There are several methods by which to disseminate information generated by SIAR:

- *Internet.* The information is available on the Internet through the web site of "Junta de Comunidades de Castilla-La Mancha" (http://www.jccm.es) or the CREA (http://crea.uclm.es) (Figure 19). Among the information provided on the web, the most valued by farmers is related to crop water requirements. Figure 20 presents an example of requirements published weekly in an area (Daimiel). The site includes other information, the most important being, fertilization advice and regional meteorological data.
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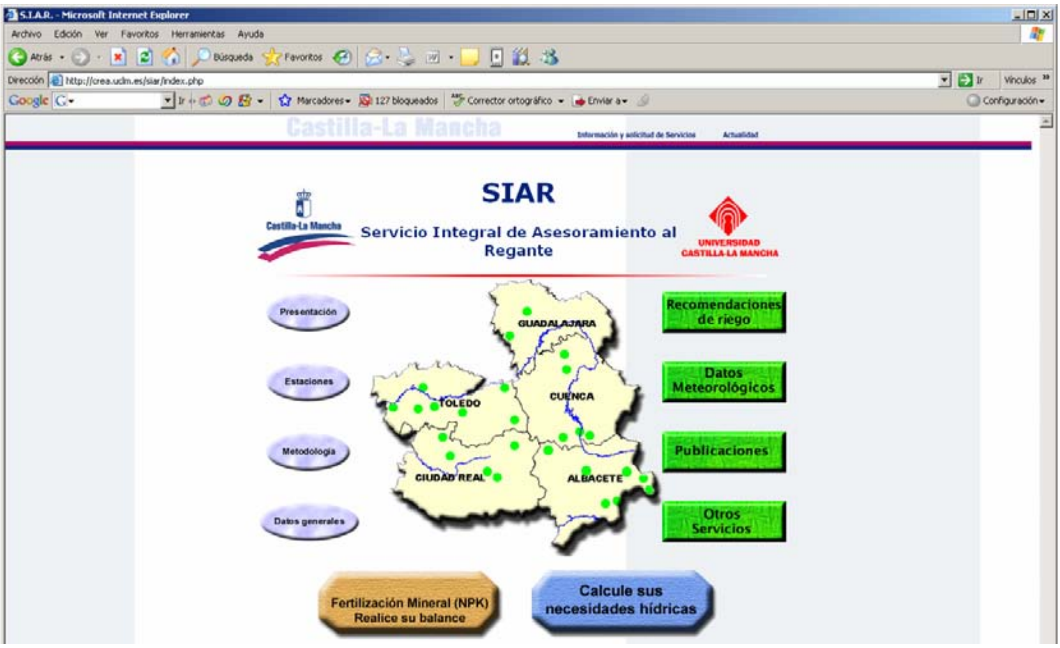
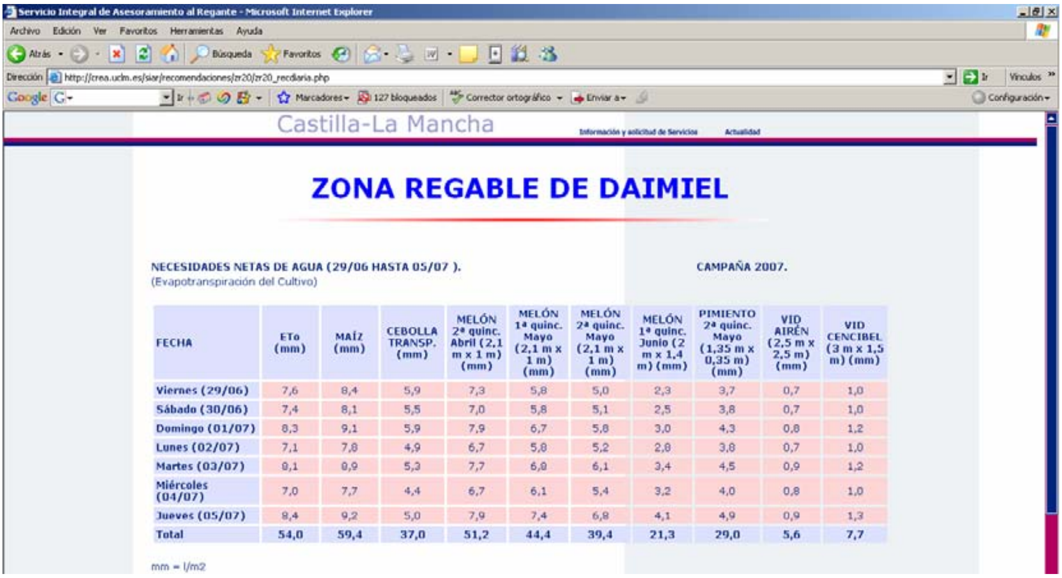


Figure 19: Access page to SIAR of Castilla-La Mancha in the web site of JCCM.



ZONA REGABLE DE DAIMIEL

NECESIDADES NETAS DE AGUA (29/06 HASTA 05/07). CAMPAÑA 2007.
(Evapotranspiración del Cultivo)

FECHA	ETo (mm)	MAÍZ (mm)	CEBOLLA TRANSP. (mm)	MELÓN 2ª quinc. Abril (2,1 m x 1 m) (mm)	MELÓN 1ª quinc. Mayo (2,1 m x 1 m) (mm)	MELÓN 2ª quinc. Mayo (2,1 m x 1 m) (mm)	MELÓN 1ª quinc. Junio (2 m x 1,4 m) (mm)	PIMIENTO 2ª quinc. Mayo (1,35 m x 0,35 m) (mm)	VID AIRÉN (2,5 m x 2,5 m) (mm)	VID CENCIBEL (3 m x 1,5 m) (mm)
Viernes (29/06)	7,6	8,4	5,9	7,3	5,8	5,0	2,3	3,7	0,7	1,0
Sábado (30/06)	7,4	8,1	5,5	7,0	5,8	5,1	2,5	3,8	0,7	1,0
Domingo (01/07)	8,3	9,1	5,9	7,9	6,7	5,8	3,0	4,3	0,8	1,2
Lunes (02/07)	7,1	7,8	4,9	6,7	5,8	5,2	2,8	3,8	0,7	1,0
Martes (03/07)	8,1	8,9	5,3	7,7	6,8	6,1	3,4	4,5	0,9	1,2
Miércoles (04/07)	7,0	7,7	4,4	6,7	6,1	5,4	3,2	4,0	0,8	1,0
Jueves (05/07)	8,4	9,2	5,0	7,9	7,4	6,8	4,1	4,9	0,9	1,3
Total	**54,0**	**59,4**	**37,0**	**51,2**	**44,4**	**39,4**	**21,3**	**29,0**	**5,6**	**7,7**

mm = l/m2

Figure 20: Example of “water requirement” data corresponding to the irrigable area of Daimiel (Ciudad Real).

- *Facsimile.* Sending weekly information by fax to farmers. Farmers associations and cooperatives often use this method of dissemination. Managers have the responsibility of making this information available to their associates.
- *Workshops.* Informational workshops to present SIAR and to present to users the catalogue of available services.
- *Communication media (newspapers, radio and local television).* This method of information distribution has been employed to inform people of the activities of the SIAR.

The achievement of recommended water requirements, by farmers, has been very satisfactory. In the new pilot areas where the SIAR was applied in the 2000–2006 seasons, farmers have steadily increased their response to recommendations. About 360 farmers from all pilot areas directly collaborate with SIAR (Fig. 21) in the monitoring of their farms (crops, yields, water application, etc.). More than 1200 farmers receive irrigation advice, mainly through associations (irrigation districts, or cooperatives), and about 20% of the irrigated land in CLM (100,000 ha) benefits from SIAR irrigation advice.

There are great differences in the follow-up of irrigation scheduling among different pilot areas (Fig. 21). In all pilot areas where resources are scarce and application costs are high, the adherence to the irrigation advice is also high. In the pilot areas of the Tajo basin (Toledo and Guadalajara provinces) where water is not as restricted (farmers pay for the irrigation water by area instead of by volume), the adherence of SIAR is low. However, even these farmers resort to SIAR for consultations related to crop management or specific problems in their irrigation systems.

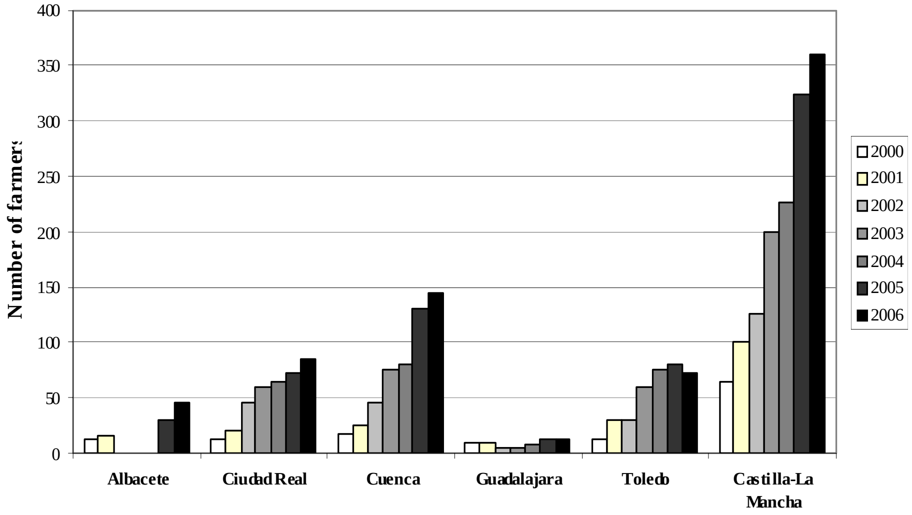


Figure 21: Progression in number of farmers who collaborate with SIAR in the action areas.

3.2.2 Water Requirements and Irrigation Scheduling

The methodology used to determine the irrigation requirements and irrigation scheduling is based on the FAO guidelines, taking into account the simplified daily water balance in the soil–plant–atmosphere set (Doorenbos and Pruit, 1992; Allen *et al.*, 1998; and Pereira and Allen, 1999). The estimation procedure begins with the determination of reference evapotranspiration (ET_o) and ends with the water balance, considering soil water content, the irrigation timing and the resulting gross irrigation depth.

ET_o is calculated using the Penman–Monteith method (Pereira and Allen, 1999). This methodology, generally accepted in the literature for semi-arid areas, has been validated for local conditions by means of measurements in weighting lysimeters (López Urrea, 2004). A 43 automated weather stations network has the sensors to calculate the ET_o by means of the aforementioned method.

The crop ET (ET_m) for different crops in each one of the pilot areas is determined from the crop coefficient (K_c) curve, and is established based on the literature and experience in the area (Doorenbos and Pruitt, 1992; Martín de Santa Olalla *et al.*, 1992; Martín de Santa Olalla *et al.*, 1994; Allen *et al.*, 1994; Allen *et al.*, 1998; Fabeiro *et al.*, 2001; and Ortega *et al.*, 2004b).

Table 14 shows the crops for which the water necessities are calculated in each one of the zones of study.

Table 14: Advisored crops by the SIAR.

Herbaceous crops	Horticulture crops	Tree crops
Alfalfa	Garlic	Almond
Maize	Green bean	Apricot
Poppy	Melon	Olive
Sugarbeet	Onion	Peach
Sunflower	Pepper	Plum
Wheat	Potato	Vineyard
Wicker	Tomato	
	Watermelon	

In the other hand, ITAP has a lysimeter station consisting of three continuous weighing lysimeters with electronic data reading. Each of them is surrounded by a square protection plot of one hectare (Fig. 22). One of them is sewn with grass (Festuca *Festuca arundinacea* Schreb) and kept under ideal growth conditions with the aim of obtaining reference evapotranspiration values (ET_o). Next to this lysimeter, there is an agro climatic station that has appropriate sensors to obtain the data needed for the estimation of evapotranspiration, and thereby comparing them to the results obtained by weighing. In the second plot, a rotation of crops is carried out in order to measure their ET_m. Thus, it is possible to get the evapotranspiration values for each crop studied and the curves of crop coefficient (Kc) by comparison to the ET_o calculated in the reference lysimeter. Finally, the third lysimeter is a monolithic with a depth of 1.70 m and is devoted to the study of grapevine irrigation (Montoro *et al.*, 2002).

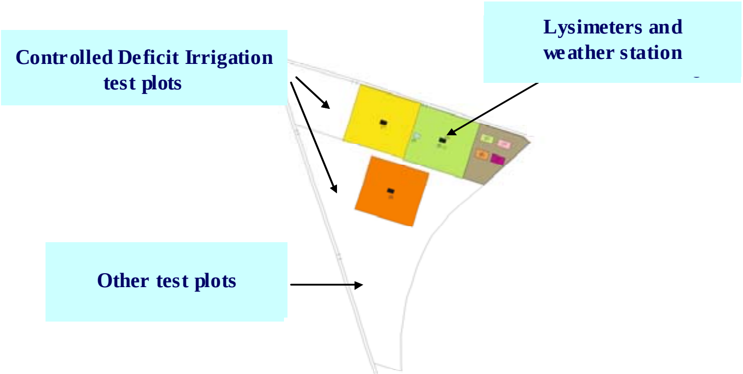


Figure 22: Lysimeter station of the ITAP in the experimental farm of “Las Tiesas” (Albacete).

The evaluation of various equations to calculate evapotranspiration (FAO-56 Penman–Monteith; FAO-24 Corrected Penman (I); FAO-24 Corrected Penman (II); Penman (1963); FAO-24 Blaney–Criddle; FAO-24 Radiation; Hargreaves (1985)) under the semiarid climatic conditions in the province of Albacete was performed. Average daily ET_o values were measured with a continuous weighing lysimeter. This comparison was conducted from 215 observations carried out during the 3 years that the experimental work persisted. The conclusion of the work was as follows. In a semiarid climate, the FAO-56 Penman–Monteith method was the most precise in calculating average daily ET_o, when comparing it to lysimeter measurements. The Hargreaves equation was the second most precise method, in spite of its simplicity (López Urrea *et al.*, 2006).

3.2.3 Field Irrigation Systems Evaluation

From the start of SIAR activities, 1301 irrigation system evaluations have been performed (Table 15). The methodology used for irrigation evaluation was derived from well-established references (Merriam and Keller, 1978; Merriam *et al.*, 1980; Bralts and Kesner, 1983; Keller and Bliesner, 1990). In the case of stationary sprinkler irrigation systems, the norms ASAE S330.1 (2004), ASAE S398.1 (2004), ISO 7749/1 (1986), and ISO 7749/2 (1990) were applied. For center pivot, the ASAE S436.1 (2004) and ISO-11545 (1994) were adopted.

Table 15: Irrigation system evaluations (2000-2006)

System	Albacete	Ciudad Real	Cuenca	Guadalajara	Toledo	CLM
Drip irrigation	126	295	224	0	233	**878**
Solid set system	20	19	60	78	52	**229**
Center pivot	12	45	23	1	113	**194**
Total	**158**	**359**	**307**	**79**	**346**	**1,301**

The average efficiency of irrigation systems is high (Figure 23). However, a set of farms have been identified, that should improve irrigation uniformity, to achieve better efficiency. In most of the cases, the problems are design-related, often including large pressure differences in the irrigation subunit.

An important problem with drip irrigation is the working pressure and the pressure differences within the subunits. In some cases, very low pressures were recorded, with average pressures of only 18 kPa and minimum pressures in subunits of 5 kPa. Under these low-pressure conditions (lower than 100 kPa), most emitters will fail to work properly. Only some pressure-compensating emitters could discharge an adequate flow rate under these conditions. There are important differences in crop categories. In general, fruit trees equipped with drip irrigation systems, and horticultural crops show the highest Emission Uniformity (EU).

In the case of center pivots, major problems are related to design and in a few cases, management (e.g. inadequate working pressure or sprinklers packages). Normally, these machines are located in areas with a limited tradition in their management. In such areas, the work of the SIAR is essential for the training of farmers in management and in the necessity of proper design.

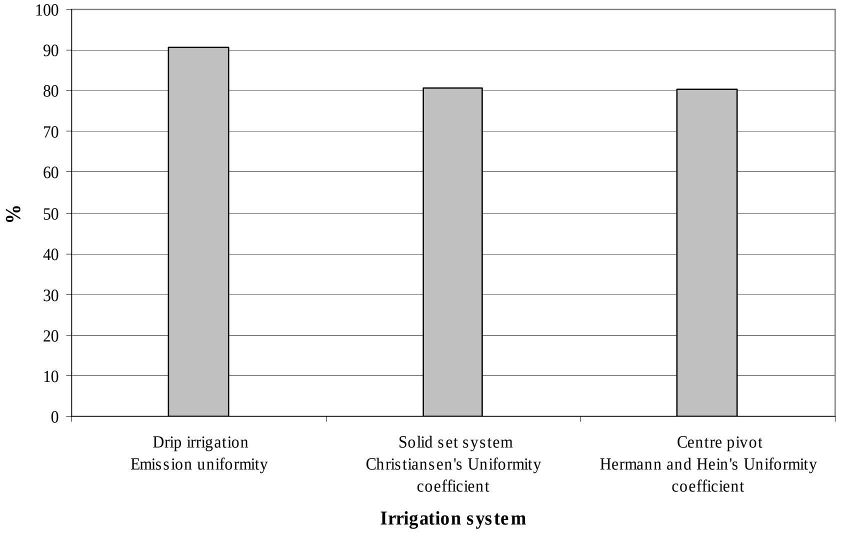


Figure 23: Average efficiency of the irrigation systems evaluated by the SIAR.

3.2.4 Fertirrigation

Fertirrigation is a technique consisting of the application of fertilizer dissolved in water to crops. It is a method of great importance in crops irrigated by means of drip irrigation systems. It is also used, to a lesser extent, in sprinkler solid set irrigation systems and pivot systems. The main difference between these systems is that in drip irrigation system all of the area does not get wet, whereas in sprinkler irrigation systems it does.

The primary objective of fertirrigation is the use of water flow to transport nutrients, which are required by the crops, to the area of root development. Thus, water use is optimized, as are nutrient uptake and energy, and contaminants are reduced.

The use of the fertirrigation in CLM started around 1985, and was applied mainly through sprinkler irrigation systems (pivot and solid set systems). Twenty years later, the number of farmers that apply this technique remains low. The main reason is the lack of formal occupational training of farmers and the lack of specialized technicians capable of advising them.

However, in the last decade, the number of farms that utilize this technique has increased. This fact is due to the research and disemination activities that are being developed in the region, and to the increase in tree crop area and extensive horticultural crops, which utilize drip irrigation systems. In terms of crops that generate a greater gross margin, but that involve greater production costs, are the farms which usually have technicians or farmers with high levels of training that are able to correctly apply fertilizing treatments.

Currently, there are two institutions that are working mainly in this field. The first is the center of investigation of El Chaparrillo that is carrying out a high number of field tests with the main crops of CLM. Second to El Chaparrillo are CREA and the JCCM, through SIAR, which are carrying out a service to give advice about this technique.

As an example, a possible fertirrigation is shown for a melon crop in the area of UH 04.04. In addition, imposed limitation in the use of fertilizers in vulnerable areas has been considered to avoid groundwater contamination by nitrates of agrarian origin (Orden 15-06-2001 de la Consejería de Agricultura y Medio Ambiente and Orden 22-09-2004 de la Consejería de Medio Ambiente) (Table 16).

Table 16: Example "Fertirrigation scheduling for melon crop" (SIAR, 2005)

Example "Fertirrigation for melon crop" (yield: 40,000 kg/ha). N reduction to 135 Fertilizer Units (Mancha Occidental).												
Phenology	**Day**	**Irrig. (m^3/ha)**	**Nutrients requirements (kg/ha)**			**Fertirrigation scheduling based on liquid fertilizer (kg/ha)**			**Fertirrigation scheduling based on soluble solid fertilizer (kg/ha)**			
			N	**P_2O_5**	**K_2O**	**Nitrogen solution**	**Phosphoric acid**	**Potassium solution**	**Complex**	**Complex**	**Complex**	**Complex**
						32% N	**52% P_2O_5**	**0-0-10**	**10-6-22**	**11-8-32**	**16-7-28**	**10-5-30**
Vegetative development fructification	**15**	49	4	2	9	13	4	90	40	0	0	0
	30	193	4	2	9	13	4	90	40	0	0	0
	45	614	10	8	35	31	15	350	0	100	0	0
Maturation	**60**	847	20	18	70	63	35	700	0	200	0	0
	75	1140	41	18	70	128	35	700	0	0	256	0
	90	1080	41	18	70	128	35	700	0	0	256	0
Harvest	**105**	783	10	5	32	31	10	320	0	0	0	100
	120	765	5	4	12	16	8	120	50	0	0	0
TOTAL		**5471**	**135**	**75**	**307**	**422**	**144**	**2433**	**130**	**300**	**513**	**100**

In addition to the customized advice for the irrigator, the SIAR has on its web page an application on line that allows the user to make a simplified balance of mineral fertilization (N-P-K) for the most important crops of CLM, in consideration of the legal rules of application of fertilization.

3.2.5 Controlled Deficit Irrigation

Controlled Deficit Irrigation (CDI) (English, 1990; English *et al.*, 1990) can be an efficient research tool for saving water without causing any significant losses in terms of the quality and quantity of the final crop yield. This technique enables an understanding of the drought stress which takes place in a plant at a given phenological stage as it relates to potential decreases in the ultimate yield and quality of the harvest. The aim is to find at which phenological stages the irrigation water supply can be decreased and the extent to which this can be done, by examining the consequences brought about by this course of action (Jordan, 1983).

The completion of this technique in a semi-arid climate region with a shortage of water resources, such as CLM, is of great importance. For this reason, the ITAP, sometimes in collaboration with CREA, and El Chaparrillo are being made numerous tests with the main crops of the region (Table 17).

Table 17: Tests of controlled deficit irrigation made in CLM

ITAP		**EL CHAPARRILLO**	
Crop	**Reference**	**Crop**	**Reference**
Purple garlic	ITAP, 2000, 2001	Maize	INIA, 1989
Sugar beet	Fabeiro *et al.*, 2003	Wheat	INIA, 1989
Onion	Martín de Santa Olalla *et al.*, 2004	Sunflower	INIA, 1989
Vine	ITAP, 2002, 2003, 2004, 2005	Melon	Ribas *et al.*, 2002
		Pepper	Moreno *et al.*, 2002
		Barley	Moreno *et al.*, 2002
		Peach tree	Goldhammer *et al.*, 2002
		Pistachio tree	INIA, 2003
		Olive tree	Moriana *et al.*, 2006

Currently, no private farms exist that apply this technique. However, it is certain that, the maximum permissible irrigation set for certain crops, as well as, the offered recommendations of irrigation from the SIAR, consider these results to try to maximize the yields for that level of deficit. The clearest examples can be seen in the tree crops such as vineyard and the olive tree. In these crops, the curves of the Kc have been modified from the results obtained in the previous trials to reduce the recommendations of irrigation (Figure 24 and 25).

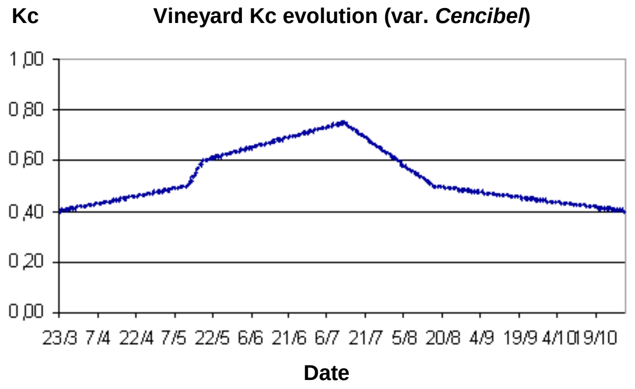


Figure 24: Evolution of the Kc for the vineyard (cv. *Cencibel*) in the province of Ciudad Real (SIAR, 2007).

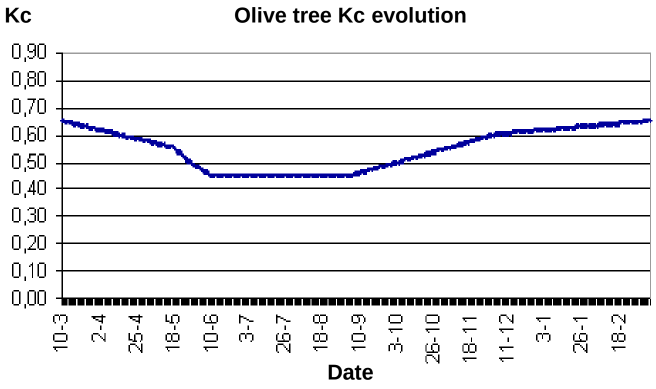


Figure 25: Evolution of the Kc for the olive tree in the province of Albacete (SIAR, 2007).

The recommendations offered by the SIAR are evaluated in the field by means of the monitoring of several control plots. Given its growing importance in the region, a curve of Kc for the crop of pistachio is being developed.

3.3 Decision Support Systems Models

3.3.1 Economic Optimization Model for Irrigation Water Management (Modelo de Optimización Económica En La Agricultura de Regadío, MOPECO)

Many factors are involved in irrigation management, including water availability, product prices and market uncertainties, plus the constraints imposed by agrarian policies. All of these factors should be considered when designing an irrigation schedule. Through SIAR, CREA uses the MOPECO decision-making tool (Ortega *et al.*, 2004a) to assist farmers in the development of irrigation strategies, while also determining correct depths of applied water, in order to economically optimize water use. Conventional irrigation management strategies are usually planned without deficit irrigation, even though the economical optimum will imply some degree of under-irrigation, depending on the crop, its water requirements and gross margin (Tarjuelo and de Juan, 1999; Ortega *et al.*, 2004a). The MOPECO model is composed of two computing models:

Module I determines "Yield vs. Gross irrigation depth" for each crop and "Gross margin vs. Gross irrigation depth" functions (Figure 26).

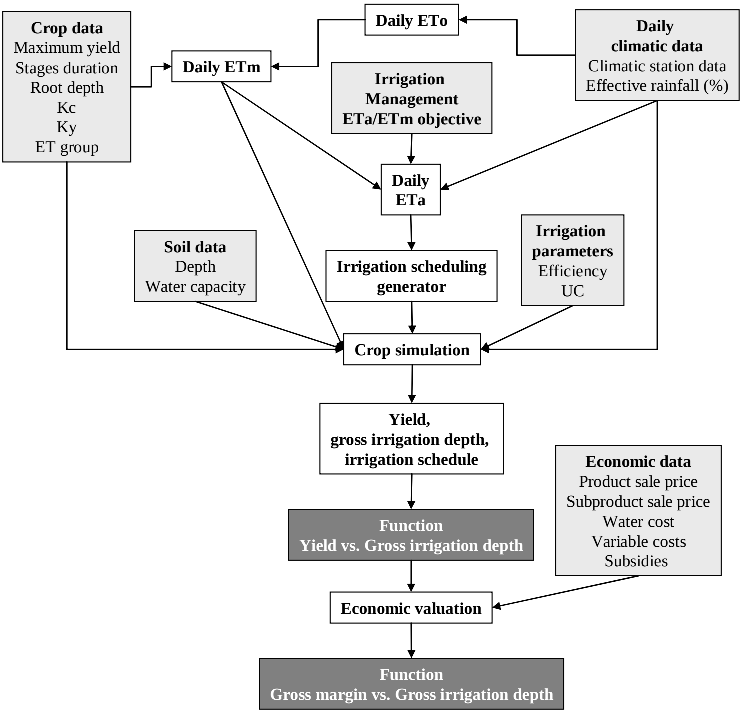


Figure 26: Module 1 sketch.

Module II determines the distribution of crops that obtain the maximum gross margin (Figure 27).

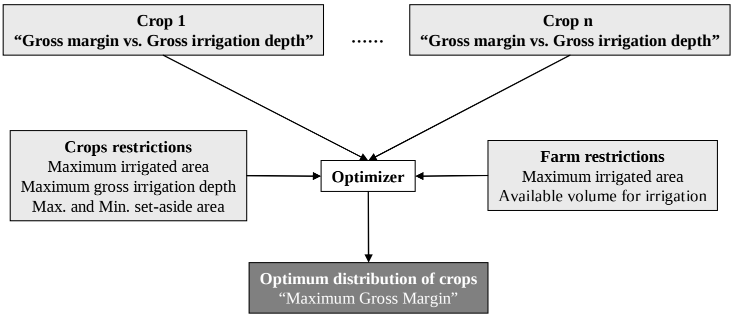


Figure 27: Module 2 sketch.

The model is based on the production function of Stewart *et al.* (1977), which estimates the crop yield based on the comparison of actual to maximum evapotranspiration.

$$\frac{Y}{Y_m} = \prod_{i=1}^{s} \left(1 - k_{yi} \left(1 - \frac{ETa_i}{ETm_i} \right) \right) \tag{1}$$

where Y is the actual harvested yield (kg ha^{-1}); Y_{m} the agronomic maximum yield that can be achieved when crop development is not limited by water availability or other factors (kg ha^{-1}); k_y the proportionality factor, shows the sensitivity of the crop to water stress; $\mathrm{ET_a}$ the actual crop evapotranspiration (mm); $\mathrm{ET_m}$ the crop evapotranspiration for maximum yield (mm); and i represents the developmental stages of the crop.

This model allows to determine the relationship between the gross margin and the gross irrigation depth. Normally, the authors work with water application cost, Coefficient Uniformity (CU) and water cost scenarios for each irrigated area. The relation between the gross margin and the gross irrigation depth allow us to analyze the water irrigation depth that maximizes the gross margin (optimum water depth).

MOPECO uses the relation between gross margin and the irrigation depth for an individual crop to optimize crop rotation on the entire farm. Crop rotation must meet certain restrictions (Fig. 27). These restrictions should ensure that the simulation setting reflects the actual situation. Table 18 shows an example of the results for the La Mancha test-site in Albacete. The total irrigated area is 15,190 ha and the available volume for irrigation is 63.8 hm3/year. These results were developed within Project DeSurvey (A surveillance system for assessing desertification. Ref. SUSTDEV-CT-2004-003950-2) funded by the European Commission. The objective of this project is to develop a methodology for fighting desertification processes (www.desurvey.net).

Table 18: Optimizer results for La Mancha test-site

CROP	RESTRICTIONS				RESULT	
	Max. area (ha)	**Max. dose (mm)**	**Max. set-aside (%)**	**Min. set-aside (%)**	**Area (ha)**	**Dose (mm)**
Maize	3,040	800	10	6	2,329	800
Spring Barley	4,560	500	10	6	0	0
Winter wheat	3,800	300	10	6	2,685	0
Spring wheat	3,800	500	10	6	3,585	396
Sunflower	1,520	500	10	6	0	0
Alfalfa	1,520	1.000	0	0	1,520	889
Potato	455	700	0	0	455	700
Onion	1,215	650	0	0	1,215	650
Garlic	1,065	500	0	0	1,065	480
Olive	910	200	0	0	910	200
Vine (cencibel)	910	200	0	0	910	200
			Gross Margin (€)		15,553,585	
			Gross Margin (€/ha)		1,023.94	

When planning strategies for the economic optimization of water used in irrigation, different gross irrigation depths must be considered. The results of MOPECO are very useful for economic analysis of the irrigation strategies in the different pilot areas, establishing the economic optimum for each scenario. This irrigation strategy, associated with a different deficit for each crop (objective relationship ET_a/ET_m) will be recommended for each experimental area.

3.3.2 Bayesian Networks Applied to Water Management

CREA built a Bayesian network (Bn) applied to water resource management in the HU of 08.29. This model was developed within Project MERIT (Management of the Environment and Resources using Integrated Techniques, Ref. EVK1-CT-2000-00085) funded by the EU from June 2001 to June 2004. The aim of MERIT was to construct Bns for four study areas that have different problems in terms of water use. These networks, regardless of the way in which they may be used in the management of each hydrographic catchment, are intended to act as a pilot program for the construction of any Bn geared towards water resource management, within the framework of the EU or elsewhere.

Bayesian networks (Cain, 2001; Jensen, 2001; Díez, 2003) are directed, acyclic graphs, in which nodes represent random variables and arcs the cause–effect relationship among these variables. Each node has a conditional probability table (CPT) associated with it that quantifies in probabilistic terms how much that node is related to its parent nodes.

The objective was to build a Bn that helps in defining a sustainable strategy for the management of the HU 08.29. Long-term sustainability can be obtained only if the consumptions are balanced, on a yearly basis, by the average recharge volume.

The construction of a Bn follows a well-defined procedure, the main stages of which are:

- Identification of the variables which affect and describe the state of the Unit.
- Identification of the relationships among these variables.

- Discretization of the states and population (filling up) of the CPT tables.

The Bn that describes the “Eastern Mancha” aquifer and its concerns is divided into five large groups (Fig. 28) and is composed of 56 variables. In turn, the group of variables that describe the agricultural consumption are partitioned into five sub-groups, the reason being that the largest consumer, i.e. agriculture, has to be described in greater detail than the other factors (Domínguez, 2004).

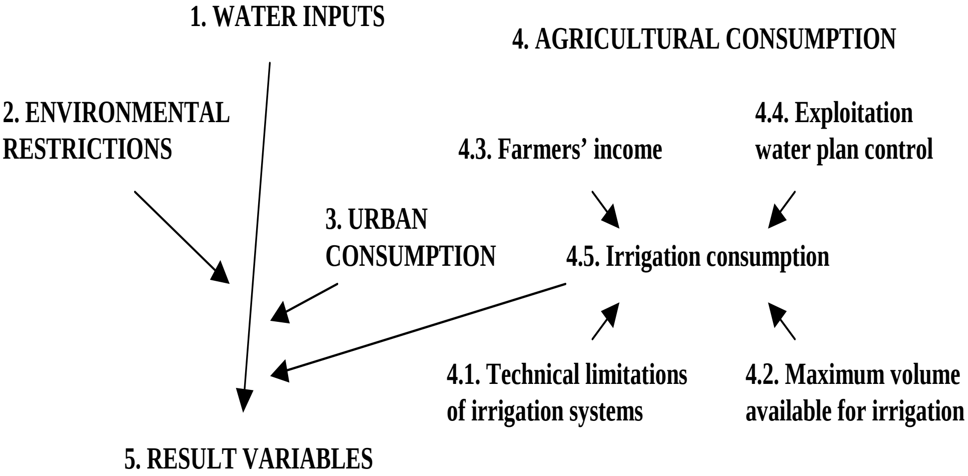


Figure 28: Groups of variables.

The Bn is structured as an annual balance, subtracting water inputs from the requirements for the different uses. In this manner, it is possible to estimate the available volume for the following HU and the groundwater extracted from the aquifer.

Explaining the meaning of each individual variable would be arduous and descriptions are therefore limited to groups 4 and 5.

Group 4: ‘Agricultural consumption’. This group is made up of five subgroups. The combination of these subgroups provides an estimate of the volume of water extracted from HU 08.29 to be consumed by irrigated crops.

Group 5: ‘Result variables’. The output volume of the Unit is permitted to be higher than 500 hm^3 $year^{-1}$. This ensures its sustainability and sufficient water for the next unit, under current conditions. Environmental restrictions do not really affect the balance. The volume of water extracted from the aquifer must be lower than 320 hm^3 $year^{-1}$ (PHJ, 1999). These variables are the model outputs.

Once the variables were defined and grouped, a preliminary Bn was constructed using the information collected through questionnaires and data bases (historical series, statistical studies, etc.). Stakeholders' meetings were used to improve and validate the Bn.

The model has been used to evaluate different ways to obtain the sustainability of HU 08.29 (Figure 29).

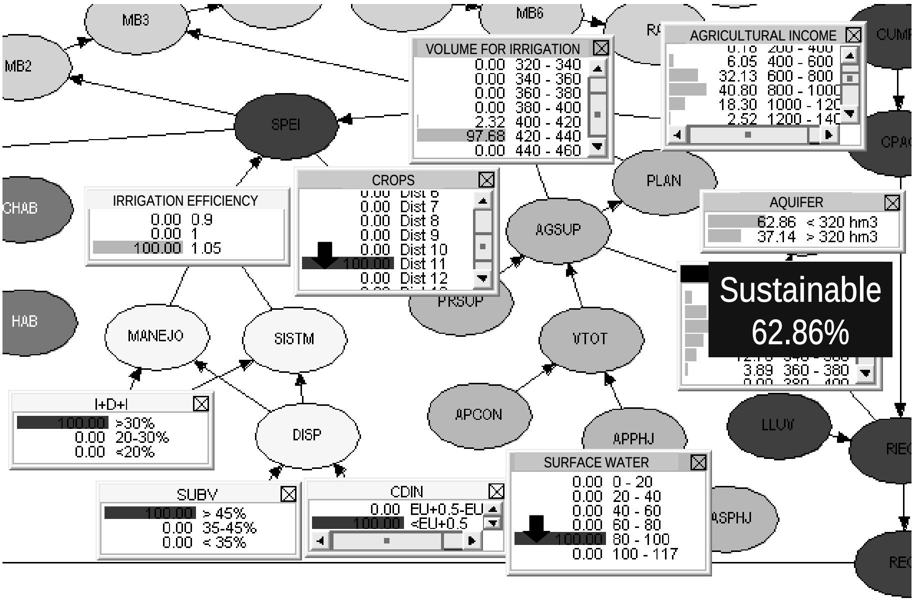


Figure 29: Combination of actions that may achieve the sustainability of the HU 08.29.

The model offers the following conclusions (Martín de Santa Olalla *et al.,* 2005):

- Bns support resource managers of the HU 08.29 in the decision-making process. The advantage of this tool is that it can predict the behaviour of the Unit, creating a model when we input one or several variables.
- Specific results offered by the model show, that although the current situation of the aquifer is not sustainable, the substitution of groundwater for the surface water volume established by the PHJ, in addition to proper actions on the part of authorities, can restore aquifer sustainability. It is necessary to increase the volume of replacement up to 115 hm^3 year^{-1} (the current PHJ estimates that 80 hm^3 year^{-1} is the required volume of surface water for reaching sustainability of the aquifer).

This tool shows the direction in which the main efforts should be directed and which should be considered as secondary priorities. Investment in infrastructure should be among the first objectives in order to expeditiously utilize the entire volume of surface water to replace groundwater. Second in priority, would be those efforts directed toward maintaining the price of surface water, improving irrigation efficiency, and the proper implementation of water exploitation plans.

3.3.3 Benchmarking Applied in Irrigation Community Management

In many economic activities, the improvement of management structures, production, etc., are possible via the comparison of different organizations and knowledge of their most effective practices. The objective is to detect the weak and strong points of these organizations, and then integrating changes to improve the management of each of them. In order to accomplish this, different methods exist. One procedure that is well defined is

"Benchmarking", which uses as its main tool, management indicators. The application of this methodology in the management of water resources is very innovative.

To date, there have been many authors who have proposed diverse indicators to measure the efficiency of an irrigation system (Rao, 1993), and applying them to a predetermined zone. However, to find examples of the application of these indicators, in which the efficiency of diverse irrigated land areas can be compared, is less feasible. More and more, management indicators are becoming indispensable tools in the management of irrigated land areas (Molden *et al*., 2001; van Koppen, 2002; Rodríguez *et al*., 2004; Malaño *et al*., 2004; Jayatillake, 2004; Ghazalli, 2004).

The general objective is to obtain a reasonable use of irrigation water, and promoting the sustainability of water resources, however, this can only be achieved by improving the management of water at the level of the user. The completion of the study that began in 2005, intended (Córcoles *et al.*, 2006):

- To apply in 7 irrigation communities the process of "Benchmarking", as a system of comparison and the improvement of irrigation.
- To integrate users in the process of management.
- To expand the indicators of the International Programme for Technology and Research in Irrigation and Drainage (IPTRID) with respect to the service quality rendered to farmers, of the efficiency in productivity, environmental quality, etc., in agreement with the regulatory evolution (*European Water Framework Directive 2000/60/CE*).
- To analyze how improvement and modernization have augmented irrigation.
- Integration of "Benchmarking" as a tool of the IAS.

In order to carry out the study, it is necessary to collect information of a diverse nature related to the CCRR i.e. general aspects of each organization. From the information collected, a series of indicators are developed, and compiled into 2 groups (description and management).

In addition to these indicators, indicators related to energy efficiency are obtained in the test-sites, as well as the quality of electrical energy supply. This aspect, which has not been thoroughly studied before, permits an understanding of energy efficiency. It also allows for the proposal of different improvement solutions, from the comparison of results between the different irrigated land areas.

Initially, contact with managers of each of the irrigation community was made. This was done, in an effort to explain the project and to make an introductory exposition of the methodology of application, emphasizing necessary information in order to carry out the objectives presented. There has been a marked increase in the interest shown by irrigators to participate in the project.

Next, began the collection of required information for quantifying the descriptive indicators of the test-site. This information has been utilized to characterize the zones of study. Of the proposed descriptive indicators, the greatest difficulty was to obtain the cropping pattern and checking the existing systems of irrigation in the different zones. This information, obtained from field work and interviews with the staff of each irrigation community, was integrated into a Geographical Information System (GIS).

With the active participation of an optimum and diverse number of farmers, the completion of 21 evaluations of the irrigation systems in the different zones were completed, as well as, a survey of the implementation of irrigation recommendations made by the SAR (Montoro *et al.*, 2004).

In this manner, it has been possible to understand the farmwork performed by a representative group of farmers in the zone, mainly the water applied, as well as knowledge of the yields and average market prices of the most representative crops of each zone.

The conclusions of the 2006 season are as follows:

- The initial results show elevated interest by managers of the irrigable areas in the application of this methodology, principally in the improvement obtained via energy indicators.
- The degree of participation of technicians and farmers has been satisfactory, with initial positive involvement that has remained throughout the entire season.

In this moment, the 2007 season is finishing.

3.4 Other Lines of Research

3.4.1 Agroclimatic Characterization and Water Consumption of Castilla-La Mancha

In the irrigable areas of CLM, the water available for irrigation is limited. Under these conditions, a valuable tool is the power to quantify, by zones, the water consumption of the crops, for farm management.

In order to obtain an understanding of water consumption, by means of empirical methods, it is necessary to know the values of crop Evapotranspiration (ETc) by multiplying the reference evapotranspiration (ETo) by the Kc (FAO Methodology) (Allen *et al.*, 1998). Depending on the method used, the ETo estimation requires diverse climatic variables that are usually not registered in the agronomic scope (Jensen *et al.*, 1997).

When a limited amount of data and number of climatic stations are available, it is necessary to estimate, and to represent spatially, the values of different variables for those zones in which data are not provided. It can be accomplished via various technical procedures such as: geostatistics, use of neuronal networks, Cluster analysis, etc.

However, when working with natural phenomena it is necessary to know the influence of the position of the sample in space and/or time. Thus, the geostatistics have as an objective the characterization of the space and/or temporal dispersion of the natural phenomena, to be able to model the natural resources and to operate them in a reasonable manner (Jiménez *et al.*, 1993). Geostatistics are a technique used in the analysis of the spatial variability of climatic data, and are supported by numerous studies (Delhomme, 1978; Davis, 1986; Hashmi *et al.*, 1994).

The main objective of this work is to create a climatic characterization of CLM, considering primarily the specific climatic variables utilized in irrigation. The specific objectives are as follows: To analyze and represent the spatial and temporal variability of the climatic variables that defines local climates (temperature, precipitation, etc.); To analyze and represent the spatial and temporal variability of the evaporative demand of the atmosphere

(ETP, ETo); Spatial and temporal distribution of the precipitation deficit; Obtaining the spatial and temporal distribution of the crop water requirements.

In order to achieve these objectives it is necessary to perform the following tasks:

- Inventory and collection of climatic data of the primary (only temperature and precipitation data) and complete stations of the region. The inventory of the primary stations (110) and complete stations (5) has been performed. The complete stations facilitate more precise information, but are very few in number. The primary stations are sufficient in number, but the data is less reliable. It is necessary to compile the available data, to analyze it and edit it, with the objective of obtaining homogenous series of 20 years (1981-2000). Only 10 stations have the complete 20 year series of data, in the stations lacking the necessary data augmentation techniques have been applied, such as: artificial neuronal networks (Nabney, 2001).
- The division of CLM into distinct zones according to various criteria. This section attempts to classify the stations via a climatic point of view and to distinguish zones with different characteristics.
- Classification of the soils and distribution of the most important crops of CLM. Utilizing the available information and existing maps, the digitalization of such resources will be done in order to combine the information with the main climatic parameters. In addition, a compilation of the available information (MAP, JCCM, INE, etc.) regarding the most important crops and their geographical distribution will be performed.
- Estimation, by different methods of the potential and reference evapotranspiration. It is necessary to perform a thorough reference review of the different methods utilized in the determination of the ETo, with the purpose of determining which one best complies with the available climatic parameters. The alternative empirical methods, which are of easy applicability, will also be calculated (Hargreaves, Thornthwaite, Blaney Criddle, Turc, etc.).
- Application of geostatistics for the representation of the spatial variability of the studied climatic variables (GEO-EAS, GEOPACK). A reference review of geostatistics as a technique for the analysis of the spatial variability of climatic data will be performed. The election and application of the suitable techniques for the construction of maps that attain isolines for temperature, precipitation, evaporative demand, precipitation deficit, crop water requirements (mainly maize, garlic, alfalfa, grapevine, and olive trees, among others) and water balance, will be performed.

3.4.2 Improvement of Energy Efficiency in Irrigated Land Operations

In Spain, agricultural activities constitute 3% of total energy consumption. However, in the province of Albacete, where the most significant crops have high water requirements, and water is pumped from very deep wells, the rate of energy consumption is higher (17.4%).

In terms of irrigation, the regional government of CLM has focused its attention on the implementation of collective on-demand irrigation networks. These irrigation infrastructures insure efficient water use, reduce farmers’ disputes and diminish the problems created by improper use of irrigation water.

Further studies are required to facilitate decision-making regarding the improvement of both water use and energy efficiency. A hydraulic and energy analysis of on-demand irrigation networks permits the obtainment of general results. With this objective, the following is proposed:

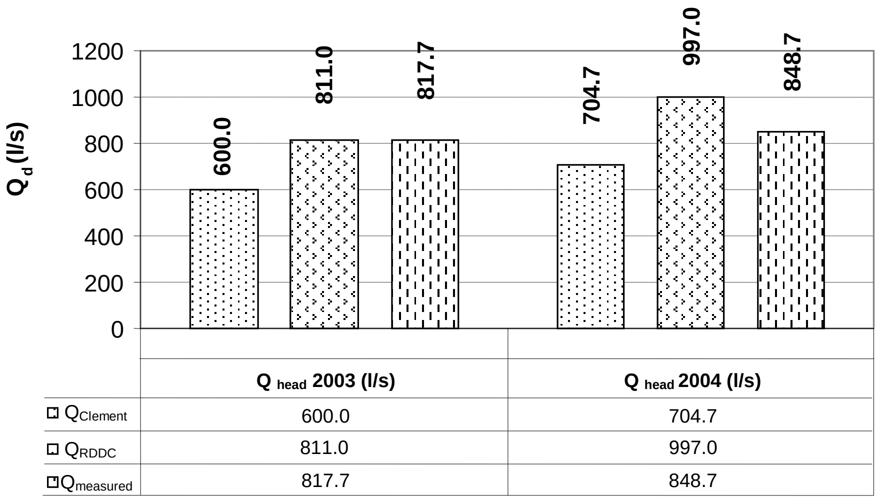
- An analysis of the mode in which farmers are managing and using water in the area studied.
- An analysis of the traditional prediction models of discharge flow in on-demand irrigation networks and a validation of the new models proposed through network measurements.
- The development of a hydraulic model of the network and its calibration, as a basic tool in improving the network operation and its management.
- Modelling of the pumping stations, and allowing an energy efficiency increase through regulation improvements.
- The development of a methodology able to define pressure and discharge more accurately.
- A study of the effect of energy supply quality and network harmonics generation, showing the problems this kind of disruptions lead to.

In order to administer this study, two on-demand irrigation networks have been analyzed (Sector I and Sector II), which form part of the “Sociedad Agraria de Transformación SOciedad de REgantes de TArazona” (SAT SORETA), located in Tarazona de La Mancha (Albacete). Sector I irrigates 550.2 ha and Sector II 494.1 ha. Water is obtained from the HU 08.29. Sprinkler irrigation is the most commonly used irrigation system when irrigating plots. However, it should be mentioned that drip irrigation systems are also utilized.

The hydraulic analysis of the irrigation network has been performed by obtaining accurate pressure and discharge measurements. In this case, the discharge data collecting system of the network has been utilized. Moreover, an ultrasonic flowmeter has been used to measure the head discharge. Pressure has been measured with pressure transducers, which have been located strategically along the two irrigation networks studied. The energy analysis has been carried out by using three electrical network analysers, which were installed at the Sector I pumping station. In addition, a series of technical visits were made in order to determine the cropping pattern and check the network topology.

The study related to water use and its management was completed by using “benchmarking” techniques, in collaboration with farmers.

Flow rates have been measured, so that the traditional methods to estimate water flow rate in each line can be validated. Furthermore, the new stochastic method proposed, based on the Daily Random Demand Curves, has been validated. Figure 30 shows the validation of the new proposed methodology and its comparison with the Clément methodology.



	Q_{head} 2003 (l/s)	Q_{head} 2004 (l/s)
□ $Q_{Clement}$	600.0	704.7
□ Q_{RDDC}	811.0	997.0
□ $Q_{measured}$	817.7	848.7

Figure 30: Results of the Daily Random Demand Curves methodology.

An analysis of the pumping station has been performed through the development of a pumping station simulation model. This allows for the study of different types of regulation on energy efficiency. Apart from which, the model can be calibrated using measured data. Thus, the regulation which provides maximum energy efficiency can be determined. Figure 31 shows the energy saving when a more efficient pumping station regulation, than the one currently used, is implemented.

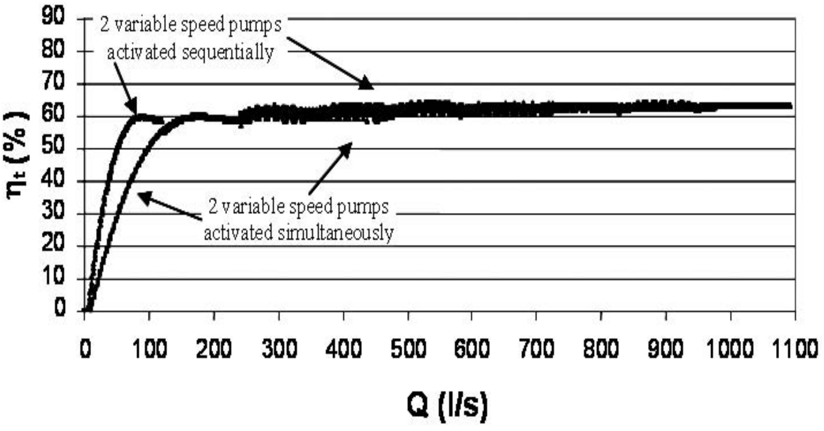


Figure 31: Pumping station regulation with different types of regulation.

The main results obtained from this research were:

- The irrigation scheduling applied by farmers is not suitable, but the total volume supplied during the irrigation season is similar to the total requirements of the crops.
- The initial hypotheses of Clément's methodology were rejected. Also, the use of hydrant opening probability, cause up to a 35-40% flow underestimation.

- Discharges around 40-90 l s^{-1} (6-10% of total discharge) are more frequent than medium and higher discharges. Therefore, optimal economic options are those able to guarantee high efficiency in the case of low discharges. In this study, the best option was the one that consisted of two variable speed pumps running sequentially and the others working as fixed speed pumps. If compared with the current regulation, in which two pumps of variable speed work simultaneously, a saving of around 16.02% could be obtained.

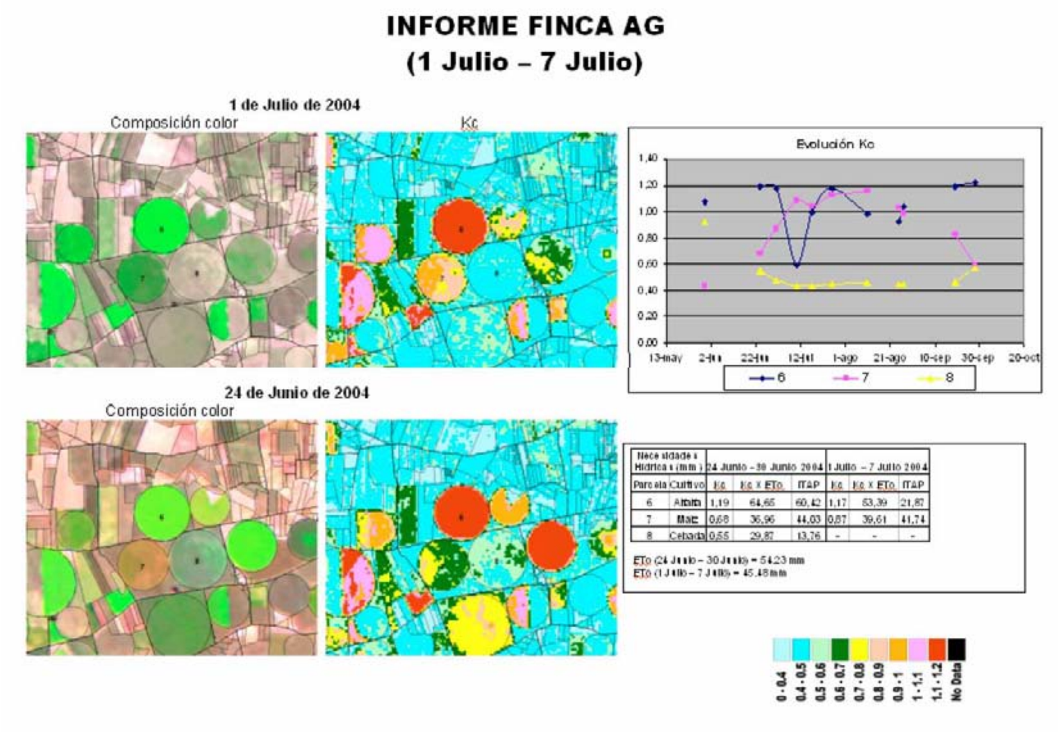
3.4.3 Earth Observation Techniques in Routine Irrigation Advisory Services (DEMETER Project)

One of the main problems that face an IAS are the high economic and labor costs involved to cover each field in extended areas at regular short time intervals. The utilization of Earth Observation (EO) technologies can be of great help in these tasks.

IDR has coordinated the Project DEMETER (DEMonstration of Earth observation Technologies in Routine irrigation advisory services; Contract EVG1-CT-2002-00078) (http://www.demeter-ec.net) funded by the European Commission. This project was designed to assess and demonstrate, in an operational perspective, how the performance and cost-effectiveness of an IAS is substantially improved by the incorporation of Earth observation (EO) techniques. This is done in combination with Geographical Information Systems (GIS), in day-to-day operations. In addition, the latest Information and Communication Technologies (ICT) offer great possibilities to transmit specialized information to users in a personalized manner (Calera *et al.*, 2005).

The main result obtained in DEMETER from a sequence of satellite images are maps of crop coefficient Kc along with the temporal pattern at a given place. Therefore, the EO-derived Kc maps can be introduced directly into the routine IAS information generation flow for irrigation scheduling. Crossing (multiplying pixel by pixel) the Kc map with a map of reference evapotranspiration, ETo, directly provides a map of crop evapotranspiration, which is then used to determine crop water requirements (Jochum *et al.*, 2006).

In order to evaluate and validate the proposed methodology, a group of representative farmers was set up during the irrigation season of 2004. Each farmer received information on a weekly basis via e-mail about crop water requirements. Figure 32 shows an example corresponding to one farm. On the left hand side, a map of actual Kc for the current weekly period is presented together with a color combination (RGB543) image for the same crop area (top panel). The same information is given for the previous week (bottom panel), in order to be able to visualize changes. On the right hand side, a temporal progression of Kc for each of the different monitored plots is displayed. Finally, information about crop water requirements from actual IAS (in this case, SAR) is also displayed in a table, to allow for the comparison with satellite derived crop water requirements.



Necesidades Hídricas (mm)		24 Junio – 30 Junio 2004			1 Julio – 7 Julio 2004		
Parcela	Cultivo	Kc	Kc X ETo	ITAP	Kc	Kc X ETo	ITAP
6	Alfalfa	1,19	64,65	60,42	1,17	53,39	21,87
7	Maíz	0,68	36,96	44,03	0,87	39,61	41,74
8	Cebada	0,55	29,87	13,76	-	-	-

ETo (24 Junio – 30 Junio) = 54,23 mm
ETo (1 Julio – 7 Julio) = 45,48 mm

Figure 32: Example of Farmer’s report (Jochum *et al.*, 2006).

4. DISSEMINATION OF RESULTS AND APPLICATION

4.1 Description of the Research Centers

CLM counts on a high number of research centers related to agriculture. This is due to the social and economic importance of the agrarian sector in the region. Subsequently, the main characteristics of the most important groups are briefly described. It is necessary to indicate that, although they are all independent, there have been many occasions in which they have worked together and continue to. In fact, the activities that each one of them performs are complementary to the others, carrying out important work for the society of CLM.

4.1.1 Regional Water Research Center (Centro Regional de Estudios Del Agua, CREA)

The risk of desertification is increasing in extensive zones of the world. CLM is a semi-arid zone where the processes of desertification will be relevant in the next few years. In order to try to stop this eventuality, the University of CLM has created various research teams that focus their attention on the problems of water availability. With the purpose of coordinating all of these research groups, in 2001 the CREA was established (http://crea.uclm.es).

CREA is a university center of research and technological development. The main objectives of CREA are:

- To provide scientific and technical support to the public and private institutions, companies and users of water. To contribute to satisffy the demand of technologies, products and services that favors innovation and improves competitiveness.
- To promote the development of initiatives, directed toward rational and sustainable water use, and favoring the conservation of the environment and looking for maximum coordination between the private and public sector.

In order to achieve the previous objectives, CREA has structured its activities in six sections. Each one of them is composed of multidisciplinary teams that collaborate closely. The main activities of each one of the sections are:

- *Agricultural water use:* Coordination of the tasks related to the SIAR; Agricultural water management under conditions of limited water availability; Field tests to improve the use of water in agriculture.
- *Economy and law:* Study of the current legislation at the Communitarian, National and Regional level from an environmental and water use perspective; Elaboration of economic reports on the effects of the use of this resource in regional agriculture.
- *Management of water resources.* This section is dedicated to the development of models that aid in the decision making process in terms of water used for agricultural purposes.
- *Surface and groundwater hydrology:* Development of models for the evaluation of water resources in their natural state, as well as for the estimation of the water demand pattern and water balances.
- *Hydraulic engineering:* Development of projects related to the transformation of rainfed areas into irrigated areas; to support the main manufacturing companies of irrigation materials in the region.
- *Limnology and hydrobiology*: Monitoring and evaluation of the chemical and biological quality of the main bodies of water in the region (surface and groundwater); Studies on residual water purification.

The staff that works directly in CREA is composed of 28 PhD holders, 13 Engineers and Graduates of various fields, and approximately 15 students. The majority of the PhD holders whom work in CREA develop their curriculum in the Technical School of Agricultural Engineers of Albacete, which belongs to the UCLM.

4.1.2. Institute of Regional Development (Instituto de Desarrollo Regional, IDR). Division of Remote Sensing

IDR (http://www.idr-ab.uclm.es), established in 1994, is a Centre of the UCLM devoted to Research and Development in several scientific areas of special application and importance in this region. The IDR's work is based in the ambition to contribute to the development of Castilla La-Mancha.

Remote Sensing and GIS have been an independent division of the IDR since September of 1994. This Division is a multidisciplinary and interdepartmental group made up of geologists, physicists, computer scientists, and agricultural, telecommunications and forestry engineers, etc., who bring their specific training into the development of different studies and R+D projects.

Remote Sensing and GIS are utilized in the development and application of Remote Sensing techniques, image and storage analyses, and coordination and study of any kind of information related to space.

The main lines of research that this group is developing in relation to the use of the water in agriculture are as follows:

- *Remote sensing:* Development and application of Earth Observation techniques and digital image manipulation. Furthermore, this section works in coordination with specialists in the development of new techniques and methodologies to be applied to an understanding of the physical environment. Some of the better developed lines of research within this field are of crop monitoring, detection of land cover alteration and estimation of evapotranspiration through remote sensing.
- *Geographic Information Systems:* Design, development, update and maintenance of GIS. There is a group of specialists in computer science, which program and develop the necessary tools for each case; GIS Technologies allow the quality control of the digital land registry that is used for the accomplishment of projects.
- *Hydrology:* Application of Remote Sensing and GIS technologies to the management of water resources; Hydrologic study and modeling (both surface and ground): aquifer dynamics, estimation of refill, runoff, rainfall space distribution, studies on soil erosion, etc; Development of tools for the management of water resources.

4.1.3 Provincial Technical Institute of Agriculture in Albacete (Instituto Técnico Agronómico Provincial de Albacete, S.A., ITAP)

ITAP (www.itap.es) is a public service that was created by the Diputación de Albacete in 1986. Its scope is the farming and agro-alimentary sector of the province of Albacete. Its objective is the transfer of technology from science to rural communities.

The main services that the ITAP offers to the farmers are as follows:

- Irrigation Advisory Service (Servicio de Asesoramiento al Regante, SAR).
- Control of agricultural plagues and diseases.
- Crop fertilization advisory service and soil analysis.
- Advisory service of Integrated and Organic Agriculture.

ITAP also develops its own research in two experimental farms. The lines of research are related to the water requirements and irrigation scheduling of crops. This institute, in collaboration with the UCLM, has published numerous studies on controlled deficit irrigation and on direct measures of the reference evapotranspiration and consumption of crops (herbaceous and ligneous) obtained with lysimeters of continuous weight, one of them monolithic (the one used for vineyard tests). In addition, it also develops experiments on new varieties of crops in the zone and in the management of the fertilization.

4.1.4 Center of Agricultural Improvement "El Chaparrillo" (Centro de Mejora Agraria “El Chaparrillo”)

"El Chaparrillo", located in Ciudad Real, was established in May of 1987. Initially, the main activities of this public center of research were: the constitution of the Regional Network of Agricultural Warnings (*Estación Regional de Avisos Agrícolas*); recovery of crab and indigenous partridge populations; recovery of wild fauna; and control of livestock disease.

Since 1986, this center has developed the following new lines of research:

- *Irrigation:* Calculation of crops water requirements and scheduling irrigation.
- *Extensive crops:* Introduction of new varieties and crops; management and adaptation of crops; quality and harvesting improvement.
- *Horticultural crops:* Introduction of new crops and varieties; management and adaptation of crops.
- *Olive tree cultivations:* Introduction of new varieties; management and adaptation of crops; quality and harvesting improvement.
- *Pistachio tree cultivations:* Management and adaptation of crops; quality and harvesting improvement.

Of the aforementioned, their contribution to the sustainable use of irrigation water should be emphasized. These actions are directed toward the determination of the actual water requirements of different crops of importance to the zone. The experiments involving controlled deficit irrigation are of special importance (Table 17).

The reduction in water use for agriculture is achieved by cultivating crops with lower water requirements than the current crops, which also generate an adequate level of income.With this aim, “El Chaparrillo has developed several experiments to study the introduction of new crops to the region. The pistachio tree is a good example of the positive results of this line of research. In terms of the horticultural crops, the melon is a crop with great possibilities.

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Chapter 3

EVAPOTRANSPIRATION ESTIMATES AND WATER STRESS INDICATORS FOR IRRIGATION SCHEDULING IN WOODY PLANTS

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ABSTRACT

Irrigation management requires information on evapotranspiration (ET). The ET of a well irrigated crop (ETc) is usually approached through an empirical equation using reference ET (ETo) and crop coefficients (Kc): ETc = ETo × Kc. Discrepancies have been observed between Kc measured in several row crops and Kc values recommended in currently used manuals. Therefore, a need arises to address this problem via further field measurements of ET. Some limitations to the application of micrometeorological and hydrological methods to measure ET in small fields or in woody crops are briefly described and sap flow methods (SF) are presented as an alternative to quantify transpiration (T), the major component of ET. A clear underestimation of T with SF data was observed in several conditions, when compared to data from eddy covariance (EC) micrometeorological method. By combining robust, low cost SF methods with reliable EC measurements, an EC-SF relationship can be developed to correct SF measurements. Using this combination, ET and Kc data series can be extrapolated in time (e.g., for a whole season) or space (when micrometeorological methods are not suitable, as in small areas). Some case studies show the combination of complementary EC-SF methods to follow the seasonal variation of ET and Kc (vineyards, kiwi and peach orchards) proving its usefulness in long term studies. A second aspect discussed is the fact that calculating crop ET as ETo × Kc implicitly assumes continuous adequate available soil water for optimum plant growth. However, even for irrigated crops, ET is often below ETc and called actual ET (ETa). Besides, due to growing water scarcity, deficit irrigation strategies are increasingly being explored. Under water stress, the reduction of ET due to stomatal closure is higher for rough canopies and/or woody crops than for low crops and cannot be neglected. Therefore, for practical purposes, ETa can be estimated as ETo × Kc × Ks where Ks is a stress coefficient (Ks = ETa/ETc). The relationship between Ks and soil water depletion (ΣET since last irrigation) can be used to estimate how much water to apply and when to irrigate. This relationship varies with soil type, ET rate, and root distribution. Hence, it must be adjusted, which can be done empirically as a function of observations of plant water status. The use of relationships between water stress indicators improves the identification of threshold values for practical purposes.

1. INTRODUCTION

The total water flux from vegetated surfaces to the atmosphere, or evapotranspiration (ET), includes transpiration (T), soil evaporation (Es) and interception (evaporation of water from the leaves outer surface, due to rain, irrigation or dew). Through quantification of ET and water balances it is possible to better understand the role of transpiration and evaporation in the water cycle and to enable more efficient use of water in irrigated crops. The validation of water use models and the understanding of the related physical and physiological processes require good methods for long-term ET measurements. Water management in irrigation has been the motivation for most of the studies of ET and its relationship with water stress.

Irrigation is essential to achieve good crop growth and economic yields whenever precipitation is low or negligible during the period of active vegetation growing, as in Mediterranean climates. Under such climate, most precipitation occurs during winter, when temperatures and ET are low. Therefore, water loss through interception represents only a small part of annual ET. Transpiration, T, becomes the most important term in ET, because high Es losses are often avoided by good irrigation or cultural practices. Another consequence of summer water scarcity is that it results in dominant stands of woody plants that can withstand water deficits while extracting water from deep below ground sources that are recharged during the winter. In such cases, sustainable water management means using irrigation as a supplement to rainfall.

Irrigation planning and management requires information on maximum ET for the specific climatic and crop conditions (ETc), often approached through an empirical equation using reference ET (ETo) and crop coefficients (Kc): ETc = ETo × Kc, (e.g. Doorenbos and Pruitt, 1977; Allen et al., 1998) with Kc accounting for both T and Es (Ritchie, 1972; Tanner and Jury, 1976; Kanemasu et al., 1979, Allen at al., 1998). ETo can be estimated using meteorological data (vd Doorenbos and Pruitt, 1977; Burman, 1983; Rosenberg et al., 1983; Jensen et al., 1990). The use of Penman-Monteith (PM) equation adapted to practical uses and with grass parameters, according to Allen et al. (1998), has been increasingly used. Kc values vary with crop phenological stages to accommodate crop changes. However, limitations in determining Kc, and more importantly, implementing ET-based irrigation scheduling, arise when agro-technical differences cause differences in crop growth and water use. Discrepancies between Kc measured in several row crops and Kc from currently used manuals (as in Allen et al., 1998) show the need for additional field measurements of actual ET in order to improve estimation methods.

Limitations to the application of ET measurement methods in small fields and/or woody crops have been often described, as discussed in Section 2. Due to such limitations, measurements of water use of individual plants with sap flow methods (SF) are an alternative to quantify T, the major component of ET. An underestimation of T from SF data has been observed under several conditions, when compared to data from eddy covariance (EC) micrometeorological method. Even where the size of the plot is large enough to allow EC measurements, it is often much easier to make long term measurements of sap flow. When a complete soil water balance is not feasible (deep, sparse roots), a combination of those methods (SF and EC) can provide reliable, long term ET estimates. This chapter shows how to combine these methods to improve ET estimates.

Two basic questions in irrigation water management in agriculture are when to irrigate and how much water to apply when irrigation occurs. When to irrigate can be indicated by determining a critical value for soil water depletion or other direct or indirect indicator of plant water status. The soil water depletion is the result of the cumulated actual ET (ETa) since last irrigation event. Therefore, it can be approached via the soil water balance, using ETa estimations. Calculating ETa as ETo × Kc implies that irrigation occurs before a critical value for plant water status is attained, meaning that irrigation takes place before ETa starts to decrease (black arrow in Figure 1) from its maximum value, ETc.

The relationship between the relative value of T or ET and the reduction in available soil water has been studied for decades (Penman, 1940; Hallaire, 1960; Denmead and Shaw, 1962), where the available soil water is the difference between the field capacity, FC, and the permanent wilting point, PWP (Figure 1). This relationships, valid in irrigation conditions with moderate stress, can exhibit a continuous decrease since irrigation occurs (dashed line) or a platform (ETc=ETa) followed by a sharper slope (full line).

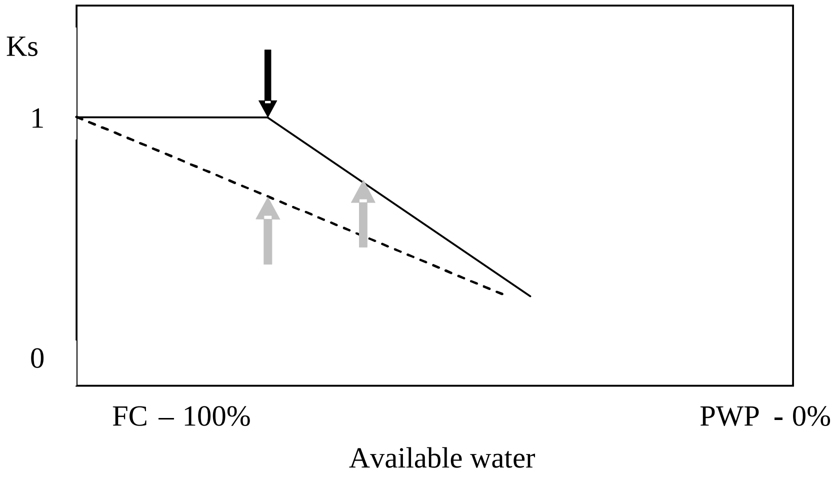

Figure 1: Possible relationships between Ks = ETa/ETc and available water in soil. Arrows indicate possible choices for irrigation applications.

Experimental evidence based on ET measurement methods that provide information over detailed time scales, suggest that ETa is often less than ETc, in irrigated rough canopies and/or woody crops. In fact, as pointed out by Jarvis (1985), water stress inducing stomatal closure has, in general, more impact on ET reduction in tall crops than for low crops. Given the extreme complexities of deterministic plant ET models, an operational alternative is to establish parameters of empirical models for ETa estimation accounting for water stress by using a stress coefficient (Ks) given by ETa/ETc, which needs to be adjusted to specific conditions. Relationships between Ks and other water stress related variables allow to perform this adjustment as suggested in Section 5.

This chapter describes basic concepts and assumptions concerning the application of ET estimations and the water-stress indicators related to irrigation scheduling, with emphasis on the specificities of woody species.

2. EVAPOTRANSPIRATION IN WOODY CROPS

The answer to the classical question - how much water to apply? - requires information on ET. In some extent, the answer to - when to irrigate? – depends on that information. However, the currently available ET models are not refined enough to dependably predict ET of tall, uneven crops with incomplete canopies, such as woody perennials and further work on ET is needed. Yet, some methods of ET measurement currently used in annual crops are difficult to apply to woody crops because of the size of the roots (deep, sparse) or the shoots (tall and/or rough canopies). As a consequence, direct ET measurements required to build and test ET models have been scarce and some aspects related with ET modeling on these stands are not well developed. Some of the particularities of most woody crop stands compared to annual crops, related with the limitations described, are the following:

a) higher surface roughness, heterogeneity and/or important anisotropy of the canopy means efficient transport of water vapor from the surface, ability to act as a trap for sensible heat (advection) and reduced vertical gradients for heat, mass and momentum;
b) as a consequence of (a), stomatal control of transpiration plays an important role, as discussed below;
c) higher water interception in the canopy which, also due to (a), can result in evaporation losses much higher than maximum transpiration losses, because the evaporation of intercepted water is independent of stomatal control;
d) higher radiation interception, particularly in dominant or isolated trees;
e) higher biomass and canopy volume which implies that, at least in hourly estimates, the heat storage in vegetation cannot be neglected;
f) different zones for energy and momentum exchanges and, in some cases, different climates at the level of the crowns and near the soil, with the need to consider multi-layer models, if the canopy is dense;
g) dispersed and deep root systems, especially in Mediterranean climate, resulting in difficult access to soil near roots and difficult characterization of root zone extent and soil properties.

Those differences have implications in general on water and energy balance (1), and particularly on the choice of methods to measure ET (2) and on ET modelling (3).

2.1 Water and Energy Balance

The starting point for the discussion of the implications of woody crops particularities on water and energy balance is described in (a) above. Turbulent diffusivity for heat, mass or momentum (K_H, K_V and K_M) in tall or rough stands is, on average, at least one order of magnitude higher than that observed in low crops (Oke, 1990; Monteith and Unsworth, 1990). In the case of woody stands, the high diffusivity requires a separate analysis for wet and dry canopies. If wet, evaporation is mainly limited by the available energy, while, for a low crop, it could be limited by the low diffusivity of water vapor to the atmosphere. In some cases, ET is higher than net radiation during limited periods, as high and rough stands act as a sink for energy from advection. If these canopies are dry, transpiration is controlled by stomata; the stomatal conductance becomes the limiting resistance in dry woody stands. Conversely, in low crops, the low diffusivity of water vapor from the leaves implies that ET is, on average, less dependent upon stomatal behaviour than in the tall and rough woody crops.

Jarvis (1985) and Jarvis and McNaughton (1986) expressed these differences using a decoupling coefficient, Ω ($0<\Omega<1$), defined by:

$$\Omega = [1+(r_c/r_a)\ \gamma/(\Delta+\gamma)]^{-1} \tag{1}$$

where the bulk stomatal resistance of the canopy (r_c), can be estimated by (Jones 1992) $r_c = r_s/LAI$ (LAI = leaf area index, r_s = average leaf stomatal resistance), r_a is the aerodynamic resistance of the canopy, γ is the psychrometric “constant” and Δ is the slope of the saturation vapor pressure curve. The interpretation of these resistances and the problems of scaling-up, from the leaf to the canopy scale, were discussed by Stewart and Thom (1973), Lhomme (1991) and Baldocchi et al. (1991), among many others. According to McNaughton and Jarvis (1983), the value of the Ω coefficient ranges from 0.1 to 0.2 for forests (vegetation coupled to the prevailing weather) to 0.8 to 0.9 for low crops (decoupled from the prevailing weather), and it decreases with increasing r_c (water shortage) as illustrated in Figure 2, where aerodynamic resistances for different crop types were selected according to McNaughton and Jarvis (1983).

Stomata adjust their resistance in such a way that the transpiration rate becomes more stable than atmospheric variations. This can be observed both in time and space. For instance, in a large irrigated field subjected to advection, stomatal resistance decreases with the distance from the leading edge in response to decreasing gradient in vapor pressure deficit (VPD), while transpiration keeps a more constant value along the transept (Davenport and Hudson, 1967; Itier et al., 1994; Brunet et al., 1994).

Thus, the annual ET from a high and rough stand can be higher than ET from a well irrigated grass (Moore et al., 1976; McNaughton and Black, 1973; Stewart, 1977, followed by many others) or much lower (Berbigier et al., 1996), depending on the precipitation frequency and environmental conditions. In low crops, the variability is restricted because the limiting factor for ET is not as dependent upon the occurrence of precipitation or advection as it is in high crops. One of the advantages of the choice of a low crop as a reference for ET practical applications - the well-known reference evapotranspiration (ETo) - derives from the relative independence of its ET from the stomatal behavior. Yet, as McNaughton and Jarvis (1991) suggested, increasing scale leads to an increase in the number of negative feedbacks that contribute to reduce the sensitivity of T to changes in stomatal closure. The differences in limiting factors for different stands can be seen as artificial because they are a consequence of the spatial scale at which experimental evidence is obtained (Avissar, 1993).

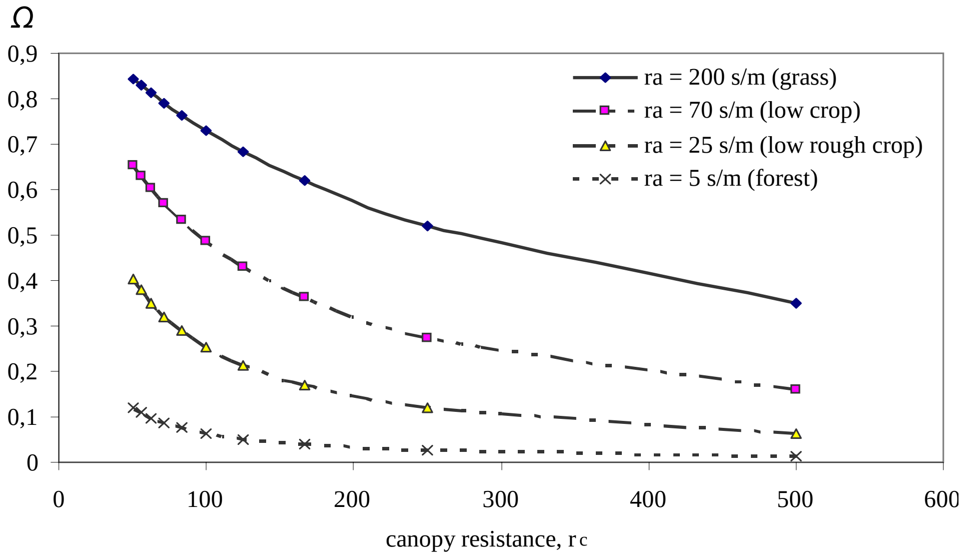

Figure 2: Modelled values of the omega factor (Ω) as a function of canopy resistance, for different values of aerodynamic resistance.

2.2 Methods to Measure ET in Stands of Woody Plants

The methods for ET measurement that have been currently used, in field conditions, can be classified in two main categories: hydrological and micrometeorological methods.

Hydrological methods are based on the application of the water balance equation, where all the variables are measured or estimated and ET is calculated. It can be applied at different spatial scales from the small lysimeter to the watershed. The temporal scale is dependent upon the spatial scale used. The use of lysimeters with woody crops is limited by the large dimensions required and by the inherent high cost, since heterogeneity between plants is often important. One single plant or a few plants usually cannot be considered representative of a stand, as indicated by experimental evidence when analysing individual tree behaviour using sap flow methods (Granier, 1987; David et al., 1996, among others). The use of the water balance equation at the canopy level is limited in trees by lack of accessibility to the deep root zone and the spatial heterogeneity of roots distribution. Furthermore, due to the poor measurement precision, it is not possible to follow ET on an hourly or even daily time scale which is needed for detailed analysis of plant behavior (Rose and Sharma, 1984; Rosenberg et al., 1983). Most applications of the water balance equation at the watershed scale require even larger time scales (Villagra et al., 1995).

For a temporal detailed analysis, micrometeorological methods are usually preferred. ET is measured from meteorological variables, observed with appropriate time interval (< 0,1 s to > 2 min) at one level (eddy covariance, EC) or two levels (based on flux-gradient relationships: Bowen ratio, aerodynamic or combinations) above the surface, using equations that describe the fluxes of water vapor in the atmosphere. Continuous data recording is necessary. These methods are applicable over large and homogeneous surfaces, in order to meet assumptions in the theory and avoid advection effects. The minimum required distance from the measurement point to the edge of the plot being measured depends upon the measurement height; it is common to consider roughly the value of 100:1 horizontal to vertical measurement height (Brutsaert, 1982), but foot-print analysis (Schuepp et al., 1990) provides more realistic fetch requirements. The measurement level depends on the plant height and on the small-scale anisotropy of the canopy. For instance, row crops with large open spaces between plants require measurements at a higher level, so that the relevant air properties at a certain horizontal level become homogenous by air mixing, as it rises. Sharma (1985), Monteith and Unsworth (1990), Jensen (1990), Rosenberg et al. (1983) and Jones et al. (1992) describe the general principles and conditions of application of these methods.

Above woody stands, the EC and the Bowen ratio methods are commonly used; aerodynamic methods or derivations are difficult or impossible to apply (Thom et al., 1975; Raupach, 1979), namely because of the very small gradients observed above these stands and the difficulty in finding appropriate functions to account for stability conditions. The Bowen ratio method should be applied with much caution whenever a large part of the radiation reaches the soil, as in many orchards, because the method supposes the same level for sensible and latent heat exchanges. The EC method, first described by Swinbank (1951), is often the only viable alternative. It is based on very fast measurements at one single level of vertical wind speed and either horizontal wind speed, temperature or humidity, according to the flux being measured: momentum, sensible or latent heat flux, respectively (see Baldocchi et al., 1988; Leuning and Moncrieff, 1990 and Kaimal and Finnigan, 1993, among others). Under certain circumstances (slopes, for instance), all components of wind velocity have to be measured in order to perform appropriate axis rotation. Developments of acquisition data systems and sensors in recent years have allowed its use in an increasing number of laboratories, but the accumulated information for woody species is so far limited, especially for long term data series.

2.3 Modeling ET

The ET measurements are used primarily for research purposes - for a better understanding of the physical and physiological process involved and for the evaluation of ET models. Evapotranspiration models of woody crops can promote a more efficient use of water at farm level where research methods are difficult to implement due to expensive equipment and specialized know-how. Furthermore, ET models provide estimations based on time-series meteorological data, usable for the statistical analysis necessary for the planning of irrigation infrastructures. As an example, a data set of estimated ET for 30 years can be analysed, using the total annual ET and the ET for the month of maximum consumption, allowing the development of a probability distribution function. According to the selected level of risk, it can be decided the annual amount of water necessary to replace ET and also the peak flow required, respectively in calculating the area to be irrigated and the capacities of water delivery systems.

When looking back to the history of the experimental tools and concepts about ET, we understand why the estimation of the maximum ET of a crop (ETc) has been approached through an empirical equation making use of the ETc of a well irrigated reference crop, the so called reference ET (ETo), and a crop coefficient (Kc), relating the ETc of a certain crop to ETo. An advantage of a reference crop with a value of Ω (Equation [1]) as high as possible (traditionally grass or alfalfa) is that its ETc is relatively independent of stomatal behaviour allowing ET estimates based on meteorological variables, for which historical records are available.

Based on this approach, many equations for the estimation of ETo have been developed and used, both empirically or more physically based, according to the available data and to the evolution of the knowledge on ET (references in Section 1). Due to the nature of the process, it is common to use equations based on currently available meteorological data. This ET estimation procedure (ETc = ETo × Kc) has provided good approximations for many applications but the answers are not adequate in all cases. Some of the limitations of this approach can be described as follows.

Firstly, it is well known that crop coefficients are not easily extrapolated because they are dependent upon cultural practices (distance between crop rows, soil cover, irrigation practices, etc.), especially when the crops do not completely cover the soil, as in many irrigated orchards. Allen et al. (1998) present an approach that takes this into account, as an improvement to the values proposed by Doorenbos and Pruitt (1977). However, using different independent methods, values of Kc lower than those suggested were measured in several row crops (Katerji et al., 1990; Ferreira, 1987; Ferreira et al., 1996; Paço et al., 2006; Silva et al., 2007).

Secondly, even if Kc is adequate and there is a good estimation of ETc, it is still necessary to solve the problem of calculating ET when the crop is stressed and actual water use (ETa) is below ETc (Figure 1). There is experimental evidence that, in some cases (for instance, in sandy soils), ET from well irrigated crops progressively decreases between irrigations (Itier et al., 1990) with average ETa being considerably less than ETc, as shown in Section 5. This deficiency can be accounted for by the introduction of a stress coefficient, defined as Ks = ETa/ETc, so that ETa = ETo × Kc × Ks. In some cases, a correction for Kc values could be considered, when those values were obtained by methods that did not allow a detailed temporal analysis (soil measurements, drainage lysimeters), as discussed later. Yet, if there is a moderate or intensive water stress due to water restrictions, e.g. for crop quality management or because of water shortage, the corresponding changes in ET are reflected by Ks. A reduction in Ks is mainly related to stomatal closure, expressed by r_C. If r_C is not available, it can be expressed as a function of other water stress related variables. As mentioned above, a well known example is the discussion by Denmead and Shaw (1962) of the relationships between the relative decrease of T and soil water depletion, expressed as increasingly negative soil water potential.

When estimating ET, a relationship has to be used that implicitly or explicitly includes the stomatal closure relative to stress, if any. Whenever a crop corresponds to low Ω coefficients (high and rough stands) the limiting factor for ET is stomatal conductance (if not the radiation input) and, as a consequence, the limitation mentioned above is even more critical. Using the words of Jones (1984), the relative insensitivity of ET to stomatal aperture variations (in low crops) has been extrapolated to inadequate situations.

Using simplistic assumptions, the reduction in ET, expressed as Ks, can be calculated as Ks = $[\Delta + \gamma\ (1+ r_{c,stress}/r_a)\ ] / [(\Delta + \gamma\ (1+ r_{c,irrig}/r_a)\ ]$. Figure 3 illustrates how the reduction on ET is relatively more important (lower Ks) for crops that tend to have lower aerodynamic resistances such as forests (same values as in Figure 2, for aerodynamic resistances: 200 to 5).

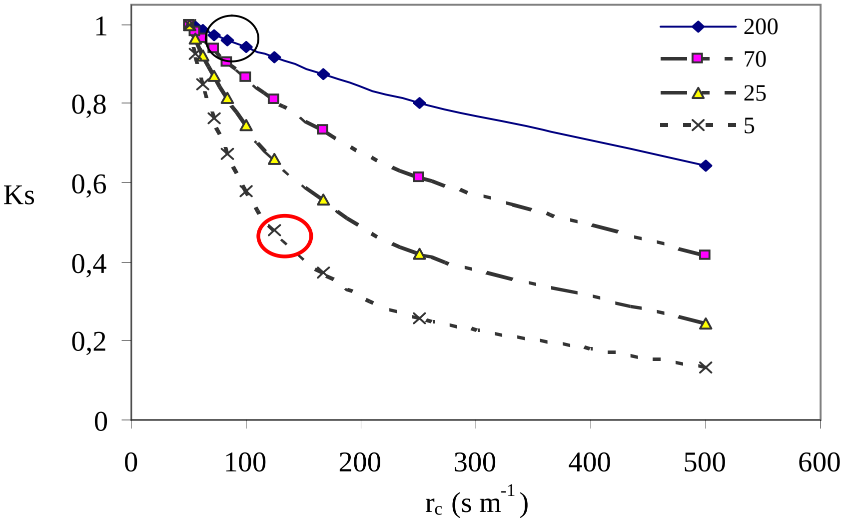

Figure 3: Stress coefficient in relation to canopy resistance r_c, for the same aerodynamic resistances of Figure 2: 200 s/m to 5 s/m, for stands with high to low Ω, respectively. The circles suggest that, for a low crop, canopy resistance tends to start from higher values (thin circle) and, for a forest, it eventually starts from lower values (thick circle), as different species can correspond to different ranges of r_c

Another approach (one-step) is the use of an ET model that directly provides ET estimations. The Penman-Monteith (PM) uni-layer or big-leaf model (Monteith, 1965) includes the stomatal resistance at the canopy level and the environmental variables in one single equation and has become the most used equation for ETa estimations, provided all the variables are known or can be estimated:

$$ET = [\Delta(Rn-G) + \rho\ c_p\ (e_s-e_a) / ra] / [(\Delta + \gamma\ (1+ rc/ ra)\ ] \qquad (2a)$$

where Rn is net radiation, G is the heat flux to the soil, ρ is air density, c_p is the specific heat of air at a constant pressure, e_a-e_d is the air vapor pressure deficit and the other symbols are defined in Equation [1]. Environmental variables should be measured above the canopy considered. Physical parameters and some of the variables can be calculated according to the equations described - for instance by Burman et al. (1983) and Allen et al. (1986).

The PM equation [2a] can be written in the same form as the Penman (Penman, 1948) equation [2b], replacing γ by γ‘, defined according to Monteith (1985) as $\gamma' = \gamma\ (1+ rc/ra)$:

$$ET = [\Delta(Rn\text{-}G) + \rho\, c_p\, (e_s\text{-}e_a) / r_a] / [\Delta + \gamma\,] \qquad (2b)$$

Using γ', the Ω coefficient can be written as:

$$\Omega = (\Delta+ \gamma)/(\Delta+ \gamma') = (\Delta + \gamma)/[\, \Delta+\gamma\, (1+ r_c/r_a)] \qquad (3)$$

If r_c/r_a is low, γ' is similar to γ, Ω close to 1 (low crops, under no stress) and the ET estimations using Penman or PM equations are similar, if environmental variables measured at the reference level are identical. If r_c/r_a is high, γ' is much higher than γ, Ω tends to zero (woody crops, in general, if not wet) and ET estimated with PM equation can be much smaller than the values from Penman equation (other inputs being equal).

One of the obstacles when using these models is to obtain reliable values of r_a. Penman (1948) suggested an empirical wind function, for average conditions. Whenever possible, the calculation of r_a should consider the conditions of instability during the day because the conductance in highly unstable conditions can increase by an order of magnitude in relation to the conditions of validity of the logarithmic wind profile (Thom and Oliver, 1977; Itier and Katerji, 1983). Furthermore, in literature there is no consistency on whether r_a includes the resistance of leaf boundary layers which can vary a lot within complex canopies, either with distance from soil (Ferreira et al., 1994) or due to shelter or directional effects (Daudet et al., 1998).

The stomatal behaviour in uni-layer ET models is expressed by the variable r_c (Equations [1], [2] and [4]). It is also called canopy resistance (Reifsnyder et al., 1991). In some cases it is directly derived from measurements with porometers but more often it is estimated using r_s models that can be empirical (Jarvis, 1976), semi-empirical as Ball et al. (1987) or modified – i.e. Ball- Berry (Leuning, 1990, 1995; Dewar, 2002) or even hybrid (e.g. Yu, 2004). Even if stomatal behaviour is not completely understood (e. g. revision by Zavala, 2004) some of these models, by integrating at least the effects of plant or soil water status, light intensity and air humidity/temperature, and often CO_2 concentration) can provide reasonable estimates. The up-scaling needed to obtain values at the canopy level is a key challenge when based on input variables.

ET is influenced by the aerodynamic and energy (radiation interception) characteristics of the canopy. Both have consequences on r_s because the leaves of layers with different environmental conditions have different values of r_s. As the relationship between ET and r_s is not linear, several multi-layer models have been proposed, in which total ET corresponds to the sum of ET from each one of the single layers sharing the radiation and momentum absorption and contributing differently to the total heat exchanges. The models described by Shuttleworth and Wallace, 1985; Lhomme, 1988a are some of the earlier well known examples. Following the comment by Roberts et al. (1993) it seems better to use multi-layer models whenever important gradients in the canopy are observed. In other conditions (Raupach and Finnigan, 1988; McNaughton and Jarvis, 1991) it seems better to use single-layer models that give very acceptable results, provided representative values of the canopy resistances are used (Lhomme, 1991). It is far more complicated to work with sparse canopies like some Mediterranean agro-forestry systems (*montado*) or highly anisotropic canopies (as some vineyards or very open orchards).

Remote sensing methodologies, using thermal infrared measurements, have recently been used to assess actual evapotranspiration of agricultural crops (Allen et al., 2007; Johnson et al., 2007; Tasumi and Allen, 2007), forests (e.g., Jones et al., 2004; Leuning et al., 2005), and riparian vegetation (e.g., Nagler et al., 2007), or to integrate different kinds of vegetated surfaces to provide water balance information on a basin scale (Bastiaanssen et al., 2005).Thermal infrared methods can also be applied to the detection of water stress (e.g., Jones at al., 2002; Falkenberg et al., 2007) or as a tool to estimate leaf area index (e.g., Xavier and Vettorazzi, 2004) or canopy cover (e.g., Wang et al., 2007). Either satellite or airborne measurements are usually used, with the latter having the advantage of not being limited to rigid large time intervals. Results of ET estimation from airborne imaging spectrometry for a *montado* system in Portugal were shown by Jones and Archer (2003).

3. EVAPOTRANSPIRATION COMPONENTS – MEASURING TRANSPIRATION

None of the ET measurement methods mentioned in the previous section allows differentiation between T and Es or can be applied in heterogeneous stands (natural landscapes, for instance), when a distinction between species is required. New opportunities for the estimation of T, typically the main component of ET, especially in arid environments, are offered by sap flow methods, usually based on correlated heat transport. These methods can be applied to investigate the responses of T to different treatments and also allow the estimation of water uptake from different root zones (as in Nadezhdina et al., 2007). The daily T of the canopy (or sap flow density per unit of ground area) can be obtained by up-scaling the measurements performed in an adequate number of individual plants of sap flow density (per unit of active xylem area) or sap flow per plant.

The thermal sap flow methods include (1) the heat-pulse methods (e.g. Cohen et al., 1981; Cohen et al., 1985; Swanson and Whitfield, 1981) where the velocity of convective heat transport is related with mass flow; (2) the method based on the cooling (in relation to a reference) of a single probe constantly heated, being the relative cooling related with sap flow density (Granier, 1985, 1987a and 1987b), (3) the heat-balance methods (e.g. Sakuratani, 1981; Valancogne and Nasr, 1989), where the convective term in the energy balance of a heated part of the stem is related with the volume of moving sap, with no need to measure the xylem area, (4) combinations of (2) and (3) as for instance in Cermák et al. (1973) or (5) the heat field deformation method (Nadezhdina and Cermák, 1999; Nadezhdina et al., 1998, 2007). Reviews on these methods can be found in Jones et al. (1988), Swanson (1994), Smith and Allen (1996), Valancogne and Granier (1997), Tatarinov et al., (2005) and Roberts (2007).

The sap flow methods have important advantages for measuring individual plant transpiration when compared to other methods. They are easily automated, allowing a continuous data record for long periods of time (Granier and Loustau, 1994; Smith and Allen, 1996). Continuous data series are particularly useful for the construction and validation of models. Sap flow methods have been widely applied, frequently together with the EC method for both forest studies (e.g., Loustau et al., 1996; Köstner et al., 1998a) and for orchards and vineyards (e.g., Green et al., 1989; Shackel et al., 1992; Weibel and de Vos, 1994;

Valancogne, 1995; Ferreira 1996b; Braun and Schmid, 1999), in order to determine the tree individual contribution to the total water vapor flux of the surface.

These methods have been compared to others for the water balance estimation such as as lysimeters (gravimetric measurements with plants in pots, as in Ameglio et al., 1993), eddy covariance (Ferreira et al.; 1997b, Berbigier et al.; 1996, Silvestre et al., 1999; Wilson et al., 2001) and also numerical modelling (Perämäki et al., 2001). Their performance has been validated, but they still need development and testing before becoming routine techniques for monitoring tree behavior and water consumption in the field. Due to the complexity of sap flow in woody plants, the application of heat dissipation sensors, though apparently simple, is not straight forward and still needs adaptation. For instance, the *Granier* method, with low cost sensors suited to large samplings used in many studies, when compared to other SF methods or with micrometeorological methods, showed good agreement in several situations (e.g. Köstner et al. 1992; Berbigier et al., 1996), but other studies showed underestimations (e.g. Lundblad et al., 2001: 50% in *Pinus sylvestris* and *Picea abies*; Wilson et al., 2001: 50 to 60% in deciduous forest, Ferreira et al., 1997a: 30% in peach orchard). The results presented in this Chapter confirm a clear underestimation for high fluxes when comparing to a relatively reliable reference, such as the EC method or weighing lysimeters. Underestimations were also observed by other researchers when using other sap flow methods (Baker and Nieber, 1989; Cohen at al., 1993; Weibel and de Vos, 1994; Khan and Ong, 1995; Tarara and Fergusen, 2001; Klnitenberg and Hans, 2004). These results indicate some uncertainty in the use of sap flow methods to quantify transpiration.

Because the research presented in next Section deals with the so-called *Granier* method applied in several stands, we are giving a brief description of the basic principle, with some indications on ways to overcome some of the problems identified - mainly the recorded underestimation.

The *Granier* method uses two probes with temperature sensors, which are radially inserted into the trunk. One of the probes, in an upper position along the vertical axis, is heated while the lower one is kept at the undisturbed stem temperature (reference temperature). The distance between probes prevents the heat applied in the upper probe from influencing the lower one. The temperature difference between the two probes is related to the flux index (k) by the following equation:

$$k = (\Delta T_{max} - \Delta T) / \Delta T \tag{4}$$

where ΔT is the temperature difference between probes and ΔT_{max} the maximum value for ΔT, occurring for null flux situations.

Sap flux density (u) is determined using k (Equation [4], based on calibrations to obtain the empirical parameters α and β for the equation:

$$u = 1/\alpha \; k^{\beta} \tag{5a}$$

This leads to a relationship initially assumed independent from species (Granier et al., 1990; Valancogne and Granier, 1997) written as (Granier, 1985):

$$u = 118.99 \times 10^{-6} \, k^{1.231} \tag{5b}$$

where u is expressed in m^3 m^{-2} s^{-1}. Sap flux F [m^3 s^{-1}] is determined from previous equations and from conducting area of the cross section, A [m^2] (Granier, 1987b): F = u A.

The ET estimate underestimations observed, mainly for sap high flows, motivated an analysis of heat dissipation process. A finite difference simulation model was used as a tool for simulating the heat field around the linear heater. With this model it was possible to visualise the heat fields for varying flux densities and to estimate the sensitivity to varying parameters such as wood thermal properties, heater power dissipation and distance between probes. In addition it contributed to the analysis of the algorithms used in converting sensor ΔT measurements to sap flow estimates (Thomsen and Ferreira, oral communication unpublished). The results obtained, while confirming the influence of varying wood properties on the parameters of the empirical equation [5a], could not explain the important underestimation obtained. Therefore an analysis of the saturation effects at very high flows still needs further investigation. This emphasizes the need to relate the SF data with data from a reliable independent method.

In addition, the influence of natural gradients (vertical thermal gradients in absence of heating) and the impact of trunk insulation were analysed. When the measurements were made close to the soil surface, it was not always possible to eliminate a peak by the middle of the morning followed by an apparent relative underestimation at midday when compared with the transpiration patterns obtained with other independent method. Experiments in chambers and open fields showed that the underestimation was linked to a positive temperature gradient (ΔT) between the two probes in absence of heating. Conversely a negative gradient leads to an overestimation of the sap flow density. In absence of any analytical solution, a pragmatic one was to use the difference between a heated ΔT sensor (two probes) and a non-heated one in order to obtain the corrected thermal gradient (Ferreira and Zitscher, 1996). When measurement is impossible in the same plant, an extrapolation based on physical parameters is suitable (orientation, irrigation events, meteorological variables).

The influence of the radial profile (variability of stem sap flow density in radial direction) on the interpretation of single point measurements at a specified depth was also considered. Corrections were made either directly, according to the method presented in Ferreira et al. (1998), or indirectly via equivalent statistical adjustment.

All the aspects mentioned were taken into account in the case studies presented in this chapter, with adaptations for each experimental situation. Besides, some lack of precision on hourly measurements (when assuming $SF \approx T$) can be related to the time lag between the water flow at the measurement point and the canopy transpiration (Senock and Ham, 1993; Loustau et al., 1996). This applies even to daily measurements as shown by David et al. (1997), when analysing the seasonal trend of time lag between sap flow and modelled T, for an *Eucalyptus globulus* stand, during a period of progressive drought.

With the Granier method, which presents operational and cost advantages, it is possible to sample multiple trees and to make long term inexpensive measurements. Provided minimum precautions and an underestimation correction based on temporary comparison with independent methods, it is possible to get reliable values of transpiration at the field level. The relationships between the values obtained from SF and EC methods (or SF and weighing lysimeters with individual plants) were used to refine T estimations. However, eddy covariance (EC) measures ET, not just T, so for comparison, soil evaporation (Es), when more than negligible, was measured and deduced from ET.

4. RELATING SAP FLOW WITH EDDY-COVARIANCE DATA – CASE STUDIES

This Section describes the attempt to join together the most useful characteristics of complementary methods. Several case-studies are presented, where EC was used to calibrate the data obtained by *Granier* sap flow and soil lysimeters (Es). The EC system measured sensible heat flux density (H) and latent heat flux density (LE), the latter corresponding to stand ET. In all cases, corrections for air density variation (according to Webb et al., 1980) and for UV radiation absorption by oxygen (according to Tanner et al., 1993) were performed. EC data were always selected according to fetch and footprint analysis (Schuepp et al., 1990) and validated through spectral analysis (Anderson et al., 1986) and energy balance equation closure (Brunet et al., 1995). The closure error of the energy balance, was used in its simplest form (Rn - G vs. H + LE). LE obtained is ET_{EC}. In the following, $T_{EC} = ET_{EC} – Es$. T_{EC} was compared to uncorrected SF data for the periods with both measurements. The relationship obtained allowed the estimation of long term T from SF data. Es, if any, was added to T to obtain long term ET. The experiments described in this Section were carried on for several woody crops and different locations in Portugal, between 1996 and 2004.

4.1 Vineyards

4.1.1 Experimental Sites

Two experimental plots were used. The first experiment (plot 1) took place at Tagus Valley (Central Portugal) near Santarém (latitude 39º 10’ N, longitude 8º 43’ W, elevation 5 m), Portugal. The climate, according Reis and Gonçalves (1981) is humid mesothermic with dry hot summer (Csa, Koppen classification), with a mean annual temperature of 16.2ºC, mean annual rainfall of 707 mm and ETo (Piche) of 1436 mm year^{-1}. The vineyard was planted in 1984 and the cultivar was “Trincadeira”, grafted in SO4, with a plant density of 3030 vines per ha (3 m x 1.1 m). The area was 24 ha, the fetch around 600 m. The soil was a deep clay sandy loam soil (Flm, according to FAO classification). There was no irrigation. The measurements were taken between floraison and maturity, during 1996 and 1997. Leaf area index, measured at veraison, was 2.39 and 1.96 in 1996 and 1997, respectively. Ground cover, based on shadowed areas near solar noon, was 28 %.

The second plot was located at Setúbal Peninsula (latitude 38º 35’ N, longitude 8º 49’ W, elevation 25 m), Portugal. The climate was similar to the first, with a mean annual temperature of 16,0ºC, mean annual rainfall of 746 mm and ETo 1407 mm year^{-1}. The vineyard, planted in 1990, was drip irrigated and the cultivar under study was “Syrah” grafted in 1103P, with a plant density of 2975 vines per ha (2.8 m x 1.2 m). The area was 216 ha and the fetch above 1000 m. The soil was sandy (ARh, according to FAO classification). The measurement period occurred between floraison and the end of the vegetative cycle. Leaf area index, measured only in 2002, was 1.32. Ground cover, based on shadowed areas near solar noon, was 18 %.

4.1.2 Measurements

Eddy covariance data for selected periods were collected using a 1-D sonic anemometer with a fine wire thermocouple and a krypton hygrometer (respectively, models CA27, 127 and KH20 from, Campbell Scientific, Inc. Logan, UT, EUA) in 1996 and 1997 and with a 3-D sonic anemometer and a krypton hygrometer (respectively, models CSAT3 and KH20 from, Campbell Scientific, Inc. Logan, UT, EUA) in 2001 and 2002. Rn and G were measured as described in 4.2.2.

SF was measured with *Granier* method (see Section 3.). The results shown, for the main plots, were obtained with sensors (UP GmbH, Landshut, Germany) installed in representative plants: 4 vines in 1996, 1997 and 2001 and in 6 vines in 2002. The probes (0.002 m diameter, 0.01 length) were inserted 0.1 m apart. Sap flow was calculated assuming that all sectional area was effective. This was verified with destructive measurements and also with the study of the radial flow profile, using the heat field deformation method. Corrections for the influence of natural thermal gradients in the trunk were made. Since there was a strong relationship between vine leaf area and SF for individual plants, vineyard SF was estimated using a four step procedure: (1) measurement of SF of individual vines, (2) determination of leaf area of these vines and calculation of SF on a leaf area basis, (3) determination of leaf area index (LAI) and (4) multiplication of stand LAI by SF per unit of leaf area. ETo was calculated according to Allen et al. (1998).

4.1.3 Results

Surface energy balance showed that the sum of measured latent and sensible heat accounted for more than 95% of the available energy (Figure 4) and therefore the data gathered with the EC method were considered valid for the purpose of the study. Evapotranspiration measured by the EC method was in the range 1.0 and 4.1 mm/day in plot 1 (1996 and 1997) and between 1.6 and 2.4 mm/day in 2001 and 2002 (plot 2).

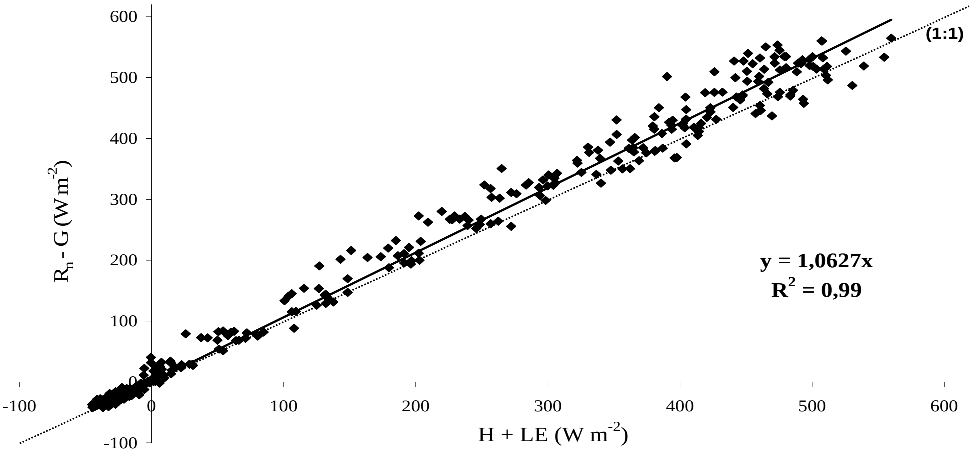

Figure 4: Energy balance closure at plot 2 (vineyard at Setúbal, Portugal) over a 10 days period (July 2002): sensible (H), latent (LE), soil heat (G) fluxes and net radiation (R_n)

Figure 5 shows the relationship between ET = T (EC data) and sap flow for half-hour fluxes obtained during periods of negligible soil evaporation (1996). Similar relationships were found in 1997 and in plot 2 (2001 and 2002). A strong underestimation for the highest flow rates was verified. Also, an evidence of some capacitance effects in the late afternoon was found. For higher fluxes, strong variations in T_{EC} occurred for small variations in SF. Therefore, it was difficult to adjust an equation to correct half-hourly fluxes.

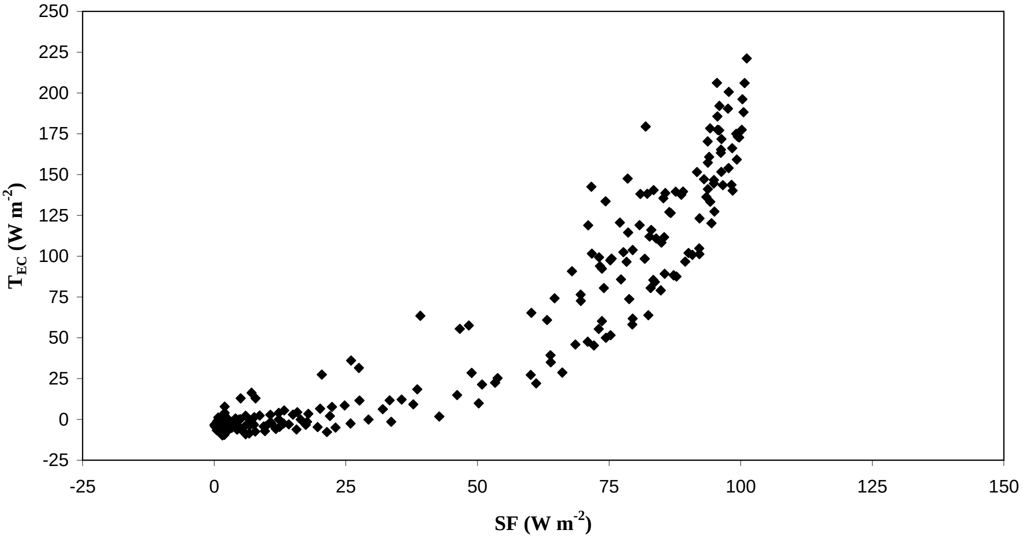

Figure 5: Relationship between SF estimated with the *Granier* method (original equation) and ET measured by EC method (half-hour fluxes) for periods of negligible soil evaporation (T ≈ ET). Plot 1 (vineyard, Portugal), 1996.

The reasons for underestimation of the Granier method can be related with wood anatomy, more critical for ring porous species, as grapevines. For ring porous, Cleawater et al. (1999) found a 45% underestimation of sap flow density.

For daily fluxes (Figure 6) and also for periods of negligible soil evaporation, a good relationship between SF (Granier method) and ET (eddy covariance data) was found ($T=1.1*T_{gr}^{1.5}$ with $r^2=0.84$) for cv. Trincadeira (V. Santarém, 1996, 1997) and Syrah (Setúbal, 2001, 2002). This relationship, valid for ET between 1 and 3 mm.day^{-1}, was confirmed with data obtained in pots, for the lower range, as described in Silvestre (2003). Being so, it could be applied in other situations, allowing corrections of SF measurements to obtain T, even in separate plots where EC could not be used. An application of this process was shown for small vineyard plots in slopes (Ferreira et al., 2004), enabling an interpretation of the effect of varying atmospheric demand (wind and radiation) and varying soil water content due to erosion effects, on total T and on T per unit of leaf area index (LAI).

Using this approach, T was estimated for plots 1 and 2, during longer periods (Figures 7, 8 and 10). In plot 1 (Figure 7), maximum T reached 4 mm day^{-1} in both years and, at maturity, when Summer drought normally imposes a moderate water stress, it reached values around 1 mm day^{-1}and 2 mm day^{-1}, in 1996 and 1997, respectively.

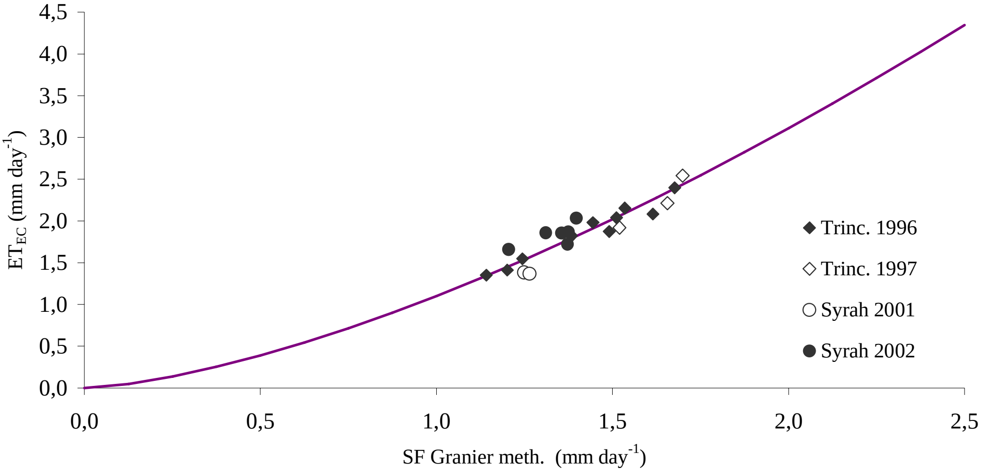

Figure 6: Relationship between daily fluxes from SF (original Granier equation) and EC methods, for negligible soil evaporation (ET_{EC}=T_{EC}) at V. Santarém (1996, 1997) and Setúbal (2001, 2002) vineyards, Portugal.

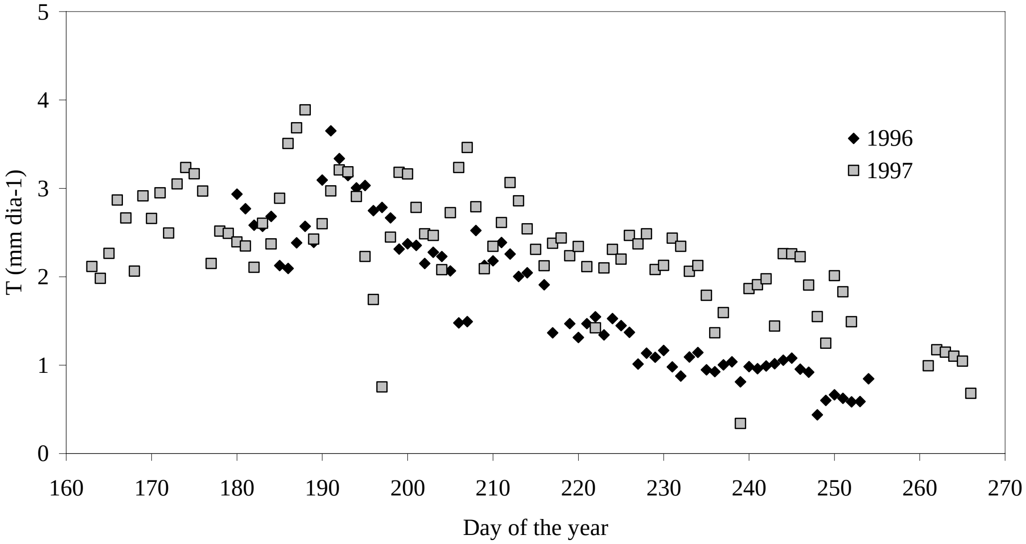

Figure 7: Seasonal evolution of transpiration in plot 1 (vineyard at V. Santarém, Portugal), during Spring-Summer 1996 and 1997.

Differences between the years were related with meteorological conditions verified: higher variations of T rates in 1997 due to the atypical meteorological conditions with important rain events during summer contributing to reduce water stress (Silvestre at al., 1999). This is shown by the seasonal trend of T/ETo (Figure 8), consistent with the evolution of water stress indicators (e.g. Figure 9), as predawn leaf water potential measured with a Scholander pressure chamber (see Section 5) and stomatal conductance (not shown). For the period of veraison (beginning of sugar accumulation) and maturity, the T/ETo decrease was less important in 1997, as a consequence of the precipitation occurred. T/ETo decreased earlier in 1996 and, at the end, was roughly half of the 1997 T/ETo values.

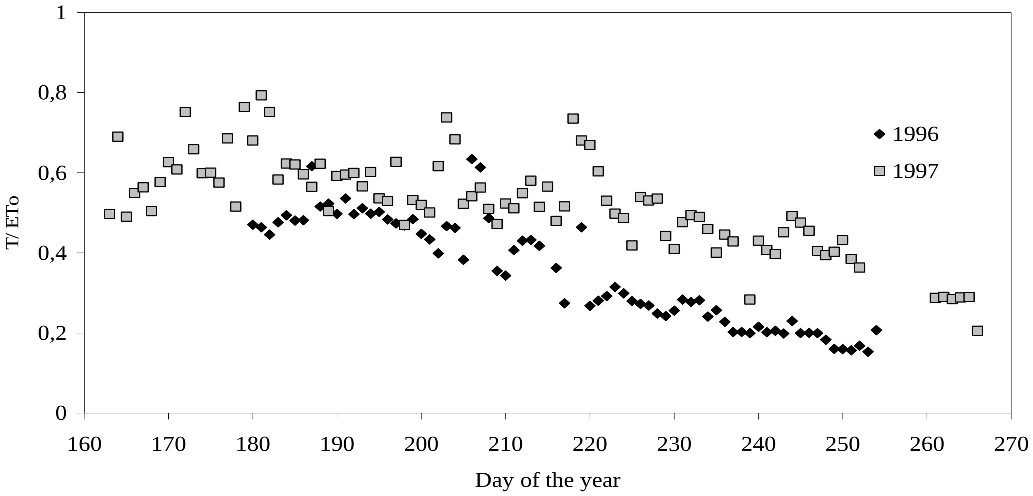

Figure 8: Seasonal evolution of the relation between transpiration (T) and reference evapotranspiration (ETo) in plot 1 (vineyard at V. Santarém, Portugal), during Spring-Summer 1996 and 1997.

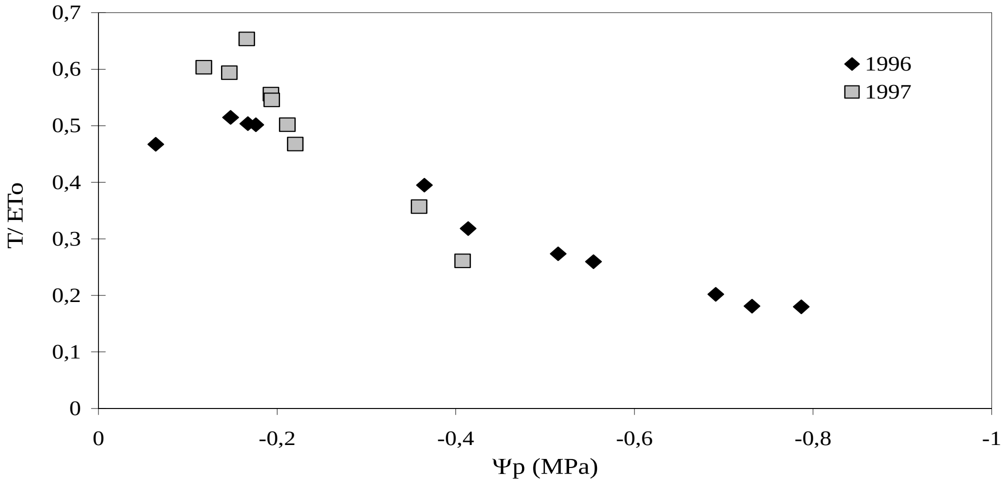

Figure 9: Relationship between T/ETo and predawn leaf water potential (Ψ_p) in plot 1 (vineyard at V. Santarém, Portugal - 1996 and 1997).

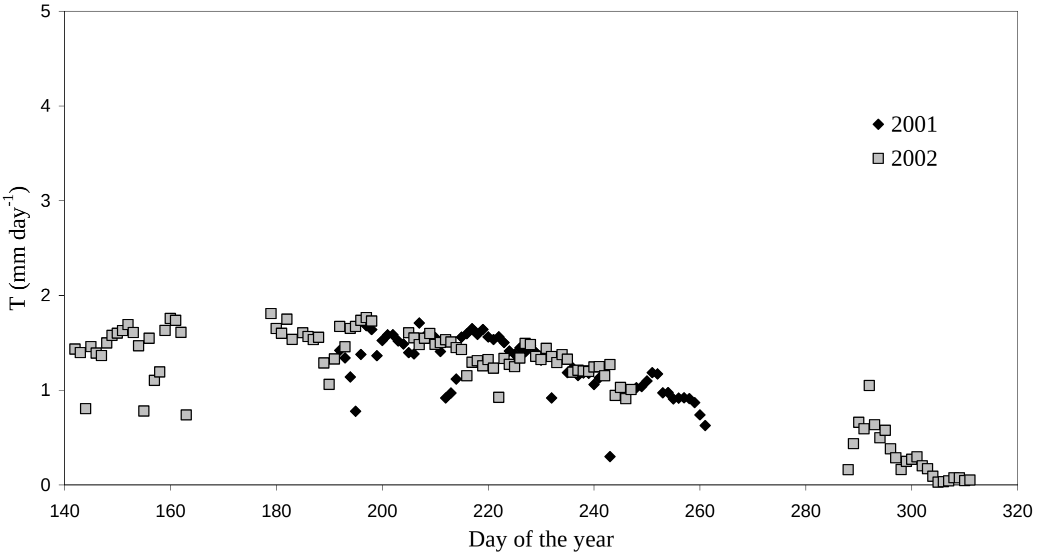

Figure 10: Seasonal evolution of transpiration in plot 2 (vineyard at Setúbal, Portugal), during 2001 and 2002.

Transpiration in plot 2 was similar in both years (Figure 10). T ranged from 1.8 to 1 mm day-1, from flowering to harvest. Maximum values of T were roughly one half of the values occurred in plot 1. There were differences in soil and cultivar, but the main reason for this difference was related with LAI. The decrease in transpiration rate during veraison to maturity was smoother than the one verified in 1996 (plot 1). This can be explained by deficit irrigation in plot 2, leading to less water stress.

In conclusion, this low cost approach provided reliable values of T for long periods. Considering the two experiments described and for average summer values for T ranging from about 3 mm/day to 1.7 mm/day, T/ETo were about 0.6 and 0.3 for plot 1 and plot 2, respectively. An intermediate result (0.5) was obtained for the vineyard in slopes, not irrigated, described in Ferreira et al. (2004).

Between middle June and late September the maximum recorded value for ET/ETo was 0.8. ET/ETo and T/ETo always decreased due to water stress, mainly the former, in spite of an increase on ETo in July and August. By the end of Summer ET/ETo was around 0.4 or below.

4.2 Kiwi Orchard

4.2.1 Experimental Sites

The ET of the kiwi (Actinidea deliciosa) was studied in a mature kiwifruit orchard irrigated daily with micro-sprinklers, in a loamy soil. The experiment took place during 2003 and 2004, in the region of Guimarães (41º31’ N, 8º27’ W, 145 m a.s.l.), NW Portugal. The climate of the site is Mediterranean with strong Atlantic influence. Average annual rainfall is 1500 mm concentrated during the colder months. Mean annual temperature is 14.1ºC. The plot was 11 ha and was slopping slightly towards the W. The orchard was planted in 1989, with a E-W row orientation and a spacing of 5 m × 5 m for female plants (var. Hayward) and

5 m × 20 m for male plants (var. Matua and Tomuri), planted in the rows between females, every 20 m (T – bar training system). Management of the orchard ground cover ensured that weeds covered a limited part of the soil surface, particularly between the rows. Below the canopy, the ground was maintained in a relatively bare condition because of shade. The bud break occurred in late March and harvesting was by early November. The orchard was daily irrigated at night (3.5 mm/day) with micro-sprinklers and additionally during the day, for the hotter periods.

4.2.2 Measurements

Evapotranspiration (ET) was measured using the eddy covariance (EC) method. Soil evaporation (Es) plus understory transpiration Tu (Esu = Es+Tu) was measured using a set of eight mini-lysimeters. Transpiration (T_{EC}) was calculated as the difference (ET-Esu) and compared with the results from SF approach.

The EC system included a 3-D sonic anemometer and a krypton hygrometer, models CSAT3 and KH2O, respectively (Campbell Scientific Inc., Logan, USA) mounted at the top of a 6 m tower. The fetch was estimated to be 350 m for the dominant wind direction. The measurements were running from 5th to 15th and from 18th to 25th August 2003 and from 3rd to 9th and 13th to 18th July 2004.

Net radiation (Rn) was measured at 6 m above the ground with a net radiometer (S-1 - Swissteco Instruments, Oberriet, Switzerland). Soil heat flux (G) measurements were made with 5 soil heat flux plates (HFT-3.1 - Rebs, Seattle, USA) placed at a depth of 5 cm and copper-constantan thermocouples at a depth of 2.5 cm, in a diagonal line between rows. Surface (0-5 cm) soil water content was measured to calculate soil heat capacity, using theta probe sensors, model ML2x (DELTA-T Devices, Cambridge, UK).

Esu was measured, using a set of 8 mini-lysimeters (ML), 15 cm diameter, 20 cm long, from the loss of mass of an undisturbed volume of soil placed accounting for the spatial variability caused by differences in incoming radiation and soil cover, properties and moisture. The MLs were weighted daily and the soil replaced every two days to avoid divergence from the surrounding soil due to changes in root extraction or transport of water within the subsoil.

SF measurements were made with 15 *Granier* sensors (UP GmbH, Germany): 12 installed on April 2003 (8 of 1 cm length and 4 of 2 cm length) and 3 on July 2004 (1 cm). The average trunk diameter was 10 cm. The length of the *Granier* sensors was based on the stem diameters and on observations of the mobility of a dyeing solution (safranin, toluidine blue and fast green) applied in the bottom section of a number of cut trunks, in a separate destructive experiment. According to this, probes were likely entirely in contact with the xylem area. It was considered that the entire trunk section below the bark was active for sap transport, with the exception of a small area with a diameter of 1.6 cm at the centre of the stem (Silva, 2002). To determine mass flow at the insertion level, u (Equation [5]) was multiplied by the area of the conducting xylem section per unit of ground area to obtain T (mm s^{-1}), in the following called T_{gr}.

In this study, the two sets of data for T were compared and an empirical correction adapted from Clearwater et al. (1999) was applied directly to ΔT (Equation [4]) obtaining ΔT corrected (ΔTc) as described in Silva et al. (2007). The correction empirically accounts (one step) for the effect of radial profile and the possible lack of contact with diffuse vessels in the xylem area.

4.2.3 Results and Discussion

The available energy (Rn-G) exceeds the convective fluxes (H+LE), during the EC measurement period, by 27% and 20% in 2003 and 2004, respectively, being within the limits often found for the closure error. Consequently, the convective fluxes obtained from turbulence measurements in the atmosphere are possibly underestimated (Tanner et al., 1985), the real latent heat flux being likely higher than the measured flux.

The verification of the original calibration equation for the *Granier* method was made during periods of simultaneous measurements of ET and Esu. DT symbols in Figure 11a represent the relationship between 30 minute values for k (Equation [4]) and sap flow density, obtained from ET-Esu. DT symbols in Figure 11b represent the relationship between daily total T, measured by the two approaches (*Granier* method and ET-Esu). Both for 30 minute and daily values, the sap flow obtained with the original *Granier* method was seriously underestimated when comparing to *T* obtained from ET-Esu. There is, however, a good correlation between the two (on a daily scale, $r^2 = 0.74$, Figure 4b).

Figures 11a and 11b (DTc) also show the same relationships after *ΔT* correction (DTc values). During the day, at noon, *T* still is underestimated (Figure 4a), although this can result from tissue capacitance or errors in T estimates (obtained from ET-Esu). For daily values, $r^2 = 0.87$.

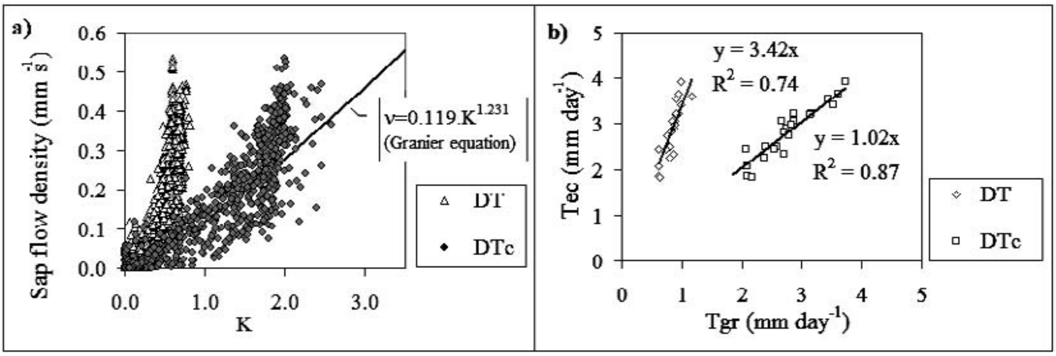

Figure 11: (a) Mean k values (Equation [4]) and sap flux density obtained from ET-Esu before the correction (DT) and after the correction (DTc) in ΔT (30 min values); (b) comparison between total daily T obtained by the *Granier* method (Tgr) and T obtained from ET-Esu (Tec), before (DT) and after (DTc) correction of ΔT (from Silva et al., 2007), kiwi orchard, Guimarães (Portugal).

Figure 12 shows daily totals for the *T* values obtained by the two approaches, after correction for T_{gr}, suggesting that the *Granier* method can provide good estimates of stand transpiration, using this correction.

After correction of ΔT, stand T was determined for the two vegetative periods (Figure 13). T increased from 1 to 3 mm/day, during Spring and early Summer, decreased progressively till November and ended abruptly after leaf fall, following a period of low air temperatures (late November).

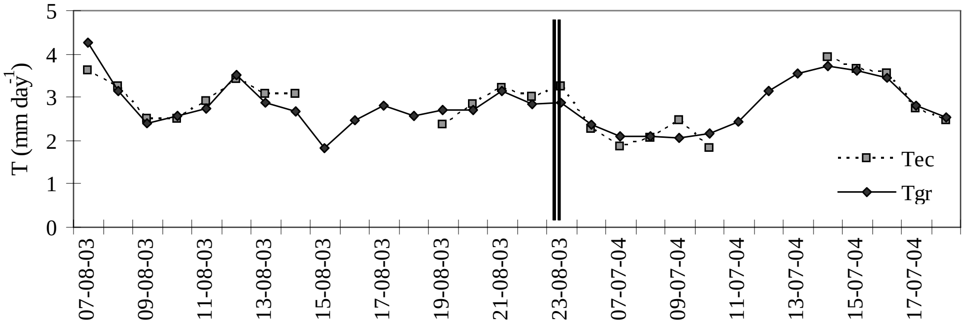

Figure 12: Daily T for kiwi (Portugal) using the *Granier* method, for the periods when the methods were combined in 2003 and 2004, separated by vertical line (T_{EC} transpiration obtained from ET-Esu, T_{gr} transpiration obtained by the *Granier* method but after correction of ΔT (Silva et al., 2007).

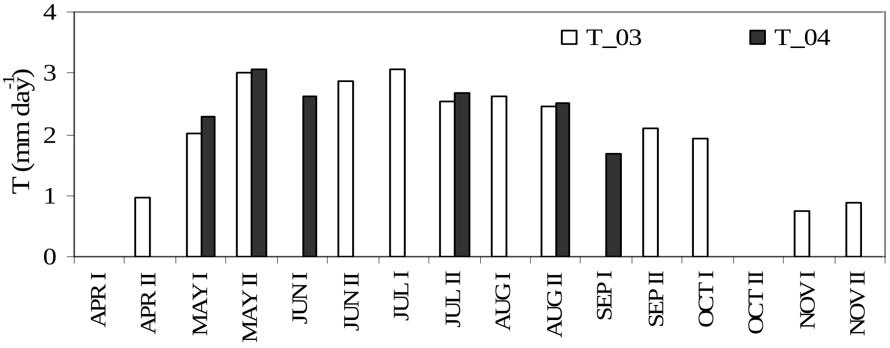

Figure 13: Two-weekly T for kiwi in 2003 and 2004 (Guimarães, Portugal), accessed by Granier method with correction.

ETo was calculated according to Allen et al. (1998) with data from nearby standard meteorological station.Taking the terminology of the dual crop coefficient approach (Allen et al., 1998), where Kc (Kc = Kcb + Ke)[1], the average basal crop coefficient, Kcb, increased from 0.4 in April to 0.7 from May to August and finally to 0.9 from September on[2] (details in Silva et al., 2007).

The average soil water evaporation coefficient (Ke) was 0.35 during July (2003) and 0.20 during August (2004). The resulting Kc for these periods was 0.9-1.0. The corresponded values suggested by Allen et al. (1998) are 1.05 for mid and for late season.

4.3 Peach Orchard

4.3.1 Experimental Site

The experimental work for the last case-study - peach (*Prunus persica* [L.] Batsch, cultivar Silver King) - took place in a 60 ha orchard near Montijo, Portugal (latitude 38º 42'

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[1] *Kc* – crop coefficient; *Ke* – soil evaporation coefficient; *Kcb* describes plant transpiration while *Ke* describes soil evaporation.

[2] According to predawn leaf water potential measurements, the plants were free of water restrictions at all times.

N, longitude 8º 48' W, elevation near 0), in the summers of 1998 and 1999. The region has cool, wet winters and hot, dry summers with average annual rainfall around 600 mm and mean air temperature around 16º C. The soil was sandy (an Arenosol, according to FAO classification). The trees were planted in 1996, at 5 x 2 m spacing and were drip irrigated (2000 emitters/ha with a flow rate of water of about 3.5 l/hour/emitter). Tallest branches reached 3 to 3.5 m. Ground cover, based on shadowed areas near solar noon, was 29% and the leaf area index was around 1.2 (1998) and 1.4 (1999). The orientation of rows was 13º NNE and dominating winds in the region blow between north and west directions.

4.3.2 Measurements

EC data were collected between the 21st June and the 4th September in 1998 and between the 9th July and the 11th August for 1999. The sensors used were a 1-D sonic anemometer with a fine wire thermocouple and a krypton hygrometer (respectively, models CA27, 127 and KH20 from, Campbell Scientific, Inc. Logan, UT, USA). Rn and G were measured as described in Paço (2003) and Paço et al. (2006).

Sap flow was measured from June to September using six sensors each year in the irrigated plot, with 1 cm (1998) or 2 cm length (1999). Corrections were explicitly made for the influence of temperature natural gradients in the trunk and to take into account the radial profile of sap flux distribution.

Soil evaporation (Es) was measured using nine cylindrical microlysimeters, 15 cm of internal diameter and 12 cm height, built and used as described in Daamen et al. (1993). Five lysimeters were located on the row between two trees and the other four between rows, near the limit of the vertical projection of the canopy. The soil cores were taken from a different place every day and the lysimeters reinstalled. Es was calculated by a weighted average in relation to the area represented by each lysimeter (with respect to distance from emitter) and results were cumulated for daily values of soil evaporation. Long term Es was obtained with specifically developed models, where Es is estimated from ETo but using an adjustment which is a function of the available energy at the soil surface (Conceição, et al., 2004). Reference and crop evapotranspiration (ETo and ETc) were computed according to Allen et al. (1998), using the dual crop coefficient approach for ETc.

4.3.3 Results and Discussion

As before, transpiration measured by the *Granier* method (T_{gr}) showed an important underestimation (over 80%) when compared to T obtained with EC method and soil evaporation measurements (ET_{EC}-Es). However, a strong correlation was found between *Granier* and EC data sets. The best relationships between ET_{EC}-Es and T_{gr} were: 1998: $ET_{EC} - Es = 1/(-2.19 + 3.77 \exp(-T_{gr})$ with $r^2 = 0.89$, for T_{gr} values between 0.2 and 0.4 mm/day) and 1999: $ET_{EC} - Es = 0.75/(-1.69 + 3.38 \exp(-T_{gr}+0.08)$ with $r^2 = 0.95$, for T_{gr} values roughly between 0.3 and 0.5 mm/day.

Differences between years may have been due to insufficient sampling or, eventually, to a possible misrepresentation of the shape of the radial profile of sap flow density, combined with the use of probes of different lengths. Regardless, the two relationships were respectively used to obtain long-term transpiration for the orchard under study for the two years which, combined with daily Es, provided ET from June to September. Mean daily ET during that period was close to 2 mm.

Crop coefficients, determined from ET_{EC} and ETo, varied between 0.3 and 1 (the highest values occurring in cloudy days), with a mean value close to 0.5. A previous study, developed in the same field site for a shorter period, in 1998 (Snyder et al., 2000), had shown already that the crop coefficient was around 0.5 on average. This value is much lower than the crop coefficient tabulated in Allen et al. (1998) for peach (0.9). An improved approach uses an adjustment for sparse vegetation and accounts for plant and soil contribution by using the dual crop coefficient method (Allen et al., 1998). The orchard had 1000 trees/ha, considered a medium density (Grappadelli and Sansavini, 1998), although it is higher than the mean density of Portuguese peach orchards (around 800 trees/ha). However, the low ground cover (29%), clearly justified the use of that adjustment for sparse vegetation. After such adjustment, the mean crop coefficient estimated for the period under study was close to 0.7. This value is closer to the measured crop coefficient ($\simeq$ 0.5) than the tabulated value, but still overestimates orchard water use. Daily ET calculated with the adjusted crop coefficient (ET_c) was over 35% higher than the measured ET. Other details can be found in Paço et al. (2006).

In conclusion, even in cases where a specific relationship T_{EC} and T_{gr} seems to be only of value for the specific conditions of the study, and independently of the importance of the underestimation, it was possible to obtain long term estimates using this approach. The condition is that both methods can be used simultaneously for a period of time sufficient to obtain the relationship EC vs. SF and lysimeters measurements can be performed to get Es.

5. PLANT WATER STRESS AND IRRIGATION SCHEDULING[3]

5.1 Water Stress Indicators

Water is more and more becoming a precious resource and deficit irrigation strategies, such as partial root zone drying (PRD), regulated deficit irrigation (RDI) and others, have been increasingly studied, in different contexts (e.g. Naor, 2006). The starting point to link water use and water stress indicators is the understanding and quantification of stomatal behavior. Quantifying r_S is important for ET estimation but also through its relationship with CO_2 assimilation rate, affected by water stress mainly due to stomatal closure (Schulze, 1986; Chaves, 1991; Jones, 1992). Besides its interpretative value, rs has a practical value in irrigation scheduling. For practical uses, its direct measure with porometers is not advisable, mainly due to the time required to obtain a representative value. Furthermore, r_S changes with rapid environmental changes and it is difficult to establish and use a critical value. Either bulk values for the canopy or the stomatal resistance of leaves in a selected position can be used.

Alternatives have been explored using other water-stress related variables, considered as a cause or/and a consequence of stomatal closure. One of the consequences of stomatal closure is the change in transpirational cooling of leaves resulting in greater leaf temperatures and possibly in greater thermal gradients above the canopy. These variables can be used directly or through more sophisticated approaches as, for instance, the Jackson index (Jackson, 1982). Even for low crops, the measurements require large plots, because of the

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[3] The discussion that follows, with a perspective of practical application, is mostly based on already published results.

instability of the observed values in advection conditions (Katerji et al., 1988). These difficulties become more pronounced on woody stands, owing to the higher turbulence in the canopies and consequent instability of leaf temperature.

Among the factors that determine the stomatal behaviour, the soil water potential (ψ_s) and soil water content (θ_s) have the advantage to be independent from diurnal atmospheric variations. The relationship between r_S and those variables is of special value if they reflect the average conditions in the roots zone. This is difficult to achieve with large root systems. The use of a few sensors in a representative point has been often the solution (Isbérie, 1992). However, it is difficult to extrapolate the location of the representative point to other soils, irrigation and root systems.

The relationship between the stomatal resistance and the leaf water potential (ψ_l) has also been broadly analysed because this variable was commonly considered as the non-climatic factor with more direct influence on stomatal behaviour. However, the large experimental evidence of a good relationship between those variables does not necessarily means a simple causality relation. Water-stress related variations on r_S can occur without correspondent changes on ψ_l. The stomatal closure is also explained by chemical signals, namely the ABA (Zhang et al., 1987; Davies and Mansfield, 1988; Hartung and Davies, 1989; Correia and Pereira, 1994), as a result of edaphic dryness, a hormonal and a hydraulic regulation simultaneously contributing to a better answer to water shortage.

For operational reasons, ψ_l is still commonly used to characterise the leaf water status influence on stomatal behaviour. Precaution is needed when making the interpretation of the experimental results on ψ_l, namely following rapid changes in spatial water application in relation to the roots distribution (Ameglio, 1998). For irrigation scheduling purposes a value of ψ_l representative of the day is selected.

The value of ψ_l measured at predawn, (ψ_p) corresponds to an equilibrium between the soil close to the roots and the plant, which is achieved after some hours without transpiration (night), except if there was not enough time to replenish the water storage in the plants organs (plants with big dimensions, under stress conditions). Other exceptions to this nocturnal equilibrium respect to positive transpiration fluxes during night, owing to the use of heat storage in the soil, air or vegetation. Night transpiration fluxes in close relationship with vapor pressure deficit were observed (not published) in the peach orchard described by Ferreira et al. (1996, 1997b). In most cases, ψ_p is used to represent an integration of soil conditions in the root zone, in respect to water.

The minimum ψ_l (1-2 h after solar noon, when T is more intensive) can also be used. Some results suggest that this choice is adequate when the plants tend to an aniso-hydric behaviour. If the plants of a certain species or cultivar behave as iso-hydric, they close stomata so effectively that they avoid an important decrease in noon ψ (Katerji et al., 1988; Valancogne, 1994). In this case, the difference in ψ_l between irrigated and stressed plants is expected to be higher in the morning that at noon and the use of predawn leaf water potential (ψ_p) can be recommended (Figure 14).

The minimum ψ_l is sometimes measured in previously covered leaves. In this leaves ψ_l equilibrates with the stem water potential (ψ_{stem}). According to McCutchan and Shackel (1992), ψ_{stem} is less disturbed by environmental conditions than minimum ψ_l and relates to soil water status in a more clear way. Several studies present encouraging results concerning the use of ψ_{stem} for orchard irrigation scheduling (e.g., McCutchan and Shackel, 1992; Shackel et al., 1998; Shackel et al., 2000a; Shackel et al., 2000b). Nevertheless, ψ_{stem} is influenced by day-to-day variation of VPD, making the establishment of critical thresholds for this indicator difficult (Marsal et al., 2002).

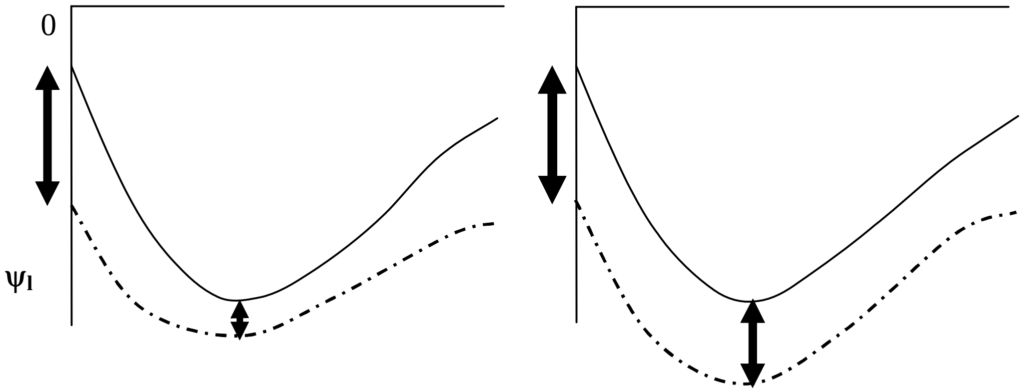

Figure 14: Schematic representation of the daily course of leaf water potential, (ψ_l) in a well irrigated plot (full lines) and stressed plot (dashed lines) for typical isohydric (left) and typical anisohydric (right) plants. The arrows indicate the ψ_l difference at predawn and at early afternoon (minimum ψ_l) suggesting that, for isohydric plants, it is easier to identify and quantify the water stress using predawn measurements.

The experiments about the role of ABA or other chemicals acting as hormonal regulators, led to a renewed attention to the water in the soil (*vd* Passioura, 1988; Kramer, 1988 and Boyer, 1989). However, due to experimental difficulties with the soil measurements, ψ_p presents advantages in representing the edaphic conditions, in both cases (iso-hydric or aniso-hydric behaviour). As the soil indicators, it has the advantage to be rather independent from diurnal variations.

The relationship between ψ_p and noon gs (=1/rs) of selected leaves (sunlit, for instance) often exhibits a change on slope and scattering for a specific value of ψ_p which can be used as a threshold value for irrigation scheduling: values about -0.4 MPa have been reported for tomato (Katerji et al., 1988), and -0.45 MPa for peach (Ferreira et al., 1996), separating a moderate from a more intensive water stress.

The use of relative conductance (gs of a stressed plot divided by gs of the well irrigated one) requires simultaneous measurements in two treatments but has the advantage of reducing the scattering due to inter-daily variation of air humidity, allowing a better identification of the critical value. In fact, air humidity around the leaves has a detectable influence on relationships with gs (Ferreira, 1993; Granier and Bréda, 1994; Ferreira et al., 1996) so care must be taken on its interpretation and extrapolation in respect to the size of the plots and inter-row advection. In a large stressed plot, where the air humidity close to the leaves is lower then in an irrigated plot, stomata react simultaneously to air and soil dryness, specially when stress is moderate and not intensive (Ferreira and Katerji, 1992). In a small stressed plot surrounded by irrigated areas, relative stomatal closure is likely to be mostly related to soil dryness, being easier to identify a threshold value. Even if the last situation is less representative of real situations, it corresponds to experiments performed in small areas.

Besides, it can be an experimental strategy to obtain critical values for practical applications, as suggested in Ferreira et al. (1996).

Another difficulty on comparing results obtained in different experiments comes from discrepancies on the value of g_S used to represent the canopy behaviour (leaves or layer where g_S is measured, period of the day when measurements are performed). It has been observed (e.g. Katerji et al., 1988) that the maximum difference between g_S on well-watered and on water-stressed plants occurs about noon, often about 1 h after solar midday. This specific value of g_S is a good indicator when relating stomatal behaviour with other variables, for irrigation scheduling purposes (e.g. Ferreira et al., 1996, Silvestre et al., 1999).

The variations in stem diameter, whose measurement can be easily automated, can also be used in scheduling irrigation, as a good relationship between stem diameter and water stress has been consistently observed (Kozlowski, 1972; Lansberg et al., 1976; Huguet, 1985; Garnier and Berger, 1986; Ameglio and Cruiziat, 1992). Stem diameter variations can be determined by other factors than water stress progression, as for example growth. Therefore, it is necessary to monitor simultaneously stressed and unstressed plants in order to establish reference values for the referred variables (e.g., RDTS). RDTS is the daily magnitude of trunk diameter (maximum minus minimum daily diameter) measured in stressed plants, divided by the correspondent value in well watered plants. A critical level can be determined and used directly, as a threshold value. However they can be highly variable, according to species and trunk dimensions, showing also a great variability among plants of the same population (Katerji, 1997).

5.2 Relative Transpiration

Relative T of stressed plants (RT) is the transpiration of these plants in relation to the transpiration of well-watered ones. Daily RT can be seen as an approximate integrated value of stomatal behaviour response to water stress. Due to SF methods, RT is easier to obtain than a correspondent value of r_S. Thus, during the last decade RT, as well as other variables whose measurement can be automated, have been studied for application in scheduling irrigation. The relationship between RT and water-stress indicators as the leaf water potential can also be a useful tool for ET modelling and water stress analysis.

When soil evaporation (Es) is very low compared to total ET, RT corresponds approximately to the coefficient Ks, in the practical equation ETa= ETo.Kc.Ks. If Es is high, Ks can be significantly different from RT and estimated or measured values of Es have to be taken into account in the Ks calculation.

The relationships described by Denmead and Shaw (1962), between ψ_s and RT, for different rates of ETc, correspond approximately to the relationship between RT and ψ_p, as in this last case, ψ_p is used to represent the soil water status. The consequence of this last approach seems to be that less scattering is expected between the lines correspondent to different ETc rates when using ψ_p, because the relationship ψ_p - RT is less dependent on the soil hydraulic conductivity, than the relationship ψ_s - RT.

According to Valancogne et al. (1996), one of the parameters in the equation ψ_p -RT can be calculated from the maximal observed value of ψ_p, for the system soil-crop in consideration. For a peach orchard in a sandy soil, in central Portugal the parameters of the relationship experimentally obtained: RT = 1.28 exp (1.474 ψ_p) with r^2=0.85 (Ferreira et al., 1997b) corresponded to those suggested by that methodology. The relationship RT-ψ_p can be directly used in irrigation scheduling, if ψ_p can be measured and a specific threshold value of RT is selected. The irrigation should take place when the measured value of ψ_p correspondent (from the equation) to the selected RT is attained. This relationship can also be useful in ET estimates, if ψ_p is measured, as it can give a day-by-day approximate value of Ks, allowing the determination of soil water depletion, as in the example given later (5.3).

The relationship between RDTS and RT can also provide the information on Ks needed for daily ET estimates. For instance, in a *Prunus persica* orchard, the value of 2 for RDTS corresponded to 65% of RT (and 50% of g_S), in relation to the well irrigated plot (Ferreira et al., 1996). The analysis of the possibilities of use of an indicator related with stem diameter variations is encouraged by the fact that it provides information for direct use, at the farm scale, that can be continuously recorded and connected to automated irrigation systems. However, results are often of difficult interpretation.

5.3. Stress Coefficients

The use of plant and soil-water-status indicators, thought useful to identify the moment for water applications does not provide information about the amounts needed to replenish the soil reservoir. Usually (see Allen at al, 1998) this is obtained by a daily soil water balance that, under non-restricted water application, that includes the estimation of cumulated ET from the previous irrigation (Σ ETa), provided ETo and Kc are available.

Under restricted water application, when a moderate water stress is imposed because of water shortage or for the sake of fruit quality, a lower critical threshold value for water applications is considered, being ETa less than ETc (Figure 1). As a consequence, another parameter or relationship has to be included in ETa estimations. The relationship between RT and the sum of ET since last irrigation (Σ ET) can be useful for this purpose. An example is presented in Figure 15, for a peach orchard: if Σ ET is calculated since last irrigation, 70% of RT is reached when soil water depletion (SWD) or Σ ET since last irrigation is about 25 mm. This relationship allows to calculate the ET, during stress periods, if ETo and Kc are available (estimating Es separately, if needed in order to obtain relative ET≈ Ks).

If the soil surface is dry most of the time, RT (cf. Figure 15) and relative ET (RET) of a stressed plot are similar. However, RET is different from Ks in case of non-daily irrigation, because it is calculated in relation to a plot, whose ET thought well irrigated is also decreasing between two successive irrigations. In the example of Figure 15, ET is simultaneously decreasing in both plots when Σ ET< 10 mm and Ks = 1. In the diagram of Figure 16a, the seasonal course of daily T, in a well irrigated plot and a stressed plot, as well as RT and Ks for the stressed plot, are shown during two stress cycles to illustrate the comment above.

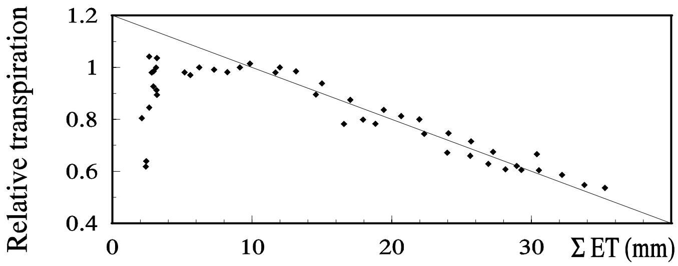

Figure 15: Relationship between RT (T of a stressed plot over the T of a well irrigated plot) and the total ET since last irrigation, observed in a peach orchard, in central Portugal (Ferreira et al., 1997b).

Figure 16b shows experimental results obtained for Ks - Σ ETa in two peach orchards, both with similar sandy soil, same region and ET rates, but different irrigation systems and frequency. The sharpest decrease was obtained in an orchard drip irrigated daily, as described in 4.3., while the line with lower slope is for an orchard with sprinkler irrigation, each 3-4 days as presented in Ferreira et al. (1997b). This difference will be later analysed.

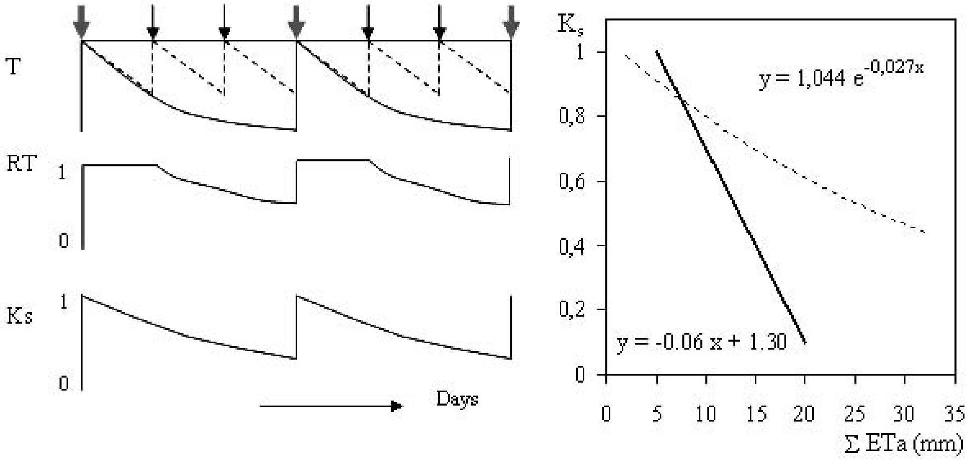

Figure 16 (a) Diagram of the evolution during a stress cycle of T in a well irrigated plot (dashed line) and stressed plot (black line), with RT and Ks in stressed plot. Black arrows indicate irrigation only in well irrigated plot and grey arrows irrigation in both plots. (b) Experimental relationship between Ks and ΣET in two experiments with peach orchards, similar soil, climate and ET rates, different irrigation systems and frequency: dashed line – sprinkler irrigation, as described in Ferreira et al. (1997b), full line - daily drip irrigation, as described in 4.3.

In fact, the detailed temporal analysis that micrometeorological methods allow, brings to light a decrease on ET very soon after irrigation, when working with high ET rates and sandy soils. In order to obtain Ks, the value of ET or T for the irrigated plot (used as a reference) is conveniently replaced by another reference: ETo.Kc (with Kc for the day after irrigation). In this case, the platform disappears and a relationship for Ks as the dashed line in Figure 1 is obtained (Figure 16a). This means that the platform effect was, in this case, an artefact due to the simultaneous decrease on ET in both treatments, during the first days, until the irrigated treatment received the second irrigation.

In the general case, if b is the value of Σ ET for which ET begins to decrease, a relationship can be established as: Ks =1, if Σ ET$\leq$ b; Ks = 1- η (Σ ET - b), if Σ ET > b. These relationships are able to give an answer to the *when* and *how much* and can be auto-sufficient in the sense that, if well adjusted, there is no need for *in loco* measurements, if a critical threshold value is known, in terms of Σ ET. An example is given in Table 1.

This relationship changes with the soil characteristics (Puech, 1972), the rate of ET (Denmead and Shaw, 1962) and the root patterns (Lee, 1973). In order to adapt to other soils or rooting depths, the value of Σ ET (soil water depletion) can be presented in terms of percentage of available water (AW): Ks =1, if Σ ET/AW $\leq$ b'; Ks = 1- η' (Σ ET/AW - b′). Parameters for a and b are shown in Ferreira and Valancogne (1997) for one tomato and one peach orchard experiments.

Table 1:– Simplified calculation of daily Ks for an hypothetic situation

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Day (i)	ETo mm	Kc	ETc =	Σ ETa (day i-1) + **ETa (day i-1)** ≈ Σ ETa (day i)	Ks =	ETa =	Σ ETa (day i) = ΣETa(day i-1) + ETa (day i)
			(2)*(3)	[(7)+(8)] day i-1	f (5)	(4)*(6)	(7) + (8)day i-1
1	6	0.75	4.5	4.5	1	4.5	4.5
2	6	0.75	4.5	4.5+4.5=9	1	4.5	9
3	6	0.75	4.5	9+4.5=13.5	0.9	4.05	13.05
4	6	0.75	4.5	17.10	0.85	3.83	16.88
5	6	0.75	4.5	20.71	0.8	3.60	20.48
6	6	0.75	4.5	24.08	0.7	3.15	23.63
7	6	0.75	4.5	26.78	0.65	2.93	26.56

The influence of root patterns is more difficult to take into account. The differences in the two lines shown in Figure 16b are interesting in that they are likely due to differences in root volume and density arising as a consequence of different wetted volumes and different irrigation frequencies: a high density and small volume for drip irrigated trees, while the others had a larger volume of soil explored by roots (mini-sprinklers) being used to moderate stress between irrigations. A poorer adaptation to water stress for the drip irrigated orchard apparently promoted a sharper decrease, which is consistent with the expected results from the analysis on limitations to water movement in soil.

The challenge, mainly for woody crops with deep roots, is to predict how these lines change. In a tentative to minimize this problem, the relationship can be adjusted from in loco measurements. For instance, the relationship Ks - ψ_p allows the construction of a double scale ψ_p and Ks (YY') for the relationship with Σ ETa (XX'). Let's suppose measurements of ψ_p and soil water depletion are performed in loco. If a certain ψ_p (= to an equivalent value of Ks) provides the value for ΣETa estimated by the first tentative relationship, it means it is well adjusted. If not, the line will be corrected according to the information obtained and the calculation of ΣET is verified with appropriate algorithms. Repeating the checks, a corrected relationship can be obtained.

6. CONCLUSION

Commonly used water requirement estimations for irrigation scheduling are not adequate under stressed conditions, being thought for complete water completion requirements. New trends are emerging, linked to the dramatically growing water scarcity problem. These trends are promoting deficit irrigation approaches that need new approaches for evaluating water needs under stressed conditions. It is the reason why a “plant approach” is also necessary, in order to estimate its real needs, up-scaling them to the total plant community (field, orchard, forest). Sap flow methods are among the most promising tools. With the Granier method (1985, 1987) that presents interesting operational and cost advantages it is possible to increase the number of trees for appropriate sampling and to make long term cheap measurements. The comparison between eddy covariance data sets (EC) and sap flow estimates (SF) provided experimental evidence of underestimation from SF measurements using the original Granier calibration equation, for all the conditions shown here. A correction allowed an adjustment of the sap flow measurements, obtaining transpiration data for the duration of the vegetative cycles. RT and stress coefficients could also be calculated from SF measurements and related with water stress indicators. Due to the complexity of the interpretation on water stress indicators, it appears that not only an isolated variable but its combination with simultaneous observations on water use and water stress indicators provide some answers useful for scheduling irrigation.

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Chapter 4

A SCIENTIFIC GUIDE FOR AGRICULTURAL WATER MANAGEMENT AND BIODIVERSITY CONSERVATION INSIDE THE NORTH AFRICAN OASIS

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ABSTRACT

In this chapter I am presenting a methodology and basic equations permitting to establish models to monitor water, nutrient and salt distribution in the oasis soil under different irrigation system, to determine the best oasis architecture for an efficient use of resources, to estimate the amount of water really needed by plants and the oasis productivity, to test the efficiency of irrigation and drainage network, to detect the eventual diseases that can attack the three vegetable stories, to predict plant species distribution, to search indicators for environmental planning and ecosystem risk analysis. Finally, a method to scale up or extrapolate results from one stand to all the region have been evoked and a case study have been presented.

1 INTRODUCTION

In North Africa region, the slogan raised by specialists is “A struggle in favour of oasis safeguard is a struggle against poverty” (Genetic Resources Action International 2002, 2003). In fact, the palm grove of those arid zones are maintained over a complicated water management system. The resources of water are limited which represent a real restraint menace in front of the durable development of the oasis and a menace for the irrigated plants (Association Network for Durable Development of Oases, 2001, 2002; Bob Brac 2002). The rural community of North Africa can not undertake them self in the debate about the biodiversity without discussed the constraints of water resources and soil erosion. The effect of climatic change in the region is characterised by long period of accentuated drought, and brief violent rainfall. Which have caused a decrease of the agriculture product yield, a degradation of the vegetation cover, an hydraulic and wind erosion of soils. Ameliorating the situation and realising a durable development need a scientific study that permits to establish equations describing the best arrangement of tolerant plants for an efficient use of resources and to develop ecosystem risk indicators for the oasis. These indicators can be linked to water resource (which is the key restricting factor for oasis ecosystems), soil resource and climate resource. We must know how the water and the nutrient are distributed inside every type of soil in the region, how they are absorbed by the roots of every species, the influence of local climatic parameter when calculating the drainage and irrigation networks, which irrigation technique to use without wasting water for every type of soil and kind of plants, how to realise effectively the drainage and the leaching, how to conserve the genetic biodiversity reserve inside the oasis?. The set of empirical and theoretical equations that we will present later for many case studies permit to elaborate models that give a response to the above requests, orient the farmer to a best use of rare resources, to realise his plan for an effectual agricultural water management inside the oasis and to safeguard the biodiversity of tolerant plant.

The work presented in this guide put on a scientific support that response to the challenges faced by traditional farmers in the region and proposals for follow up. It is a holder that help them when broaching negotiation at local, regional and international level. In fact, the fight against desertification and rational use of water is being a priority in the political development of North Africa region and worldwide. Also, institutions are tending towards valorizing traditional farming knowledge and products, which help maintain biological diversity (Association Network for Durable Development of Oases, 2001; Genetic Resources Action International 2002, 2003). We can’t forget that policy makers in charge of agricultural, water, and biodiversity management are moving in direction of including agriculturist and scientific researchers in fields of cultivation at all decision levels. Finally, the utility of my contribution is more clear when reminding that in North Africa, legislation concerning rational and long-term management of natural resources are enforced and any innovation involving natural resources or agricultural genetic diversity is a subject to an environmental impact assessment with the participation of local communities.

In this guide we will begin by reminding the tendency of the International and regional organizations specialized in nutritious security toward revive traditional know how in agricultural water management and local biodiversity conservation inside the oasis of North Africa. The problems, challenges and occupations of the farming communities working for the oasis ecosystem in North Africa will be discussed. To degage the practical value of my intervention I will resume the objectives of some projects executed or currently under execution in favor of the oasis of North Africa countries. After I will present a set of equations describing water, nutrient and salt distribution for different type of soil that characterized the arid zone of the region, under many irrigation systems used or can be used in the oasis and for every sorts of plant. The interaction soil-plant-atmosphere will be evoked later. Under the same heading we will formulate the solar radiative exchange and the heat and mass transfer inside the oasis. Those equations permits to estimate the biomass productivity of plants, to detect the eventual vegetation diseases by analyzing the leaves optical properties, to calculate the water really needed by plants by determining the evapotranspiration and finally to test the best arrangement between plant (species, density, orientation of rows…) to an efficient use of resources. To scale up a result done in a particular oasis to those of all the region we will present the useful methodology. It can be also used for the problem of extrapolation of data. The results of measurement studies done inside the oasis of the south of Tunisia and models established using the same basic equation will be detailed.

2 CHALLENGES OCCUPATIONS, PROBLEMS AND PROJECTS IN REALISATION FOR THE OASIS ECOSYSTEM IN NORTH AFRICA

2.1 Challenges

In North Africa, the majority of the oasis are constituted from private small gardens considered as familiar fishpond in which we found an important diversity of original plant: Date palm, olive, almond, fig, apricot, pomegranate, orange, vine, lucern, wheat, oats, barley, market gardening. Those particular agro-system are dispersed on the Sahara and they occupy more than 200 000 ha (Bob Brac 2002). The cited species can be found in the same field inside the oasis of the region. The oasis then can be considered as an agricultural genetic biodiversity reserve. By considering the local management of agricultural biodiversity, the region of North Africa is distinguishable by the fact that it shelters a rich flora of about 4000 vascular species in which 20 % are endemic (Bob Brac 2002). Those species are familiar and very adapted to arid climate. The Sahara of this region is an arid and very hot desert. The rainfall is les than 100 mm/year and the temperature can reach 50 °C in summer. The biodiversity of the region is judged to be a resources of species that resist to the drought and salinity (Bob Brac 2002). Those species, considered as Mediterranean, are very searched to ameliorate the agriculture product if installed in other places at worldwide level (Genetic Resources Action International 2003). The urbanisation of the oasis has appreciably participate in the evolution of the farming system. In fact, in the last two decades the oasis agriculture has been transformed from subsistence farming to market agriculture. The dates are the principals oasis source of revenue. It occupies the first rang of agriculture product exportations revenue for Algeria and it is the second for Tunisia. For the oasis the principal scourge is the bayous disease. The bayoud causes the decay several millions of trees (National Institute for Agricultural Research. Thème 1, 2005). The incidence of this disease is stressed for the economy of the small farmer. The best variety like Deglet Nour and Mejhoul are very susceptible to this disease. Elaborating models that permit to detect the eventual plant sickness and to control the vegetation sanitary at the scale of hour or day is primordial. I will give later the basic equation need for this purpose and a case study of a model established for the oasis of Tunisia (Sellami and Sifaoui, 1999). The preservation of local farming inside the zones of ancient cultivation and the protection of endemic species depend on upholding all the agrarian system inside the oasis. The aridity of the environment causes soil degradation, desertification and the risk of lost of agriculture genetic diversity. To be adapted to the resources diminution, the population exercises more pressure over the environment by intensifying the productive system and deforestation. The problem of non scientific and non controlled overexploitation of those spaces (oasis) judged as marginal and fragile exert a real menace that can cause social crisis on all the region. In fact there is a tendency towards the withdrawal of oasis and the rural depopulation (Bob Brac, 2002).

2.2 Occupations

After trying conservation management of genetic sources ex situ (a selection at laboratory level in order to ameliorate the product of plants) there is an orientation toward the conservation of genetic resources in situ in order to have plants more tolerant to local climatic conditions, to local techniques of agriculture water management and to natural diseases (Alain 2006; Bob Brac 2002, Genetic Resources Action International 2003). To conserve the environment in situ, many North African countries have installed many parks and protected surfaces over vast regions (Tassili Park Algeria). Those parks can not secure definitively the genetic resources because of there limits in space. In the arid zones the sources are dispersed over very large surface what makes it difficult to protect them, on both, technical and administrative sides. Added to the fact that generally there is expulsion of local population from those protected regions what generate conflicts with traditional farmers. This will influence badly later when to convince them to install those genetic resource either to try the amelioration or to reinforce the local and export markets. The best is to make an approach based on a participative management inside all the traditional oasis of the region. So every oasis will be a reserve of genetic resource and the farmer will act as a manager of the conservation operation (this Scientific guide will be very helpful to him). We will then produce a species tolerant to local conditions (salinity, solar radiation, hulmidity…) and adapted to traditional agricultural methods used. If we want to test a new technical, new nutrients, new quality of water, new system of production in the purpose to have a particular product that the market needed we can do that without any problems. The durable management of ecosystems is very difficult. To be done successfully a scientific studies and a formulation of problems must be realised. So every time we need to make experiments that are generally hard, difficult and time consuming we can apply those equations. Also, most of time we have to make a quickly decision to propose, accept or refuse a scenario of management, the set of equations that we will propose describe well the situation and give an estimation close to real values when thinking to establish models.

2.3 Agro-Pedological Constraints and Problems Linked to the Hydro-Agricultural Planning

The soils in the region are generally gypseous and saline. Depending on the dominance of the content of gypsum we can found the following class of soil: mineral brut, calci-magnesite, salsodic, sandy, gypseous, calcareous-gypseous, sandy-silty (Ben Mohamed June 2002; Bob Brac 2002; Genetic Resources Action International 2002; Kadri and Van Ranst, 2002; Minister of Environment and Durable Development, 2005; National Institute for Agricultural Research Thème 2, 2005). The soil has generally a fine texture with a high infiltration rate and feeble hydrous retention capacity. We can’t forget the effect of soil deposit and soil erosion linked to wind dynamic. Due to those physical characteristics, the irrigation gift must be given frequently in small doses, a kept drainage network is inevitable and the presence of organic substance is obligatory (Sécheresse Info, 2007). Basic equations to simulate and to model those parameters for every type of soil and every species will be given later. I must signal that for the majority of the oasis in the region we found at the soil surface a continued thick gypseous layer. This is owing to water table level close to the surface. Installing local varieties of date palms, fruit trees and market gardening tolerant to salinity is necessary (Genetic Resources Action International 2002, 2003). Also modelling the efficient level of water table to reach by applying a holding back technique for every species and sort of soil, in each season and phenological stage is highly useful for agricultural water management and for ameliorating the farming productivity inside the oasis. We will write out in the following parts many formulas that can help to elaborate models. The abundant use of salt water for irrigation and the water table ascent (hydromorphy) lead to soil degradation, poor harvest in quality and quantity for the three stories, net diminution of the date palm vigour (number of green palms by foot, height and diameter of the trunk). Those phenomenon are very observed in the oasis of the region (Bob Brac 2002). Found methods to estimate the exact amount of water that the plant really need at the level of hours by considering the local conditions and the water table rising help deeply in biodiversity and soil conservation. Also thinking to calculate the amount of water needed for leaching at a small scale in space and time is needed for the growing diversity project inside the oasis. The utility of an efficient drainage system computed according to plantation architecture, season and traditional know how is more lucid. The equation that we will give can be very helpful. An other enquiry that we can note easily for several oasis of North Africa is Problems linked to the hydro-agricultural planning. In fact, soil salinity and risk forecast have not been sufficiently considered when implanting new oasis. The hydro-pedological and arrangement aspects that influence the productivity (salinity, hydromorphy, fertilisation, agricultural labour, trimming, harvest…) were neglected during all the project steps: the conception, realisation and rehabilitation (Bob Brac, 2002; INRA, thème1, thème2, thème3, 2005; Sécheresse Info, 2007). In the case of the oasis where the water table and the irrigation water are distinguished by there high salinity, we must expect to study the interaction soil-plant-atmosphere by elaborating models in order to have a success in the hydro-agricultural planning and to degage increment of the productivity in the irrigated plots existing in the oasis. Case studies elaborated for the oasis of Tunisia with the fundamental equations will be flaunted (Sellami and Sifaoui, 1999, 2007).

2.4 Importance Attached to the Oasis of North Africa: Projects Realised or Currently Under Execution

The environmentalist at international level attach too much importance to the oasis of North Africa region. It is considered for them as a genetic reserve for biodiversity (Association Network for Durable Development of Oases. 2002; Bob Brac 2002; Genetic Resources Action International 2002, 2003). We must signal that, for a question of nutritious security, there is many projects and programmes of re-establishment and rehabilitation of the agro-ecological systems of the oasis initiated by public power like Non governmental Organisation(Associative Network for Durable Development of the Oasis, 2001) and International organisation (Alain, 2006; Global Environment Facility’s Small Grants Programme, 2006). Those initiatives encourage the dynamic management of local varieties that the farmers follow through the use of there farming traditional systems to surmount the local conditions constraints (soil, water, climate). The cultivators can then contribute in the selection of a diversified material adapted with different environmental conditions (resistance to parasites, tolerance to drought…). The field observation shows that the oasis farmers have conducted a selection and they have obtained tens of tolerant plants. There is an International tendency to recognize their right to be patented in order to encourage them (Bob Bac, 2002). A scientific guide as we are presenting in this work can be very helpful to all intervening. Inside the oasis of the North Africa the cultivators have common problems, challenges and occupations. In fact we can found problems linked to hydro-agricultural management, ways to minimise the consequences of irrigation with salt water, questions of irrigation water availability and methods for its rational use, constraints of soil pedology and agricultural management techniques for the oasis ecosystem. Also there is a regional request to elaborate a preventive manual for rehabilitation and valorisation actions inside the oasis (case of Rjim Maatoug oasis for Tunisia). This manual can be used to establish land-use plan and programme curriculum of water for the oasis in North Africa region. In this manual we must found a description, a diagnostic and exploitation conditions of the hydraulic systems inside the oasis. We must also propose many scenarios of agriculture water management inside every oasis. Also we must make a simulation of management and operation of irrigation and drainage networks. It is important to think to sewage system and storm water drainage, wastewater disposal and treatment, reuse of treated wastewater, protection of aquatic systems. Many specifications have been launched searching design offices to elaborate those manuals for many oasis in the region. Many ONG have started actions of rehabilitation of some oasis in North Africa, we can cite here:

Tunisia

1. The project of the development of the oasis of TAMEGHZA have been initiated by the Non-government Organization ASPHADT (Association pour la Promotion Humaine et l’Auto Développement à Tameghza). The project belongs to the Operational program on sustainable land management (land degradation, biodiversity) and it is on hand (Global Environment Facility’s Small Grants Programme, 2006). This project has as target the rehabilitation of the oasis by intensifying the second (fruit trees) and the third (market gardening) plantation stories, realising a programme of soil improvement and valorisation of water resources and oasis products with an approach participative and finally introducing the oasis in local and regional eco-tourism tour.
2. Agricultural cooperation agreement between Tunisia and Monaco principality to valorise the Oasis of Ras El Ain Nefta signed the 07/09/2006. It concerns the preservation of natural resources of this oasis, to contend against erosion and desertification and to create a space for ecological tourism. This cooperation is a part of the National plan to protect and valorise the traditional oasis of Tozeur in order to ameliorate its productivity (Investir en Tunisie news, 08/09/2006).
3. An agricultural study effectuated by the department of the environment for the Oasis of Nefzaoua. This work aimed to evaluate the crop production constraints at all levels (soil, plants, climate, social effect) and to propose scenarios of sustainable development (Kadri et al, 1997; Kadri A. and Van Ranst E., 1998, 2002).

4. A proposition to create new oasis in Regim Maatoug and Ibn Chabbat in the purpose to increase the agricultural productivity (Minister of Environment and Durable Development, Tunisia, 2005).
5. For the oasis of Chenini Gabes a rehabilitation action started by a French ONG (ex name is CIEPAD now it named CARI) since 1993/1994 (Associative Network for Durable Development of Oases, 2001). The objective is to put a vocational training and to give a technical support for the oasis farmers concerning the agro-ecology, restoring and fertilisation of soil, water economy, biodiversity, valorisation of oasis product, oasis tourism. This action is a decentralized cooperation backed up by the CCFD, general committee of Hérault and the MAE. This development project is now under the direction of a local ONG (ASOC: association de sauvegarde de l'oasis de Chénini).

Morocco

1. A project to reinforce the water natural resources and to valorise the biosphere reserve in the oasis of the south of Maroc (Alain, 2006). In this project they propose to rehabilitate the irrigation system and revive a traditional technique of drainage called "Khettarats" inside the palm grove of Ihandar (Ferkla El Oullia, Tinjdad, Errachidia, Maroc) (Association Oasis Ferkala for Environnement and heritage. 2006). Also this project has in view , to implant new oasis, to conserve those existing by valorising of oasis product, to remedy to soil salinity, running aground and erosion problems and to qualify the human potential living from the palm grove farming. The oasis valorisation program for the Morocco is supported by local and international organisations (Department of territory planning, l'ADS, l'ORMVA/TF, Water and forest Commissionership, l'INRA, the FFEM, the Principality de Monaco, le PNUD, the general council of l'Hérault et CARI association).
2. The Oasis Area of Morocco's Ziz Valley farming is based on traditional, intensified, polyculture systems (date palm, fruit trees, olive, alfalfa, cereals & vegetables) developed in response to high population density, limited irrigation and environmental factors (drought, salinity, and high temperature)(Alain, 2006). Many experts judge that the farmers of this oasis agroecosystem, by using their traditional knowledge, and in the sharing of improved methods they have succeed to improve and conserve *in situ* a genetic resource well adapted to local dry conditions (INRA, thème1, thème2, thème3, 2005).

Mauritania

A Program of an agricultural redress of the oasis after the long drought of the years seventy that the Mauritany undergone (Cristiana, 2003). The project points to increase the agriculture productivity inside the oasis (date palms, market gardening and fruit trees) by encouraging the local diversities, to contend the desertification, soil degradation and salinity and water table descent, to ameliorate the vital conditions of the oasis farmers and to reinforce the institutions concerned with services, planning and financing the farming communities. The target of the project is 11 000 farms inside the oasis (problem of parcelling) that nourish 230 000 persons. Those farms are concentrated on five regions from twelve that the country allows (Adrar, North of Tagant, Assaba, the two Hodhs).

By analysing the objectives of those projects we degage that the national, regional and international communities have the same challenges and occupation about the oasis. There is an agreement for the socio-economical part that the oasis play in the region of North Africa added to its leading role as a genetic biodiversity reserve at International level. We can say that there is many works to do because of the large area of the oasis and also because we have to study the impact on the agrarian-system of each activity realised inside every plot. So when extrapolating the results or scaling up to large zone we take the positive acts and avoid the negative ones. As we say "it's in the heat of battle that we learn." Our guide will be very helpful to them for both sides. Also this guide is fruitful when thinking to open out quantitative methods to understand environmental problems for the oasis ecosystem in North Africa region. These methods give the opportunity to establish and develop many indicators to study and analyse the oasis ecosystem risk at local and regional scales (Rita and Andrea, 2006; Wei-de LI et al, 2007).

3 EQUATIONS TO ELABORATE MODELS FOR AGRICULTURAL PLANNING INSIDE THE OASIS

As said in the previous paragraphs there is many problems in the oasis of the region that concern the methods adopted to manage the distribution of nutrients and water between plants. The soil of the oasis is isotropic, homogeneous and very porous. We found different kinds of market gardening, different types of fruit trees and many sorts of date palms in the same filed. Those canopies are arranged in different ways and directions. Many questions we must ask which nutrient to use to which type of plant in this kind of soil? How it is distributed and what is the quantity really absorbed by the roots of plants? If the amount of water used to irrigate represents really what the plants need? How the water infiltrates in this type of soil? How to quantify the water lost and how to distribute it between plants with an efficient manner for this special architecture? If the disposition of the existing species is the best for an efficient use of solar radiation in order to minimise evapotranspiration and maximise the photosynthetic process? Which kind and number of plants to add or remove from the existing oasis to ameliorate its architecture for a best use of resources? When renewing the traditional oasis, which species to install for date palms, fruit trees and market gardening, their densities and orientations to reach the best efficiency use of resources (nutrients, water, solar radiation)? How elaborating models to answer those questions only by introducing, physics properties of soil, quality and amount of water that we dispose and climatic parameters of the region (solar radiation, temperature, precipitation, wind velocity…)?

The set of equations that we will present now can be used to reply to those demands, to model and describe those phenomenon and to propose a solution for agricultural water management inside the oasis by only applying the inverse problem and the optimum control theories (Ralf, 1999).

3.1 Equations to Formulate the Management of Salt Leaching and Nutrient Uptake by Plants Inside the Oasis

In this part we will present the equations that describe the solute transport inside the soils for general cases. Those equations are very useful because they are concerned by very general conditions. So they can be applied to a vast region (oasis of north Africa) where we can found many type of soils, many boundaries, different climate…After we will give formulas and equations for particular situation. Quantifying and specifying the nutritive elements of plants for every type of soil and for every plant species is an important stage for agricultural management inside the oasis. Also searching indicators for an efficient use of nutrient is very helpful.

3.1.1 Equations Describing Solute Transport Inside the Soil

To simulate the transport of a non-interacting solute in the soil during non-steady infiltration, the effects of convection, ionic diffusion and mechanical dispersion must be investigated (Bresler 1973; Hamdy, A. and Choukr-allah, R. 2002).The one-dimensional solute transport is expressed by the convection-diffusion equation:

$$\frac{\partial(\omega C)}{\partial t} = -\left[\sigma_h(V) + \sigma_p(\omega)\right]\frac{\partial C}{\partial x} + V\omega C$$

This equation can also be represented as follow:

$$\Phi_{solut} = -\sigma(V,\omega)\frac{\partial C}{\partial x} + qC$$

Φ_{solut} is the total flux of solute;
C is the solute concentration of the soil solution
V is the average interstitial flow velocity
x is the flow direction co-ordinate;
$\sigma(V,\omega)$ is the combined diffusion-convection coefficient ($\sigma(V,\omega)=\sigma_h(V)+\sigma_p(\omega)$)
q is the volumetric flux of solution ($q = V\,\omega$)

The diffusion coefficient in a clay-water system is considered independent of the salt concentration but dependent on the water content only. Accordingly, it can be written as:

$$\sigma_p(\varpi) = \sigma_0 a \exp(b\varpi)$$

σ_p is the soil diffusion coefficient
σ_0 is Diffusion coefficient in a free water system
ω is the volumetric water content and
a and b are empirical constants characterising the soil

Solutes are transported at average velocity of the solution by convection, and in addition they are dispersed around the mean position of the front. Mathematically the mechanical dispersion may be treated as a diffusion process if one replaces the diffusion coefficient with the mechanical dispersion coefficient. The latter can be taken to be proportional to the first power of the average flow velocity. Under saturated and steady conditions we have:

$$\sigma_h (V) = |\lambda| V$$

σ_h is the mechanical dispersion coefficient
V is the average interstitial flow velocity
λ is an experimental constant depending on the characteristics of the porous medium

The convection flux generally causes hydrodynamic dispersion, an effect that stems from the microscopic non-uniformity of flow velocity in the various pores. Thus a sharp boundary between two miscible solutions becomes increasingly diffuse about the mean position of the front. The change of solute content within a soil is related to the difference in the mass flux of solute applied to, and leaving the soil profile. As many authors (Brandt, A. et al, 1971; Bresler E. et al, 1971; Thorburn et al., 1990), we can describe this by the following equation:

$$z\,\varpi_t \frac{dC_{soil,z}}{dt} = IC_i - LC_{soil,z}$$

$C_{soil,z}$ is the solute concentration of soil water, at depth z
t is the time
ω_t is the moisture content at which leaching occurs
I is the average infiltration rate
L is the leaching flux, past some soil depth z
C_i is the solute concentration of infiltrating water

We can then express the solute concentration of soil water at any time as follow:

$$\overline{C}^{t}_{soil} = \overline{C}^{t=0}_{soil} + \left[\left(\frac{IC_i}{LP}\right) - \overline{C}^{t=0}_{soil} \right] \left[1 - \exp\left(-\frac{(LP_n\, t)}{(\theta_t\, z)}\right) \right]$$

$\overline{C}^{t}_{soil}$ is the average value of $C^{t}_{soil,z}$ to depth z at instant t
$\overline{C}^{t=0}_{soil}$ is the value of $\overline{C}_{soil}$ at t = 0.

P_n a non-dimentional parameter ($P_n = \frac{C_{soil,z}}{\overline{C}_{soil}}$)

In the case of upward movement of solute into the root-zone from a shallow water table, $\overline{C}^{t}_{soil}$ increases continually with time, unless downward diffusion of solute equal or exceeds the upward solute flux. This formulation can be used for assessing the effect of irrigation on soil salinity because of its ability to interpret first of all the non-steady conditions and secondly, leaching flux value.

3.1.2 The Solute Movement in Soil in Presence of Plant Water Uptake in a Shallow Water Table Environment

This situation is preponderant for the oasis in the region. The following analysis and equations can be very helpful for agricultural and water management inside. The salts can move (Wagenet (1984)) in the soil by both the convective transport and the diffusion process. The importance of each of these process varies as the magnitude of water flux varies. When the water flux becomes smaller, the diffusion becomes relatively important. The convective and the diffusion fluxes can be combined to give a total flux (Brutsaert, 1982). To predict the solute movement in soil in presence of plant water uptake in a shallow water table environment, we can use the advection-dispersion equation. To solve the equation, the root zone can be divided into a series of layers. Then, for each layer we introduce a constant coefficient form with layer-averaged values for each property. In this case, the solute transport in the soil can be described as(Connel and Haverkamp (1996)):

$$\frac{\partial(C\omega)}{\partial t}=\frac{\partial}{\partial z}\left[\omega\sigma\frac{\partial C}{\partial z}\right]-\frac{\partial(qC)}{\partial z}+A_r(z,t)$$

C is the solute concentration,
ω is the unsaturated volumetric moisture content
σ is the dispersivity,
z is positive downwards
q is the soil moisture flux
A_r (z, t)is the root water uptake at position z and time t

If we assume that the solute and water uptake relationship can be approximated as vertical one-dimensional process we can write (Connel and Haverkamp (1996)):

$$\omega\frac{\partial C}{\partial t}=\frac{\partial}{\partial z}\left[\omega\sigma\frac{\partial C}{\partial z}\right]-q\frac{\partial C}{\partial z}+A_r(z,t)C$$

This equation can be easily solved if we use a transformation that permits to write it as follows:

$$\frac{\partial f}{\partial t}=\frac{\partial}{\partial Q}\left[\omega^2 D\frac{\partial f}{\partial Q}\right]-\left(q_0-\int_0^{x(Q)}A_r(\overline{x},t)d\overline{x}\right)\frac{\partial f}{\partial Q}+\frac{A_r(x,t)}{\omega}f$$

Q is a space transformation replacing the moisture flux, q(x, t) with the surface moisture flux q_0(t) and using the equality f(Q,t) = C(z,t) (Connel and Haverkamp (1996)).

Also we must signal that the solute movement in an isotropic soil during one-dimensional dispersion can be modelled analytically by assuming that both the velocity and the dispersion coefficient are constant with respect to time and space.

3.1.3 Solute Transport in a Tile-Drained Soil-Aquifer System

The governing equation for two-dimensional solute transport in unsaturated-saturated zones during steady state water flow that includes the effects of convective transport, dispersion, and linear equilibrium reactions between the solute and the porous medium on solute transport in a tile-drained soil aquifer system (Kamara et al., (1991)) is as follows:

$$\omega R_f \frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(\omega\sigma_{xx}\frac{\partial C}{\partial x} + \omega\sigma_{xy}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial y}(\omega\sigma_{yx}\frac{\partial C}{\partial x} + \omega\sigma_{yy}\frac{\partial C}{\partial y}) - \frac{\partial(q_x C)}{\partial x} - \frac{\partial(q_y C)}{\partial y} + \Phi(x,y,t)$$

C is the dissolved solute concentration,
R_f is the retardation factor,
ω is the volumetric water content (equal to the porosity in the saturated zone)
σ_{xx}, σ_{xy}, σ_{yx} and σ_{yy} are components of the dispersion coefficient tensor
q_x and q_y are the Darcian specific discharge components
$\Phi(x,y,t)$ is a source or a sink term

The retardation factor in the equation accounts for linear equilibrium interactions between the solute and porous medium and is given by

$$R_f = 1 + \frac{\rho K_d}{\omega}$$

ρ is the bulk density of the medium
K_d a solute distribution coefficient

The dispersion coefficients for a two-dimensional isotropic porous medium can be calculated as follow:

$$\sigma_{xx} = \sigma_L(\frac{q_x^2}{q^2}) + \sigma_T\left(\frac{q_y^2}{q^2}\right)$$

$$\sigma_{yy} = \sigma_T(\frac{q_x^2}{q^2}) + \sigma_L\left(\frac{q_y^2}{q^2}\right)$$

$$\sigma_{xy} = \sigma_{yx} = (\sigma_L - \sigma_T)(\frac{q_x q_y}{q^2})$$

$$\sigma_L = \frac{\alpha_L q}{\theta}$$

$$\sigma_T = \frac{\alpha_T q}{\theta}$$

α_L and α_T are the longitudinal and transverse dispersivities,

Those equations predicted reasonably well the two-dimensional solute transport in groundwater. They are very useful when modelling the rising water table for every season, kind of soil and sort of plant. So we can choose the efficient hydro-agricultural technique to apply and the tolerant plant to install.

3.2 Equations to Estimate Water Flow Distribution and Solute Transport in Soils under Irrigation Systems

When to propose ideas of management inside an agriculture field like the oasis, an important question to ask which irrigation technique to apply and if we can apply many techniques in the same field? To give a convincing respond we must formulate the water flow distribution and uptake.

3.2.1 Equation to use when Analysing Water Flux under any Irrigation System in Regions with Irregular Boundaries for Soil Properties

For a vast region (North Africa), a more generalised case must be studied: unsaturated, partially saturated and saturated porous media, regions with irregular boundaries for physical properties of soil, vegetation and climate, non-uniform soils having arbitrary degree of local anisotropy…To analyse the water flow under any agricultural system for those general cases in vertical, horizontal and three-dimensional plan, we can use the following equation (Feddes at al. 1978; Vogel and Hopmans 1992; Hamdy, A. and Choukr-allah, R. 2002):

$$C\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}+K_{xz}\frac{\partial h}{\partial z}+K_{xz}\right)+\frac{\partial}{\partial z}\left(K_{zx}\frac{\partial h}{\partial x}+K_{zz}\frac{\partial h}{\partial z}+K_{zz}\right)-A_r$$

h(x,z,t) is the soil water pressure head;
C(h) is the specific water capacity;
A_r is the sink term that represents the root uptake;
x and z (positive upwards) are spatial co-ordinates;
t is the time
θ is the volumetric water content
K_{ij} is the hydraulic conductivity in the directions i and j
i and j are the spatial co-ordinates x and z respectively

To describe the water flow, solute transport and water uptake by the roots we can as many authors consider a volume of soil on which the mass balance is applied and for which the concentration of solute is considered per a unit volume. We can then simulate seasonal variations of soil water distribution and salinity in irrigated soil subject to water extraction by the developing plant roots. The governing equation describing soil water flow in two dimensional saturated-unsaturated soil system is based on the assumptions that the air flow is negligible and water is the only fluid in the porous media and that the Darcy’s law is applicable. Also we assume that the soil-water pressure and the hydraulic conductivity are continuous functions of the soil water content.

3.2.2 Distribution of Water for Several Type of Soil under Trickle Irrigation

In the case when to install new oasis in large zone with several type of soil and for which we think to apply the trickle irrigation, the equations that govern the flow of water and non-interacting solutes in unsaturated soil system are given as follows (Bresler, 1973, 1975):

$$\frac{\partial \omega}{\partial t}=\frac{\partial}{\partial x_i}\left[\chi(\omega)K_{ij}\frac{\partial h(\omega)}{\partial x_i}+\chi(\omega)K_{i\mu}\right]$$

$$\frac{\partial (C\omega)}{\partial t}=\frac{\partial}{\partial x_i}\left[\sigma_{ij}\frac{\partial C}{\partial x_i}-q_i\,C\right]$$

x_i (i=1, 2, 3,) spatial co-ordinates (x_3 is the vertical);
χ is the relative hydraulic conductivity, between 0 and 1;
K_{ij} is the hydraulic conductivity tensor at saturation for the directions i and j
i =1, 2, 3 and j = 1, 2, 3;
ω is the volumetric water content ;
t is the time;
h is the pressure head;
σ_{ij} is the hydrodynamic dispersion coefficient;
q is the specific flux of the solution
C is the solute concentration in the soil solution

For an isotropic and homogeneous porous media the hydrodynamic dispersion coefficient will have the principals axes of dispersion oriented parallel and perpendicular to the mean direction of flow. Then the hydrodynamic dispersion coefficient can be defined as follows:

$$\sigma_{ij}=\frac{\lambda_T\left|V\right|\delta_{ij}+(\lambda_L-\lambda T)V_i\,V_j}{\left|V\right|+\sigma_P(\omega)}$$

λ_L is the longitudinal dispersivity of the medium;
λ_T is the transversal dispersivity of the medium;
δ_{ij} is Kronecker delta;
V_i is the component of the average interstitial solution velocity V in the direction i
$\sigma_p(\omega)$ is the soil diffusion coefficient

Many authors (Brandt et al. (1971); Bresler (1975); Lomen and Warrick (1976)) consider that in presence of a trickle source the water flow and solute transport can be treated as a two-dimensional problem using axi-symmetric cylindrical model where the cylindrical co-ordinates are considered.

If we assume, under irrigation from a trickle source, that the soil is stable, isotropic, and homogeneous porous medium(for the same oasis the soil has generally those characteristics), the differential equation that describe the flow of water in the system can be expressed in terms of diffusivity form as follows (Brandt et al (1971):

$$\frac{\partial\omega}{\partial t}=\frac{\partial}{\partial x}\left[\sigma(\omega)\frac{\partial\omega}{\partial X}\right]+\frac{\partial}{\partial Y}\left[\sigma(\omega)\frac{\partial\omega}{\partial Y}\right]+\frac{\partial}{\partial Z}\left[\sigma(\omega)\frac{\partial\omega}{\partial z}\right]-\frac{\partial[k(\omega)]}{\partial Z}$$

I must signal that the same equation can be used in the case of a single trickle nozzle or a number of nozzles spaced far enough to prevent overlapping and when a set of trickle sources are placed at equal and close distance so that their wetting fronts overlap after a short time of irrigation.

The one-dimensional transient soil moisture and solute in the vertical direction is described by the Richards equation as follows:

$$\frac{\partial\omega}{\partial t}=\frac{\partial}{\partial z}\left[K(\omega)\frac{\partial h}{\partial z}\right]-A(z,t)$$

ω is the volumetric water content;
t is the time;
z is the soil depth;
K(ω) is the hydraulic conductivity;
h is the soil hydraulic head pressure;
A(z,t) is a root-extraction term

The root extraction term, that intervene as a sink, is given by the following equation:

$$A(z,t)=\frac{\left[P_{root}+zR_{root})-P_{soil}(z,t)-P_{solute}(z,t)\right]\Gamma\ (z,t)K(\omega)}{\Delta x\Delta z}$$

P_{root} is the root water potential at the soil surface;
R_{root} is the root resistance term
$P_{soil}(z,t)$ is the soil matrix potential;
$P_{solute}(z,t)$ is the solute potential;
Γ(z,t) is the proportion of the total active roots in the depth increment Δz;
Δx is the distance between the plant roots and the point in the soil where P_{soil} and P_{solute} are measured.

3.2.3 Distribution of Water in Drip Irrigated Row Crop

We will give here simple expressions (Coelho and Or (1996) describing and predicting uptake patterns within the wetted soil volumes of drip-irrigated row crop. The simple expression for describing and predicting root uptake patterns within the wetted soil volume could improve drip irrigation design and management inside the new oasis. The background of those expressions is based on field observations, the introducing of a sink term into the Richards' equation to model the influence of water uptake on unsaturated flow regime and the use of Bivariate Gaussian density function as a parametric models.

The water distribution patterns around a dripper is influenced by: 1) the total value of applied water; 2) dripper flow rate, source configuration and initial and boundary conditions; 3) the soil physical properties and their distribution; 4) the root activity; 5) irrigation management.

By considering the co-ordinates system originate at the base of plant, we can made three different solutions for three different way of placing the drippers. We can then write the fraction of total uptake intensity occurring at any point inside the field by the following expressions.

If the surface drip line is on the crop row the maximum uptake intensity is given by the estimated mean deviation in the radial direction and by the estimated mode in the vertical direction we write:

$$I_u(r,z)=\frac{\alpha}{2\pi z\Delta_{st,rad}\Delta_{st,z}}\exp\left\{-\frac{1}{2}\left[\frac{(r-\Delta_{mean,rad})^2}{\Delta^2_{st,rad}}+\frac{(\ln z-\Delta_{mean,z})^2}{\Delta^2_{st,z}}\right]\right\}$$

If the dripper is buried close to the vertical centre of the active root zone, the maximum uptake in this case is expected to be between the surface and the dripper we have:

$$I_u(r,z)=\frac{\alpha}{2\pi\Delta_{st,rad}s_z}\exp\left\{-\frac{1}{2}\left[\frac{(r-\Delta_{mean,rad})^2}{\Delta^2_{st,rad}}+\frac{(z-\Delta_{mean,z})^2}{\Delta^2_{st,z}}\right]\right\}$$

If the surface and the subsurface drip lines are placed between plant rows. There is a large degree of asymmetry between the water source and plant roots and the correspondent expression is:

$$I_u(r,z)=\frac{\alpha}{2\pi rz\Delta_{st,rad}\Delta_{st,z}}\exp\left\{-\frac{1}{2}\left[\frac{(\ln r-\Delta_{mean,rad})^2}{\Delta^2_{st,rad}}+\frac{(\ln z-\Delta_{mean,z})^2}{\Delta^2_{st,z}}\right]\right\}$$

$I_u(r,z)$ is the fraction of total uptake intensity occurring at point (r,z),
$\Delta_{mean,rad}$ is the mean deviation, of uptake distribution in the radial direction,
$\Delta_{st,rad}$ is the standard deviation, of uptake distribution in the radial direction
$\Delta_{mean,z}$ is the mean deviation in the transformed co-ordinate, ln(z),
$\Delta_{st,z}$ is the standard deviation in the transformed co-ordinate, ln(z),
α is a scaling parameter

Those equations represent a simple parameterisation of complex information that could improve drip irrigation design and management.

3.2.4 Distribution of Water and Salt in Furrow Irrigated Soil

Inside the existing oasis of North Africa, a very preponderant technique of irrigation used is the irrigation by furrow. If we know some equations to model the water and solute distribution we can do an interesting plan for the arrangement of the oasis. The profile of water and salt in furrow irrigated soil can be deduced from the following equation (Noborio et al (1996):

$$\eta\zeta\frac{\omega}{\beta}\frac{\partial P_{mat}}{\partial t}+\frac{\partial\omega}{\partial t}=-\frac{\partial}{\partial z}\left(\frac{\Phi_{l,z}}{d_{soil,w}}+\frac{\Phi_{v,z}}{d_{pure,w}}\right)-\frac{\partial}{\partial y}\left(\frac{\Phi_{l,y}}{d_{soil,w}}+\frac{\Phi_{v,y}}{d_{pure,w}}\right)$$

P_{mat} is the potential matrix
η is zero for matrix potential $P_{mat} < 0$ and 1 for $P_{mat} > 0$
ζ is the specific storage
β is the soil porosity
$d_{soil,w}$ is the density of soil water
$d_{pure,w}$ is the density pure water
Φ_l represents flux density for the liquid phase
Φ_v represents flux density for the water vapour phase
z and y indicate axes of Cartesian co-ordinate system

To formulate the hydraulic conductivity of the liquid flux for a soil in an oasis where we utilise the irrigation by furrows we can consider a gain factor G that depends on the water content, soil type, water drainage. The hydraulic conductivity of the liquid flux can be given as follows (Hamdy, A. and Choukr-allah, R., 2002):

$$K_T=k\left(P^0_{osm}G\ \frac{1}{\tau^0}\frac{\partial\tau}{\partial T}+\mathrm{E}_{osm}\frac{\partial \mathrm{P}_{osm}}{\partial T}\right)$$

$$\frac{\partial P_{osm}}{\partial T}=\frac{R}{M_w}\ln(h_\pi)$$

G is the gain factor
τ is the surface tension of soil water
E_{osm} is the osmotic efficiency coefficient
P_{osm} is the osmotic potential
M_w is the molecular weight of water (0.018015 kg mol^{-1});
R is the universal gas constant (8.314 J mol^{-1} K^{-1});
T is the soil temperature (°K)

The following equation can suggested when reconsidering the salinity effects on the surface tension (Hamdy, A. and Choukr-allah, R. 2002):

$$C_{mol/kg}=\frac{C_{kg/kg}}{\left[M_{salt}(1-C_{kg/kg})\right]}$$

$C_{mol/kg}$ and $C_{kg/kg}$ are respectively the concentration in mol kg^{-1} and Kg Kg^{-1},
M_{salt} is the molecular weight of a soluble salt (=0.05844 kg mol^{-1} for NaCl)

4 METHODOLOGY AND APPLIED EQUATIONS TO USE FOR ACTIONS OF REHABILITATION INSIDE THE OASIS

The equations that I have presented above deal with the ways of distribution of water, salts and nutrients in the soil under different irrigation systems. Those irrigation systems are used or can be proposed to install when renewing the oasis. To calculate the irrigation scheme or network we must know the tolerant species to install, there densities and the amount of water really needed. Those information can be modeled for each type of soil as I will show later. The quantity of water that the irrigation network must bring inside the oasis is that necessary for plant consumption (net irrigation requirement for each sort of plant), water lost when distributed in the soil (evaporation and percolation) and water used for leaching (Brutsaert,1982). When fixed we can then propose the technique of irrigation to apply. It depends on the situation of the oasis, the geometry of the filed (form, length, width) and the socio-economic orientation. We can opt for a traditional technique by submersion for example, for a modern technique by aspersion or drip by drip and finally for a combination (Vaughn E. Hansen, 1980). We have to determine the number of nozzles to fix, diameter, length and number of pipes to utilize, the number and length of furrows to make, the surface of basin to realize. All those parameters can be calculated easily after determining the best and efficient oasis architecture.

4.1 Formulas to Analyze the Irrigation Scheme Efficiencies Inside the Oasis

4.1.1 Calculating Water Needed for Action of Salt Leaching

When irrigating with salt water, which is frequent for the oasis of the region, salts are left behind when water is taken up by plants or lost by evaporation. The consequence is that there is a gradual accumulation of these salts in the root zone as the season progresses and from one year to the next year. The level of salinity is affected by the salt content of irrigation water, by the method of irrigation, by soil drainage characteristics and by the prevailing cultural practices. The leaching requirement is the minimum amount of irrigation water that must percolate below the root zone in order to maintain soil salinity at a given level. This later must be maintained at a value for which the particular crop would not suffer an unacceptable reduction in yield level. The fraction of the total volume of irrigation water supplied, which should be used for the leaching of salts may be calculated by the following equation (Salisu et al, FAO 1992; Charles and Maurice 1981; Vaughn et al. 1980):

$$L=\frac{\Im_w}{\xi_{effi}[5\Im_{soil}-\Im_w]}$$

L: leaching requirement

$\Im_w$: electrical conductivity of irrigation water

$\Im_{soil}$: electrical conductivity of the soil saturation extract

ξ_{effi}: leaching efficiency

For an accumulation rate creating intolerable salts levels in the root zone during the season, leaching has to be done concurrently with irrigation. If not, leaching can be done before or after the season.

4.1.2 Formulas to Determine the Efficiency of Irrigation Network Inside the Oasis

The gross irrigation requirement is the water which must be available at the head of the scheme. It concerns the flow or discharge, which must be received by the irrigation network. It includes the amount of water really needed by plants, the quantity that can evaporate or percolate when distributed in the soil and the water to use for leaching. Hence more water should be applied than the net irrigation requirements in order to cater for the losses. It can be estimated from the following relationship (Charles and Maurice 1981; Vaughn et al. 1980):

$$q_{gir} = \frac{q_{nir}}{E_{sce}}$$

q_{gir} is the gross irrigation requirement
q_{nir} is the net irrigation requirements
E_{sce} is the irrigation scheme efficiency

The net irrigation requirement is the amount of water that the plant really need. It can be calculated and monitored at hour scale if we found a method to follow the farming transpiration inside the oasis. It is the subject of the coming paragraphs.

To determine irrigation scheme or network efficiency inside the oasis we must analyze the different levels at which water losses occur:

- at the level of the plant, when applying water to the soil
- at the level of the field, after water has entered the field
- at the level of the canals, during conveyance of the water between the main scheme inlet to the field offtake

The concept “efficiency” denotes that fraction of the total amount of water, which will benefit the field respectively the crop. Inside the oasis this efficiency must be calculated for all the component of an irrigation network. In fact, losses may occur due to deep percolation below the root zone and unwanted drainage (runoff) of water from the field. Deep percolation almost certainly will occur as it is nearly impossible to achieve uniform water distribution within a field and the correct rate of water application at the crop level. Field application efficiency is affected by the type of irrigation system, soil type and the skill of the farmer. It is defined as (Salisu et al FAO; Vaughn et al. 1980; Charles and Maurice 1981):

$$E_{fae}=\frac{W_{srz}}{W_{rfi}}$$

E_{fae} is the field application efficiency
W_{srz} is the water stored at root zone
W_{rfi}: is the water received at field inlet

The field canal efficiency is the efficiency of water conveyance in the canals within a sector, block or sub-unit inside the oasis. The unit may be the tertiary unit, but may also be the quarternary unit or even the subquarternary unit. The exact definition of the "field" unit depends on the definition of the scheme as wall as on irrigation organizational aspects (farmers groups, irrigation groups). The canals at this level are usually unlined and seepage losses along them are high. Field canal efficiency is defined as:

$$E_{fce}=\frac{W_{rfi}}{W_{rbi}}$$

E_{fce} is the field canal efficiency
W_{rfi} is the water received at field inlet
W_{rbi} is the water received at block inlet

The conveyance efficiency is the efficiency of water conveyance in the main canal system, which transports and conveys water from the scheme head works to the various sectors, blocks or sub-units. The scheme head works may be the intake at the river of the storage reservoir, but it may also be the head of a tertiary unit in case the tertiary unit is considered as the scheme. Depending on the length of the canals and the porosity of the bed (lined, unlined, soil type) seapage and evaporation can be high. Conveyance efficiency is defined as:

$$E_{coe}=\frac{W_{rbi}}{W_{rhw}}$$

E_{coe} is the Conveyance efficiency
W_{rbi} is water received at the block inlet
W_{rhw} is the water received at the head works

The distribution efficiency (E_{de}) is the efficiency of water conveyance and distribution between the head (inlet) of the scheme and the farm or field off take (turn-out/inlet). Covers all the losses inherent to the transport of the water and is a function of lay-out of the system, water transport type (canals, pipes), nature of the canal bed, soil type, maintenance, irrigation method and scheme management. The distribution efficiency is independent of crop type and crop stage it is expressed as follows:

$E_{de} = E_{coe} E_{fce}$

E_{de} is the distribution efficiency

The overall, scheme or project efficiency now can be defined as:

$$E_{sce} = \frac{W_{srz}}{W_{rhw}}$$

E_{sce} is the Scheme efficiency
W_{srz}: Water stored in the root zone
W_{rhw}: Water received at the head works

The scheme efficiency can also be calculated by:

$E_{sce} = E_{fae} E_{fce} E_{coe}$

Irrigation efficiencies formulas can be ameliorated and established for every oasis in the region through research by monitoring irrigation inside each field.

4.2 Formulas to Calculate a Drainage Network Inside the Oasis

Inside the oasis irrigation management is concerned with the management of the supply of water to the crops. The goal is to maintain optimum water supply so that neither water deficit nor water excess conditions are created. This is achieved by refilling the profile when soil moisture content has been depleted to a certain level and by draining excess water. To perform this management task effectively both the water requirements of the crop and the water storage characteristics of the soil have to be known. The drainage of the agriculture field consists at evacuate the surplus water from soils in order to prepare an optimal environment to plants roots and obtain the maximum crop product. A drainage network contains drains and collectors (primary, secondary, tertiary… it depends on the surface of the field to drain). The drains transport the water to the collectors those later conduct the water to the drainage channel after to the outlet (a lake, sea, plain). To determine the dimension of a drainage network we must calculate the optimal number of drains, their diameter, their clearance and their mean maximum length (the same for the collectors). Those parameters are deduced after calculating the distance between the drains and by using the geometry of the farming field (length and width). We will present here the important formulas used to calculate a drainage network. All the formulas established are function of the type of flow and the nature of soil. We will try to discuss all the cases.

For a permanent flow with rail cutting very permeable and when the drains repose directly over the impermeable substratum, to determine the mean distance between the drains in the case of permanent discharge, the most used formula is (Riadh Wasfi Assoufi, 2002):

$$\frac{I_r E^2}{4} = H^2 K \left(1 - 2R\,\frac{I}{K} \right) - \delta^2 K$$

The water height δ inside drains is generally neglected. The precedent formula becomes:

$$\frac{I_r E^2}{4} = H^2 K \left(1 - 2R\,\frac{I_r}{K} \right)$$

For a permanent flow and when the drains not attain the impermeable substratum, we propose this equation:

$$\frac{I_r E^2}{4} = \frac{K\ H_d^2}{\dfrac{1}{\left(1 + 2\dfrac{\delta\ \Delta}{H_d}\right)} + \dfrac{4\ H_d}{\Pi\ E}\ln\dfrac{\delta + \Delta}{\chi}}$$

In the case when the soil permeability is high we introduce the concept of equivalent height (δ’), and we can use the following formulas (Riadh Wasfi Assoufi, 2002):

$$\frac{I_r E^2}{4} = a\ K H_d^2 + 2\ K\ H_d\ \delta'$$

Where δ' is estimated from $$\frac{\delta'}{E} = \frac{\dfrac{\Delta}{E}}{1 + 4\ \dfrac{\Delta}{E}\left(1{,}1 + \dfrac{20\ H}{E} \right)}$$

And

$$\frac{I_r E^2}{4} = 2\ K\ H_d\ \delta'$$

Where is δ' is deduced from $$\frac{\delta'}{E} = \frac{\dfrac{\Delta}{E}}{\left(1 - \dfrac{\Delta}{E}\sqrt{2}\right)^2 + \left(\dfrac{8}{\Pi}\ \dfrac{\Delta}{E}\ \ln\ \dfrac{\Delta\sqrt{2}}{d} \right)}$$

d : Diameter of the drains
E : Space between drains (m)
H : Height of water table from the substratum (m)
I_r : Intensity of rain collected inside the drain (m/jour)
K : Soil hydraulic conductivity (m/j)
R : Coefficient equal to 0,25
$H_d = H - \Delta$
δ : Height of water inside the drain or the rail cutting (m)

Δ : Depth of the substratum under the drain m
χ : Wet perimeter (m)
δ': Equivalent height

After proposing equations that can serve as base to take decision about scenarios of management of the oasis soil, I will pass now to the vegetation component in order to study its interaction with the local environmental condition.

5 THEORETICAL BACKGROUND FOR MODELLING OASIS PRODUCTIVITY, MONITORING IRRIGATION GIFT AND CONSERVING BIODIVERSITY RESERVE

5.1 Application of the Radiative Transfer Equations Inside the Oasis

A vegetation canopy is a porous medium for the radiation. In more specific term it is considered as semi-transparent to solar radiation. At macro-scale, the plants intercept a part of the incoming radiation and diffuse (ascendant flux and descendant flux) the others. This is done by the participation of all the vegetation components (leaf, fruit, branch, trunk). At micro-scale (molecule level) the plant canopy absorb a share of the incident radiation and diffract (reflection and transmission) the rest. The farming canopy is accounted as participating environment for solar radiation. The oasis that is expanded over a vast region can be treated as homogeneous, participating and fluid medium where the solar radiation arrives at any point in all directions from the atmosphere. For such a medium the most used equation to describe the radiative transfer is (Lopez and Semel 1999; Kryzhevoi et al 2001):

$$\frac{d\Phi_{\Omega,\nu}(s,t)}{ds}+K_\nu(s,t)\Phi_{\Omega,\nu}(s,t)+\sigma_\nu(s,t)\Phi_{\Omega,\nu}(s,t)=\Phi_{j,\nu}(s,t)+\frac{1}{4\pi}\sigma_\nu(s,t)\int_{\Omega,=4\pi}P(\Omega,\rightarrow\Omega)\Phi_{\Omega,,\nu}(s,t)d\Omega,$$

$\Phi_{\Omega,\nu}$ is the spectral specific intensity of radiation
ν is the frequency of the radiation
Ω is the direction of propagation
s is the position
t is the time
K_ν is the spectral volumetric absorption
σ_ν is the spectral diffusion terms
$\Phi_{j,\nu}(s , t)$ the spectral emission terms
$P(\Omega)$ is the scattered radiation angular distribution function (phase function)

If we consider the solar radiation as source, the second term on the left represents the amount of solar radiation absorbed by the vegetation at any position s and any time t. It is analogues to the part of radiation intercepted. The third term on the left represents the radiation scattered out the oasis, it is equivalent to the solar radiation reflected by a vegetation layer or to that ascendant at any level of the oasis. The first term on the right express the spectral radiation emitted by the components of the oasis canopy (leaves, branch, trunk). The second term on the right show the scattering phenomenon inside the studied environment. For the oasis, an important part of the incident solar radiation will undergo a multiple re-diffusion to be arrested later by the vegetation elements. This radiation is putted on by the phase function. It can be considered as the radiation path or the optical depth.

If we assume some hypothesis related to the vegetation properties (homogeneous or pseudo-homogeneous), integrating the above equation from the entrance of the canopy to a point inside located by leaf area index, and after summing on all direction in space, we can express the solar radiation intensity by the following general expression (Lopez and Semel 1999; Kryzhevoi et al 2001):

$$\Phi_{\nu}=\int_{\Omega} \Phi_{0,\nu}(\theta,\varphi,t)\exp\left[-\int_{s=s_r}^{s} K_{\nu}(\bar{s},t)d\bar{s}\right]d\Omega d\nu$$

$\Phi_{0,\nu}(\Omega,t)$ is the radiation intensity at the top of the farming
$\Omega(\theta,\varphi)$ is the solid angle over which we have integrated for all possible directions (θ, φ) of the incoming radiation from the atmosphere.

This radiation must be absorbed or intercepted by a material point or a vegetation layer inside the oasis. Consequently, it represents the amount of spectral incident radiation really used by plants in photosynthetic activity (agricultural productivity and biomass production) or for transpiration (water consumption). Many empirical formulas exist in the literature to make the conversion. The knowledge of the radiative climate inside the oasis by modelling solar radiative transfer within is important for more than one practical implications. First, to evaluate intercropping performances, identification of environmental resources and different planting configurations may be tested when we think to renew the oasis. Second, models can be used when tools for studying mono-crops are inadequate or in order to infer radiation variables difficult to obtain from field measurements.

Analysing the solar radiative transfer inside a vegetation canopy, like the oasis(an intercropping system that has three production levels with different trimming) and determining the amount of all the radiation flux exchanged (intercepted flux, ascendant flux, descendant flux, absorbed flux, reflected flux, transmitted flux) at any point in space (vertical and horizontal) and at hour scale for every day and for all the seasons of the year is beneficial at all sides when considering the agricultural planning for the oasis of North Africa. In fact from estimating solar radiative flux we can deduce the amount of evapotranspiaration at any point of the oasis and at any height in the canopy so the quantity of water really needed by every species can be calculated (Monteith and Unsworth, 1990). Also determining the solar radiative flux reflected by the leaves of a plant inside a vegetation storey, by a layer in or by all the storey (market gardening, fruit trees, date palm) is very helpful to detect the eventual diseases that can attack the plants and to follow their photo-sanitary state (Grancher et al , 1993; Jones 1992). The reasoning is as follow: If we have a library of data for the reflectivity at the level of leaf, plant or layer of plants when the plant itself is in good health, this can be done by direct measurement in situ (photo satellite, radar in plane, portative radar) or ex situ (spectroscopy measurement). Simulating this reflectivity (ratio between the reflected solar radiation and the incident solar radiation) for each hour, every day and all the season of the year by a model that we can elaborate. Any difference recorded between the simulating values and those measured for a plant in good health, is an indicator for the photo-sanitary specialists to intervene. Finally the biomassproduction and the harvest of a farming can be deduced and forecasted by modelling the solar radiation absorbed or intercepted by every species, any farming storey and all the oasis. This is because the physiological properties of plants, their geometrical characteristics and their densities can be the input or the out put of the model. We will present now a set of applied equations for the oasis emerged from the radiative transfer equation cited above.

5.2 Reasoning to Model the Oasis Architecture for an Optimal Use of Resources

5.2.1 Formulating Solar Radiative Transfer Inside the Oasis

The global solar radiation is defined as the sum of direct solar radiation and diffuse solar radiation. The first is that arriving from the sun directly and received by a unity of surface perpendicular to the radiation. The second is that received from the vault of heaven by the surface. The celestial vault is chatted into solid angle sectors and hemispherical fluxes are computed by numerical integration of the directional fluxes. When traversed a vegetable layer, the global incident solar radiation at depth f inside the vegetation suffered a diminution that expresses the amount of solar radiation intercepted (Grancher et al., 1993; Berbigier and Bonnefond, 1995; Tournebize and Sinoquet, 1995.). This depth is located with the Leaf Area Index accounted from the top of the canopy. The subtraction is the combination of the removal from the direct radiation and from the diffuse radiation. The direct beam radiation received at depth f can be written like this:

$$\boldsymbol{\Phi_{rs} = \Phi_{rs,0}\,\mathbf{exp}\left[-\mu(\alpha, h_s)f\right]}$$

The diffuse radiation received from the celestial vault at depth f can be expressed by

$$\Phi_{rd} = \Phi_{rd,0}\exp\left[-\mu'(\alpha, h_r)f\right]$$

The global solar radiation received at the level f inside the oasis is:

$\Phi_{rg} = \Phi_{rs} + \Phi_{rd}$

$\mu(\alpha, h_s)$ extinction coefficient for the direct solar radiation

h_s is the sun elevation

f the leaf area index accounted from the top of the oasis

$\Phi_{rs,0}$ is the direct solar radiation received above the canopy

$\Phi_{rd,0}$ is the diffuse solar radiation received above the oasis

μ' (α, h_r) is the mean extinction coefficient for the diffuse flux density

α is the mean inclination of leaves on the trees

h_r the mean elevation of the radiation sector

After penetrates inside the vegetation, the incident beam will suffered a multiple rediffusion under the effect of leaves, trunks and branches. The beam will be scattered in upward and downward directions. The study of the multiple scattering process at the scale of all the canopy needed to elaborate the radiative balance for a thin canopy layer inside the vegetation and the use of some hypothesis. We can found the following 2nd order linear differential equations:

$$\frac{d^2\Phi_r^-}{df^2}+\left[R^2-\left(1-T^2\right)\right]\Phi_r^- = R\mu(\mu-1)\Phi_{rs,0}\exp(-\mu f)+R\mu'\left(\mu'-1\right)\Phi_{rd,0}\exp\left(-\mu' f\right)$$

$$\frac{d^2\Phi_r^+}{\times df^2}+\left[R^2-(1-T)^2\right]\Phi_r^+=-\mu\left[(1-T)T+R^2+\mu T\right]\Phi_{rs,0}\exp(-\mu f)+\mu'\left[(1-T)T+R^2+\mu' T\right]\Phi_{rd,0}\exp(-\mu' f)$$

Φ_r^+ is the ascendant rescattred flux density (upward direction).

Φ_r^- is the descendant rescattred flux density (downward direction)

T is the transmittance factor of the leaves or the plant in a stand

R is the reflectance factor of the leaves or the plant in a stand

μ'' is the extinction coefficient for rescattered radiation

The general analytical solutions of the 2nd order linear differential equations are:

$$\Phi_r^+(f) = X_1\exp(\eta f)+X_2\exp(-\eta f)+Y_1\Phi_{rs,0}\exp(-\mu f)+Y_2\Phi_{rd,0}\exp\left(-\mu' f\right)$$

$$\Phi_r^-(f) = X_3\exp(\eta f)+X_4\exp(-\eta f)+Y_3\Phi_{rs,0}\exp(-\mu f)+Y_4\Phi_{rd,0}\exp\left(-\mu' f\right)$$

Where η is expressed by $\eta = \left(\left(1-T^2\right)-R^2\right)^{\frac{1}{2}}$

The different variables ($X_1, X_2, X_3, X_4, Y_1, Y_2, Y_3, Y_4$) are expressed as a function of the optical properties of leaves (reflectivity, transmittivity, absorbtivity), as follow:

The Y terms are:

$$Y_1=\mu\frac{(1-T)T+R^2+\mu T}{\mu^2-m^2}; \qquad Y_2=-\mu'\frac{(1-T)T+R^2+\mu' T}{\mu'^2-m^2}; \qquad Y_3=\frac{R\mu(\mu-1)}{\mu^2-m^2};$$

$$Y_4=\frac{R\mu'(\mu'-1)}{\mu'^2-m^2}$$

The X terms are

$$X_1 = \frac{e^{-mF}\left[Y_1\,\Phi_{rs,0} + Y_2\,\Phi_{rd,0}\right](n-a) + e^{-\mu F}\left[-Y_3 + a\left(1+Y_1\right)\right]\Phi_{rs,0} + e^{-\mu' F}\left[-Y_4 + a\left(1+Y_2\right)\right]\Phi_{rd,0}}{e^{mF}\left(\frac{1}{n}-a\right) - e^{-mF}(n-a)}$$

$X_2 = -\left[X_1 + Y_1\,\Phi_{rs,0} + Y_2\,\Phi_{rd,0}\right]$; $X_3 = X_1/n$; $X_4 = X_2\ n$

The m et n variables are

$$m = \left[(1-T)^2 - R^2\right]^{0.5} \ ; \ n = \frac{-m+R+1-T}{m+R+1-T}$$

The arrest of solar radiation by the vegetation is expressed by the extinction coefficient as follows (Berbigier and Bonnefond, 1995):

$$\mu(\alpha,h_s) = \frac{2\cos h_s \sin\alpha \sin\left[\ \arccos\left(\frac{-tgh_s}{tg\alpha}\right)\ \right] - \cos\alpha \sin h_s\left(\pi - 2\arccos\left[\frac{-tgh_s}{tg\alpha}\right]\right)}{\pi \sin h_s}$$

Where α is the mean inclination of leaves that characterise also the orientation of a plant in a row and a row in a stand. Many authors have expressed the distribution of orientation by analytical formulas (Grancher et al , 1993). We can quote here:

The planophile distribution for a mean orientation of about 27°

$g(\alpha) = 2/\pi(\ 1 + \cos(2\ \alpha))$

The érectophile distribution for a mean orientation of about 63°

$g(\alpha) = 2/\pi(\ 1 - \cos(2\ \alpha))$

The plagiophile distribution for a mean orientation of about 45°

$g(\alpha) = 2/\pi(\ 1 - \cos(4\ \alpha))$

The extrèmophile distribution for a mean orientation of about 45°

$g(\alpha) = 2/\pi(\ 1 + \cos(4\ \alpha))$

The spherical distribution for a mean orientation of about 57°

$g(\alpha) = \sin(\alpha)$

The variable (h_s) in the extinction coefficient is the altitude of the radiation source (angular elevation above the horizon) which gives an indication on the hours of the day. Its presence in the expressions of the radiation flux point out their utility for monitoring, at the scale of hour, day and season, the farming productivity inside the oasis, the photo-sanitary state of plants and when testing a new species for a genetic biodiversity conservation in situ. In fact, the elevation of the radiation source is given by the following expression (Grancher et al., 1993):

$\mathrm{Sinh} = \sin L_{at} \sin D + \cos L_{at} \cos D \cos t$

D is the sun declination determined from

$D = 0.0066241+0.406149 \sin (0.0172029(T-81.95)) + 0.006675 \sin (0.0344057(T-42.85)) + 0.003009 \sin (0.0516086(T-21.42)) + 0.000149 \sin(0.0688115(T-17.57))$

L_{at} is the latitude of the location calculated by:

$\mathrm{Cos}(t_1) = - \mathrm{tg}(L)\mathrm{tg}(D)$

T: day number of the year

t : hour angle of the sun (angular distance from the South, 1 hours = 15°)

t_1 is the half of the astronomic day duration

From the expressions of the radiative flux we remark easily that they are expressed as function of the physiologic properties of every sort of plant, the geometrical characteristics of vegetation, plant densities and time. In fact the optical properties (reflectivity, transmittivity, absorbtivity) for a leaf, a plant or all the stand of plants, due to the re-diffusion phenomenon of solar radiation, depend on the state of the leaves surface, the disposition between leaves, branch and trunk for the same plant, its geometrical form, its position in the field and the orientation of row. The distinction of a type of vegetation from the other in our calculus is net when I remind that molecules arrangement for a kind of plant differs from that of an other and the optical properties belongs to the level of molecular diffraction. So the analysis of the optical properties gives indication about the sort of plant. Also, the reflectance ratio is deemed the photochemical reflectance index, and it is linearly related to the degree of down-regulation. Applying the technique to monitoring whole canopies requires modelling of the down-regulation process and of the propagation of radiation in the canopy. The geometrical or architectural effect is lucid in the optical properties signification and is plain in the meaning of the leaves inclination that characterise the orientation of a leaf in a plant, a plant in a row and a row in a stand. The presence of plant density in those equation is obvious in the signification of the leaf area index. This is calculated from the cumulated surface of all the components of the trees in high canopies like the forest or the traditional oasis. The presence of time appear in the meaning of the radiation source elevation which gives the hours of the day. So we can follow the plant productivity, photo-sanitary and architecture effect at any time asked. Also we can by knowing the need of tolerant plant to the efficient radiation and to oasis environmental conditions cited in the above paragraphs we can propose the plant species to install, their density and their orientation (architecture).

The solar radiation intercepted by a vegetable layer, situated between the leaf area index levels f and f + df, is generally considered equivalent to that absorbed and is determined by the balance between the received and the lost radiation:

$$\Phi_{r,int}(df)=\left[\Phi_{rs}(f)+\Phi_{rd}(f)+\Phi_{r}^{-}(f+df)+\Phi_{r}^{+}(f)\right]-\left[\Phi_{rs}(f+df)+\Phi_{rd}(f+df)+\Phi_{r}^{-}(f)+\Phi_{r}^{+}(f+df)\right]$$

The formulations that we have presented now are sufficient to describe the radiatif climate inside an intercropping systems formed by three vegetal levels: date palms, fruit trees and market gardening at any time and location. Special attention is given to light sharing between the three crop stories and spatial variability of light transmitted through them. As the detailed geometrical structure of the oasis in the region of North Africa is largely unknown, the equations presented above can help for the proposal of a best architecture for an efficient use of resources when thinking to install new oasis with tolerant species. Also, for the projects of rehabilitation and the biodiversity arrangement of the existing oasis in the region the cited equations are very useful. But the challenge is to extrapolate a results found for one oasis to the others and to scale up a model applied for a limited field to a vast region.

5.2.2 Formulating Heat and Mass Transfer Inside the Oasis

An important method to analyse and monitor the heat and mass transfer inside the vegetation is to consider a formulation that introduces many specific parameters concerning plant physiology and leaf microenvironment (Chen, 1984). I cite here the stomata conductance, stomata resistance, leaf area index, photosynthesis rate for all the plant component, leaf temperature, turbulent transfer resistance, aerodynamic resistance, boundary layer resistance, wind velocity, net and global solar radiation, air temperature (Jarvis and Mc Naughton, 1986). In the same meaning, we can consider an electrical analogy with circuits for the sensible and latent heat exchanged between the different farming stories inside the oasis (Sellami and Sifaoui, 2008). The net radiation absorbed within each layer of the oasis canopy represents its current source. Sensible and latent heat flux supplied by the layer inside the canopy are considered as intensity of the electric current. Potential sources, analogy of tension for the electric current, were air temperature at a reference height for sensible heat circuit and the water vapour pressure of the air at a reference height for latent heat circuit. Inside the oasis, in the vertical direction, the driving forces (potential) is determined from difference in temperature between layers for sensible heat density and from difference in water vapour pressure between layers for latent heat flux. Applying the analogy of electrical circuit theory and using the energy balance equations permit to formulate the latent heat flux, the sensible heat flux, the set of resistances to heat and mass transfer and the biomass productivity inside the oasis with the following equations:

$$\Phi_{c,i} + \Phi_{v,i} = \Phi_{r\text{-}net,\, i}$$

$$\Phi_{c,i}=\rho c_p\left(\frac{T_{l,i}-T_{a,i}}{r_{c,i}}\right)$$

$$\Phi_{v,i}=\frac{\rho c_p}{\gamma}\left(\frac{e(T_{l,i})-e(T_{a,i})}{r_{v,i}}\right)$$

$$r_{c,i}=\frac{r_{b,i}}{2LAI_i}$$

$$r_{v,i}=r_{c,i}+\frac{r_{s,i}}{2LAI_i}$$

$$r_{s,i}=\frac{\rho c_p}{\gamma}\frac{\beta D_i}{\Phi_{r-net,i}}$$

$$r_b\,(z)=\left[\frac{l}{u(z)}\right]^{\frac{1}{2}}\frac{1}{\alpha_0}$$

$\Phi_{c,i}$ is the sensible heat flux the canopy layer i
$\Phi_{v,i}$ is the latent heat flux for the vegetation layer i inside the oasis
$\Phi_{r\text{-net}, i}$ flux of net radiation received by the vegetation layer i
ρc_p is the volumetric heat capacity of air,
γ is the psychrometric constant,
$T_{l,i}$ is the temperature of the leaves corresponding to canopy layer i
$T_{a,i}$ is the temperature of the air corresponding to canopy layer i
$e(T_{l,i})$ is water vapour pressure of the air at the canopy layer i for $T_{l,i}$
$e(T_{a,i})$ is the water vapour pressure of the air at the canopy layer i $T_{a,i}$
$r_{c,i}$ $r_{v,i.}$ is resistance to sensible heat flux for the layer (i) inside the oasis
$r_{v,i.}$ is resistance to sensible latent flux for the layer (i) inside the oasis
$r_{b,i}$ is the aerodynamic resistance of the boundary layer around the leaves in layer i
LAI_i is leaf area index for the layer i
r_{s1} and r_{s2} are stomata resistance for the superior and the inferior face of the leaves
$r_{s,i}$ the mean stomata resistance for the vegetation layer (i) inside the oasis
β is an a-dimensional coefficient equal to 3.77 10^{-3}
D_i is the water vapour pressure deficit of the air for canopy layer i
l is the leaf width,
u (z) is the wind velocity at level z
α_0 is a constant coefficient

The gross daily photosynthetic production of the whole canopy can be estimated from the following simple empirical formula (De-Xing and Coughenour, 1994):

$$\Phi_{PAR}=C_v\sum_{1}^{24}\left[\psi_{psl}LAI_{sl}+\psi_{psh}LAI_{sh}\ \right]$$

$$\Psi_{psl}=0.95\left[1-\exp\left(-A_{abs}LAI_{sl}\right)\right]$$

$$\Psi_{psh} = 0.95\left[1 - \exp\left(-A_{abs} LAI_{sh}\right)\right]$$

Φ_{PAR}, is the sum of individual leaf photosynthesis
C_v is a conversion constant
Ψpsl is average leaf photosynthesis rates for sunlit leaves
Ψpsh is average leaf photosynthesis rates for shaded leaves
A_{abs} is absorptance of plants
LAI_{sl} is leaf area index for sunlit leaves
LAI_{sh} is leaf area index for shaded leaves

We can remark easily that the proposed formulations of mass and heat transfer inside the oasis are opened over the proposed formulation of solar radiative transfer. A model for heat and mass transfer inside a traditional oasis of Tozeur utilising both the basic equations presented above and the output of the model of solar radiative transfer (Sellami and Sifaoui, 1999) had been established (Sellami and Sifaoui, 2008). Scaling up for all the oasis of North Africa and applying the out put for genetic biodiversity conservation needs thorough knowledge of the physiological properties of all the species and the different microenvironments inside the oasis of the region (set of resistances, optical properties of the species components, microclimatic parameters).

5.3 Method for Scaling Up Models Elaborated for One Oasis to all the Oasis of North Africa

5.3.1 Methodology

The goal we seek is producing mechanistic models of conductance, assimilation, and transpiration that are transferable among species, sites, and various altered climates. As said above the traditional oasis in the region of North Africa is formed of three canopy stories where we found the majority of species either for the market gardening, fruit trees and date palm. The microenvironment, microclimate and kind of soil differ from level to level and place to place in the same oasis and they differ from oasis to oasis. Establishing relationships and models that can be applied to all the oasis of the region is an important goal for agricultural water management inside (Andrew et al. 2006; Mike Austin, 2007). This generalisation need the use of the scaling up and extrapolation tools (Hinckley et al, 1997). There validation demands repeated experimentations in time (hours, day, seasons) and space (many oasis in the region and many position in the same oasis). The survey of microenvironment distribution must be done from leaves level to branch, plant, stand and to regional levels (Gutschick., 1991). This survey must extend to species in many oasis in the region and must covered at list 2 years in order to follow the season variation effect and to verify with the second years the results recorded in the first. I should signal that at larger scales many additional phenomena appear, such as soil evaporation, canopy boundary-layer resistances, aerodynamic resistances, stomata and leaf boundary-layer resistances. We should consider them in all the stapes when extrapolating the results from scale to scale. To resolve which physiological (and micrometeorological) features explain the most variance in observations, it is better to develop models of observed fluxes in a hierarchy, from simple to more complex. A requisite for understanding larger-scale fluxes in terms of vegetation amount and physiology is quantifying the amount of vegetation, as leaf area index, and also the species components. We can do direct measurement of the geometrical properties (leaves inclinations and surfaces, diameter and length of the trunks and branches, densities of the components of the species and of the plants on the stands, projected surfaces of plants, fruit geometry) on a representative numbers of plants for all the region. Also we can proceed by doing aerial photography of select sites. The analysis of images permits to quantify leaf area index, using pixel-wise classification into leaf, non-leaf, and mixed pixels. The fraction of leaf in view will be related to LAI with models of canopy structure and light penetration. After, distributions and autocorrelation functions that link the surface or the volume occupied by every plant component and by every kind of plant in the stand to the surface or the volume dominated by the oasis of a zone and to that of all the region (François et al, 2007). Those function would be used later to extrapolate all the flux measured or modelled (sap flow, intercepted solar radiation flux, photosynthetic radiation, water potential, transpiration, sensible and latent heat flux) at leaf scale to branch scale, from branch to trees level, from trees to stand and from a stand to the oasis of all the region.

Scaling up requires not only technologies to measure fluxes on different time and space scales. But to establish many empirical relationships from repeated filed measurement in space and time scales for the same oasis and for the majority of oasis in North Africa. Those equations should relate between flux measured (gas exchange, air temperature and humidity, shortwave and thermal infrared flux densities, windspeed, CO_2 concentration) and the physiologic parameters of local species inside those oasis. They must consider, the detailed characterization of leaf microenvironments (leaves on a plant are displayed at different angles and at different optical depths, temperatures, etc.), and of single plants within a stand, and of small regions within a large region which are distributed rather than uniform (Baldocchi and Harley 1995, Waring et al 1995). We must know these distributions. If elaborated for a representative number of oasis in the region, those empirical relationships can be used to extrapolate the results of the models and microclimatic measurement found in the oasis of Tozeur to other oasis in North Africa.

5.3.2 Scaling Up Method used to Search the Oasis Transpiration in Tozeur

To scale up the sapwood section from a tree level to all the stand we have studied all the trees of the plot and we have measured their geometrical properties (high, diameter at different position of the trunk, number of palms and leaves, …) and we have made a classes of trees as function of those dimension. The distribution of the sapwood cross-sectional area, tree health, stem shape and contact with neighbouring crowns of the trees sampled were considered as criteria for determining the selection of a sample in the oasis. After sampling, 20 date palms and 20 fruit trees, that represented the circumference's range of the plot (every tree from the 20 chosen represents a class), were selected. The cross sectional area of sapwood of each tree was calculated from its total circumference. The cross sectional sapwood area of the stand per unit of the ground was given by the arithmetic mean of the sapwood surface values of the sample of 20 trees, expressed per unit of ground area (Granier, Loustau, 1994; Sellami and Sifaoui, 2003). The total sap flow transpired by a tree on a day is equal to the sum of the sap flow transpired every hour. The transpiration for the entire stands and for every storey of the oasis is assimilate for its total sap flow (sap flow transpired by all the trees of the stand). The mean sap-flow density per unit area of sapwood in the oasis was estimated from the arithmetic mean of the sample averaged by the cross-sectional area of sapwood (Jarvis and McNaughton 1986). The transpiration for fruit trees and date palm were estimated from:

$$E_{ft}=\overline{J}_{ft}*S_{ft}$$

and

$$E_{dp}=\overline{J}_{dp}*S_{dp}$$

E_{ft} Fruit trees transpiration (mm h^{-1})

E_{dp} Palm date transpiration (mm h^{-1})

$\overline{J}_{ft}$ Mean sap flow density per unit area of sapwood for fruit trees expressed as kg dm^{-2} s^{-1}

$\overline{J}_{dp}$ Mean sap flow density per unit area of sapwood for date palm expressed as kg dm^{-2} s^{-1}

S_{ft} and S_{dp} are, respectively, the cross-sectional sapwood area of fruit trees and date palm expressed as dm^2 m^{-2}

After calculus we found that the total transpiration of the stand is about 3.11 mm /day (1.91 for date palms and 1.2 for fruit trees). Monitoring this parameters at the scale of the hours is very needed to fix the irrigation gift. But the sap flow apparatus are very sensitive to climatic condition they can’t be installed for all times. So elaborating models to estimate the heat and mass transfer and after the evapotranspiration inside the oasis is very profitable for water management. The results of a model in this direction established by my self is the object of a paper published (Sellami and Sifaoui, 2008).

6 MODELLING AND MEASUREMENT STUDIES EFFECTUATED FOR THE OASIS OF TOZEUR

The models established and experimentations realised for the oasis of Tozeur deal with many subject that concern the agricultural water management: solar radiation intercepted and shared between canopy species inside the oasis, plant productivity and transpiration, heat and mass transfer, biodiversity conservation by simulating the water really needed by every species and by detecting the eventual diseases that can emerge at hours scale, the optimal arrangement between plants, there orientations and densities for an optimal use of resources (Sellami and Sifaoui, 1998, 1999, 2003, 2008). Those models have been tested only at local level while the principal test of their generality and their significance in climate and climate impacts is in scaling up to large regions like North Africa region. Also the importance of the work done for the oasis of Tozeur is bright when reminding that the International Scientific Community are interested by scientific work that combine mathematical modelling with ecology and management of the environment and its natural resources and the scaling to vast regions. They give priority to the use of ecosystem theory to quantify the reaction of ecosystems to perturbations (impact of man’s violent activities), to predict plant species distribution at landscape level and to analyse the dynamic biodiversity-landscape.

6.1 Results from the Measurement of Microclimatic Factors and Sap Flow Transpired

The field in which we have conducted the experimental protocol is a traditional oasis of about one hectare surrounded by others belonging to other farmers (problem of parcelling out). At the middle of this plot we have installed the 12 m mast with the apparatus to avoid the fetch effect and where the three stories exist and are not traversed by passages or soil canals. This form is repeated in the surrounded oasis. At levels 2, 5 and 12 m of the mast, we fixed three stems of about 2 m length. Every stem included a net pyrradiometer, a pyranomater, a cup anemometer, a temperature probe and a humidity probe. A net pyrradiometer placed 30 cm from the ground to determine the net radiation transmitted across all the oasis and that reaches the soil. The global radiative flux transmitted to the soil is measured by a set of six pyranometers installed arbitrarily to account of horizontal heterogeneity in the canopy structure. The average of the data loggers by those six probes represents the total global radiation transmitted across all the oasis. The probes mounted at 12 level deal with the total net and global incident radiation received above the oasis. The values recorded at that level gives an estimation of, respectively, the amount of water transpired by all the oasis and the total amount of photosynthetic active radiation used for the photosynthetic process inside the oasis. Those installed at 5 m provided measurements of net and global solar radiations transmitted across the palm storey and received by the fruit trees. The sensors placed at 2 m above ground gave us the net and global radiation transmitted through the fruit trees storey and entertained by the market gardening. The ambient air temperature, humidity and wind velocity were measured with the corresponding probes at different levels(2, 5 and 12 m). The radiation intercepted by each farming storey in the oasis is obtained by the difference between radiation measured at the level right above (received radiation), and that measured at the level right below the storey (lost radiation). The radiation intercepted by the total oasis is the difference between radiation measured at 12 m and the radiation measured on the ground. The efficiency for the intercepted radiation is the ratio between intercepted radiation and the sum of input radiation above the farming types. The density of sap flow within the xylem of the palm grove and the fruit trees, expressed on a sapwood area basis, was monitored continuously during the experimentation period. The total sap flow in the trunk was obtained by the cumulative products of flux densities and associated cross sectional areas. The mean sap flow in a stand and the mean sap flow density are given as the arithmetic average of those measured on each trees. The canopy transpiration was estimated by multiplying the mean sap flow density and the cross sectional sapwood area of the stand per unit of the ground.

An hourly and daily evolution of all climatic parameters and of the plant transpiration (an approximation of water needed by plants) at three levels inside the oasis were realised. A quantification of the amount of global radiation, net radiation and photosynthetic active radiation (needed to determine the oasis productivity) intercepted in every storey were determined. The analysis of the profiles of net radiation, global radiation and sap flow at different level inside the oasis permits the establishment of divers relationships for the three plant storeys (Sellami and Sifaoui, 1998, 2003):

- The daily global incident radiation intercepted by date palms is equal to 14 % of the global incident radiation received above the oasis about 640 w/m² per day from which 307 w/m² used for photosynthesis
- The daily global incident radiation intercepted by fruit trees is equal to 19 % of the global incident radiation received above the oasis about 853 w/m² per day from which 409 w/m² used for photosynthesis
- The daily global incident radiation intercepted by market gardening is equal to 30 % of the global incident radiation received above the oasis about 1380 w/m² per day from which 662 w/m² used for photosynthesis
- The daily net radiation intercepted by date palms storey is equal to 19 % of the net radiation received above the oasis about 0.77 mm per day
- The daily net radiation intercepted by fruit trees storey is equal to 20 % of the net radiation received above the oasis about 0.81mm per day
- The daily net radiation intercepted by date palms storey is equal to 42 % of the net radiation received above the oasis about 1.66 mm per day
- The daily net radiation intercepted by all the oasis is equal to 81 % of the net radiation received above the oasis about 3.24 mm per day
- Daily transpiration, measured from sap flow method, for date palm storey represents 32 % from global radiation measured above the oasis
- Daily transpiration, measured from sap flow method, for fruit trees storey represents 21 % from global radiation measured above the oasis
- Daily transpiration, measured from sap flow method, for all the oasis represents 53 % from global radiation measured above the oasis
- Daily transpiration, measured from sap flow method, for date palm storey represents 59 % of net radiation intercepted inside the oasis and 53 % of that measured over the oasis
- Daily transpiration, measured from sap flow method, for fruit trees storey represents 37 % of net radiation intercepted inside the oasis and 33 % of that measured over the oasis
- Daily transpiration, measured from sap flow method, for all the oasis represents 96 % of net radiation intercepted inside the oasis and 86 % of that measured over the oasis.
- Hourly transpiration, measured from sap flow method, for date palm storey represents 43 % of net radiation intercepted inside the oasis plus 0.15
- Hourly transpiration, measured from sap flow method, for fruit trees storey represents 21 % of net radiation intercepted inside the oasis plus 0.15
- Hourly transpiration, measured from sap flow method, for all the oasis represents 64 % of net radiation intercepted inside the oasis plus 0.15

If we know the optimal need of the oasis plant on heat and water we can be repeating those measurement on other places of the same plot or other fields where there is different disposition of plant deduce about the best architecture to an optimal use of resource. The optimal requiring of the oasis plant on heat and water can be deduced by laboratory research or by field observation. In which oasis or in which zone of the same oasis the quality and the quantity of the product is the best to have an idea about probably the best disposition and the optimal need of temperature, radiations, humidity.

6.2 Results of Modelling inside the Traditional Oasis of Tozeur

The models that I have established for the traditional oasis of Tozeur concerns both the solar radiative exchange (Sellami and Sifaoui, 1999) and the heat and mass transfer (Sellami and Sifaoui, 2008). Considering the fact that the detailed architecture of the oasis is largely unknown and the nature of transport in oasis canopies is not fully understood, the models treat every storey of the canopy as a homogeneous turbid layer. In every vegetation layer they distinguishes between the interception of direct, diffuse and scattered radiations and they emerge the aerodynamic resistance and the stomata conductance of all the species. We have to signal that the basic equations of the two models are those presented in paragraph V and that the one is open on the other. In fact, plant growth and biomass production depend on leaf. photosynthesis, stomata conductance, solar radiation, sensible and latent heat flux partitioning.

For the model of solar radiative transfer, special attention is given to light sharing between the three crop stories and spatial variability of light transmitted through them. We had been able to determine the amount of solar radiation intercepted by each crop levels as function of time and space and to estimate the mean solar radiation that penetrates inside the vegetation from above-canopy measurements only. The calculus need the knowledge of the leaf area index and leaves transmittance and reflectance, so we have measured them. Those parameters, considered as input for our calculus can be accounted as out put of the model when we think to use it to detect the eventual diseases of plants or when to search the optimum plant densities and the best tolerant species to install. After comparing the modelled values to the experimental data, we had signaled a good behaviour of the model.

For the model of heat and mass transfer, we have succeed to determine the evolution of sensible and latent heat flux at hours scale and to quantify the biomass production inside a traditional oasis in the south of Tunisia. Temperature in and above the canopy also humidity, wind velocity, net, global and photosynthetic active radiation and sap flow within the xylem of date palm and fruit trees are included in the mathematical treatment. For validating our model, we have compared latent heat flux, sensible heat flux and biomass production predicted to respectively sap flow data, thermal budget and photosynthetic active radiation measured inside the oasis. We can say that the simulated values are on the verge of those measured. While, due to the fixed position of the sensors and the poor documentation about the detailed geometrical structure of the trees inside the oasis, we notice some difference between measurement and calculus especially for the market gardening. The quality of the two models can be better, in order to make the output more close the values measured, if we can sweep more space by mobile sensors and if we use more sophisticated method to determine the geometrical structure of the trees inside the oasis and their stomata resistances. As it is this work provides an initial attempt at modelling the penetrated radiation inside a vegetation with three production levels, a tool for analysing the light competition within intercropping and a method to describe the heat and mass transfer inside a traditional oasis for which the correspondent architecture is preponderant in North Africa region. More, the models are important to test absorption efficiency and the farming productivity in different cases of structure and row distances, to choose the best arrangement and to maintain the equilibrium of the mixture. Although the problems and challenges of those models are manifold, it is clear that more informations are needed before the goal of applying it to all the oasis of North Africa can be achieved. Those informations concern principally the architecture parameters of a representative number of oasis in the region of North Africa, microclimatic parameters inside the majority oasis, physiologic properties of the tolerant plants to local conditions. So it's a hard research work that must be done in order to establish a real walking encyclopaedia for the farming inside the oasis of the region. These later is considered as tools for the two models when used to test the best disposition between plant for an optimal use of resources by changing the parameters concerning the plants (turbulent diffusivity, stomata resistance, rate of CO_2 assimilation, leaf area index, inclination of leaf, its disposition on the branch, dimension of the trunk, distances…), to detect the indicators of possible plant diseases by monitoring the optical properties of leaves and to determine the photosynthetic active radiation needed to estimate biomass product. This analysis can be done at the scale of a storey (market gardening, fruit trees, date palm) and it can be refined at plant level inside the storey (which kind of plant to which architecture). Finally I have to evoke the fact that the two models can be parameterised largely with remote sensing data when predicting future oasis productivity on large scale. However, the diversity of plants as sinks and water-vapor sources is great, while remote sensing data cannot hope to resolve plant species and stress status. It is profitable, then, to seek regularities in individual-plant physiological behaviour. This is easy feasible inside the oasis with the two models presented.

7 CONCLUSION

In North Africa region, oases are among the most intensive and biotically diversified traditional agro-ecosystems in the world. Conserving local landraces and improving it in situ by using well adapted species to the local dry conditions maintains the high genetic diversity of crops in these systems and conserves water over non-adapted varieties. Also, empower people to use local knowledge and management strategies in order to improve local environments, to conserve the natural resources (water and soil) and to protect the polyculture systems in the oasis region is a road for durable development in the region that all the international experts advice to follow. The scientific guide subject of this chapter enhance the establishment of models that help in taking decision carefully and rapidly about actions to rehabilitate and to valorise the oasis product and environment with a participative spirit. In fact, after evoking the preponderant problems in the oasis of North Africa (soil and irrigation water salinity, agro-pedological constraints, water table rising, hydro-agricultural problems) I have presented the basic equations to describe the water, nutrient and salt distribution in different type of soil, under many irrigation systems that can be utilized inside the oasis and for all type of plants. Some equations presented can be used to monitor the ascent of water table at different time scales and to foresee the period to pull down its level according to phonological stage of plant. Also I have pointed out many formulations to determine the salt leaching requirement, to analyse the irrigation scheme efficiencies for the oasis and to calculate all the component of a drainage network very needed to avoid the problem of hydromorphy. I have putted on the radiative transfer equation, its application for studying the solar radiatif climate inside the oasis and to estimate the amount of solar radiation intercepted by every farming storey inside the oasis and by every plant inside the storey. I have introduced the reasoning to follow and the correspondent equation in order to deduce the productivity for the market gardening, fruit trees and date palms, to detect the eventual plant diseases before there spreads, to control phytosanitary situation of the vegetation in order to conserve the biodiversity, to test the best oasis architecture for an efficient use of resource by plants (water, nutrients, solar radiation) and to propose the tolerant species to install, their densities and orientation. I have formulated the heat and mass transfer inside the oasis by the use of the thermal budget equation and the Ohm's law. The input parameters are the aerodynamic resistance, leaf boundary layer, stomata resistance of each sort of plant, geometrical characteristics of all the species, microclimatic factors. So we can easily determine the water really needed at hour scale hence monitoring the net irrigation requirement inside the oasis. The biomass productivity for each storey, very useful to search the best oasis architecture, can be estimated from the later formulation. Scaling up a result elaborated at leaf level to branch, from branch to plant, from plant to stand and from stand to a vast region like North Africa is an occupation for all the intervening. I have presented a general methodology and the results of its application for the traditional oasis of Tozeur (Tunisia). I have found satisfactory value for the transpiration by every storey and by all the oasis (Sellami and Sifaoui, 2003). The results of microclimatic factors measured at different levels inside the oasis of Tozeur (Tunisia) (Sellami and Sifaoui, 1998), their analysis and the empirical formulas established appear in the text. I have succeed to relate the global and net radiation intercepted, and the water transpired by every storey to the incident radiation measured above the oasis. A case study of two models established and validated for the oasis of Tozeur figures (Sellami and Sifaoui, 1999, 2008) were detailed. They treat the latent heat flux, sensible heat flux, biomass product and the solar radiative flux exchanged inside the oasis. The basic equation of the two models are those shown previously. Finally I have to signal that the content of this guide can be used in controlling and managing the oasis ecosystem risk in the research area. This can be done by discovering and monitoring many ecosystem risk indicators for the oasis. They must have clear meanings and can be compared in different oasis in North Africa region in the purpose to achieve more indicators, especially, for the interrelation between ecology and socio-economy (Rita and Andrea, 2006). I can't forget the fact that the equations presented and the models established can be integrated with new simulation models (François et al, 2007; Mike Austin 2007) which describe processes of agricultural ecosystems and predict plants species distributions in order to derive optimum management strategies like fertilising shemes and crop rotations.

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Chapter 5

WATER USE IN THE CHILEAN AGRICULTURE: CURRENT SITUATION AND AREAS FOR RESEARCH DEVELOPMENT

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ABSTRACT

Agricultural activity in Chile is very important both in terms of economic impact and in particular in terms of social aspects. This activity depends on great extent, and over most of the territory, on the availability and the efficient use of water for irrigation purposes. Taking this into account, both the Chilean government and the private sector have made significant investment efforts for the improvement of irrigation infrastructure. For example, the Law 18.450 has provoked an important increment on the irrigated surface in Chile. Also, the water code, which dates from 1981, was recently modified, with the aim of introduce modifications allowing a better access and use of water by the privates.

Within this context, it is also worth to mention that the Chilean Government has defined as one of the strategic lines of actions of the governmental plan to transform Chile into a leading producer of agricultural goods and food by 2010. Although it is true that this goal include several components, it seems rather clear that water management in relation with agriculture will continue to be a key aspect of the strategy as well as Chilean Governmental efforts. Moreover, recently (2006) it was published, by a Chilean Governmental Institution the "Agricultural Innovation Agenda", where are defined and proposed innovation actions in 15

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key productive chains and themes, being one of them water resources. There are several specific lineaments and actions described in the referred document representing the visions of public entities (Universities, Research institutions) as well as the private sector. Some of the lineaments defined in that document, can be summarized in the following way: "To promote an integrated vision of water resources at the watershed level, in relation with the water market improvement and to the availability and use of base information of water to be used for irrigation purposes, avoiding environmental pollution problems". Based on this premise, and considering the information gathered and obtained by the authors, an analysis is done in relation to current agricultural water resources situation as well as research opportunities for the Chilean irrigated agricultural activity, mainly based on particular, but widely representative, experiences in two basins of the North-Central South-Central zones.

INTRODUCTION

Because of its length and width Chile is a country of contrasts. On a sunny day, the peak of the Aconcagua mount, located in Argentina, can be seen from the coast of Valparaiso. At the same time, the country is so long that covers 38 degrees Latitude, from a little further north the Tropic of Capricorn to the Antarctic Polar Circle. On the other hand, the driest desert in the world is located in Chile (Atacama, 23-26º S) as well as one of the areas with the largest water availability (Aysen, 44-47º S).

Considering the diversity in weather, physiographic traits and lithologic characteristics existing in Chile, it is possible to identify along the country five great subareas which posses weather characteristics and similar hydrology responses: a) Arid North (18-27º South Latitude), with scarce precipitation; b) Central North (27-33º S), or area of transverse valleys, with an average precipitation of 100 mm and an agricultural activity focused on the early production of fruit for export and foreign markets; c) Central Area of Chile (33-38º S), characterized by three morphologic longitudinal belts, and where the major population and agricultural production of the country are brought together, with precipitation up to 1500 mm/year on the South border, and a vegetable, annual and fruit crops oriented agricultural activity; d) South Area (38-42º S), with precipitation over 1500 mm/year, mainly focused on stockbreeding; e) Far South (from 42º S), with precipitation that may reach 4000 mm/year. This evident climatic and hydrological polarity North/South is also reflected in terms of the water resources availability for the population, where there is also an important change in the country. In the Central North and North areas this does not exceed, except for the Coquimbo Region, the 1000 m^3/hab/year. Extreme cases are those of the North Area, where this figure ranges between 250 and 700. By contrast, on the Central Area this indicator reaches the figure of 3000 m^3/hab/year, and in the South Area of the country it exceeds the 4000 m^3/hab/year (Salazar, 2003).

Regarding the water use in Chile, it exceeds 2.300 m^3/s, 30% corresponding to consumption uses (mainly agriculture, as discussed below) and 70% to non consumption uses (mainly hydroelectrical use). From the consumption uses, between 15 to 20% corresponds to industrial, mining and tap water uses, while between 80 to 85% of the water is set aside for irrigation on agricultural activities, allowing the development of this activity in a little more than a million hectares. However, water is frequently used with as high as 30% rate efficiency (distribution, conduction and application). On the other hand, the water distribution for the various uses is highly variable along the country. In fact, while in the northern regions of the country water is used mainly in the mining industry, in the North-Central, Central and South parts of the country the use of water is mainly for agricultural irrigation purposes.

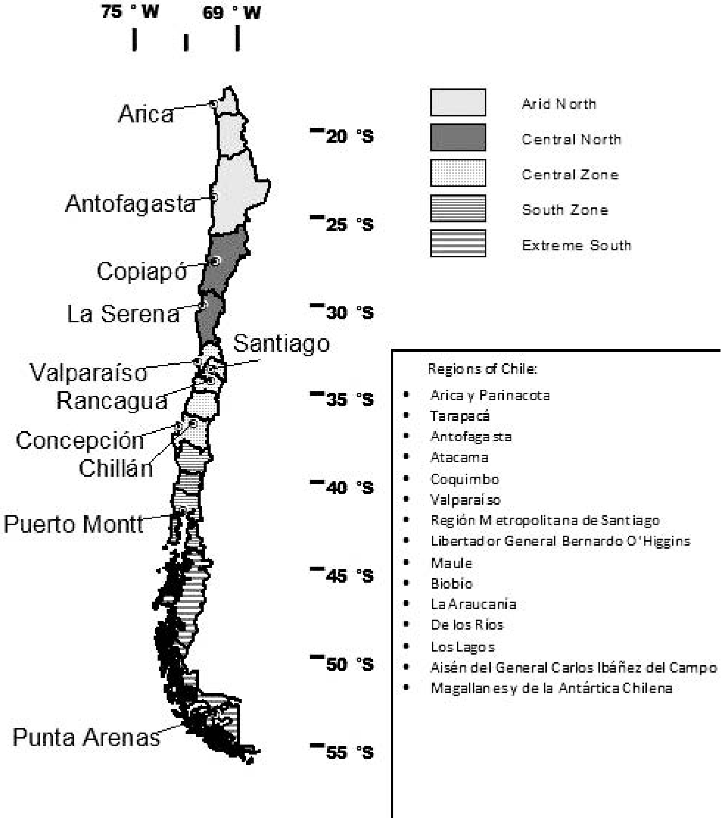

Figure 1: Chile and the five mentioned sub-areas, main cities and political division.

The aim of this chapter is to render a general view of the authors about the needs and opportunities for research existing in Chile, related to water management on the agricultural activity. For this purpose, given the Chilean context, we will consider aspects such as the current national vision to become an agricultural food power, the current legal frame, and others factors conditioning the management of the water resources on the Chilean agriculture. After describing the context, some needs for research for the management of the water resources will be discussed.

WATER USE IN CHILEAN AGRICULTURE

Legal Context of the Water Resources Use in Chile

The management of water in Chile and its consequences correspond to a case of administration of a scarce natural resource within a neo-liberal economical and political context, represented by the 1981 Water Code. Such legal body diminished the Government attributions and transferred the ownership of rights for water use, and therefore its usage, exploitation and disposal, to private entities, generating the power to freely negotiate and use the ownership rights for water use.

In the late 70's and beginning of the 80's a series of planning began, oriented to the generation of incentives to invest and modernize the techniques for water application and management. The basic premise was set that the market and the private property of the rights for water use would effectively allow its saving and the sale of the exceeds or its investment on new activities, which, in turn, would add dynamism to the local and national economy.

In 1979, the 2603 Act (Decreto Ley) introduced modifications on the Civil and Water Codes in force at that time that changed the global view regarding the water issues. On the mentioned law, Article 1 had a constitutional level and established that "the rights of particulars on water acknowledged or constituted according to the Law, will grant the owners the property on them". Then Article 2 empowered the President of the Republic to issue regulations for the General Water Law (Guzman y Ravera, 1993). The mentioned decree was the keystone for the elaboration of the 1981 Code (Law Enforced Decree 1122) since it imposed the liberal and privatizator spirit that the Government at that time wanted to imprint on the general economy policy and, particularly, on the water governance in Chile.

The Title I of the 1981 Water Code divided inland water into surface water and groundwater, defining the first one as that "which can naturally be seen by the sight of human beings…" and the second one as that "which is hidden on the ground and has not emerged" (Codigo de Aguas, 1981). On this title, it is important to understand the intention of the Code to conceptually separate surface water from groundwater, with the purpose of creating, later on, different "exploitation rights" for each of them. In general, the owners of rights on groundwater tend to operate individually, while those with rights on surface water become part of user associations. Regarding the latter, two types can be mentioned: Surveillance Board and Channel Associations or Water Communities. Surveillance Boards are in charge of water management of natural flows, i.e. rivers, creeks, and Channel Associations are in charge of water management on artificial aqueduct, i.e. channels (Segura, 2003).

Regarding ownership and water exploitation, Title II clearly established that "water is a national good of public use and privates are granted the right to exploit it". It is important to mention that rights for permanent exercise are granted only at "non over-allocated" sources of supply, and that those of eventual exercise only allow the use of water during the time in which the matrix flow presents "surplus after the permanent exercise rights have been supplied". From this, we infer that permanent rights will not be granted on over-allocated flows, but eventual rights only.

In 2005, after years of questioning the 1981 Water Code, some modifications to this legal body were approved, which focused on subjects such as the justification of the request for exploitation rights (which must be in accordance with the later water use), new attributions for the DGA (Dirección General de Aguas, major water legal authority of the Chilean government) such as, for example, authority to declare, by itself, areas with restriction in the case of groundwater, and user organizations (in particular for groundwater systems). Although the main objective of these modifications was to diminish the degree of speculation associated to the water property, e.g. by imposing a patent for non-use, its practical effects are still uncertain.

Governmental Strategy of Support for Irrigated Agriculture: Chile, an Agricultural Food Producer Power

The “agroindustrial-exporting” development strategy of the Chilean agricultural sector has been one of the bases of the economical growth experienced by the country in the last two decades. In the context of this strategy, irrigation agriculture becomes a key factor: the production of irrigated agriculture represents 60-65% of the Gross Domestic Product (GDP) of the Chilean agricultural sector, contributing with more than 80% of the agricultural products export of the country. Such strategy has laid the foundations of a second phase in this process, oriented to positioning Chile as an agricultural food power, which is expected to be carried out by the second decade of this century. The most indicative fact has been the modernization of the agricultural and forest activity, with outstanding increases in productivity and quality; the exporting development of the main agrifood chains as a response to the opportunities aroused from the commercial agreements signed by the Chilean State; the ability to make compatible the supply to the evolution of the habits and preferences of consumers in the context of globalization, and the public-private integration as a strategy to reach new markets under a common project.

The results to date have been notorious: in the year 2005 the export of fresh and processed food rose above US$ 8.000 million, locating Chile among the 20 countries with best agricultural-related goods exporting capacity. As a result, the food industry is an important source of wealth and job opportunities, generating around 30% of the national GDP and using 20% of the work force, in more than 4.000 companies along the country.

Certainly, the insertion of Chile in the food markets requires growing volumes of products in quantity and quality, which calls for the participation on this process of the largest amount of the national production in the shortest period possible. Thus, a growing pressure and constant dynamism on the forestry and farming national activity is expected. In fact, estimations from the Bureau for Agricultural Studies and Policies (ODEPA), indicate that, in order to sustain the demand for agriculture products from foreign markets, 400 to 460 thousand ha of new irrigation soil over the next 10 years will be required.

Based on the strategic orientations previously exposed, the current Government in Chile has prioritized a series of plans and programs; one of these strategic guidelines is the National Program for Irrigation Promotion (Programa Nacional de Fomento del Riego). Indeed, recently the Agenda for Agricultural Innovation (Agenda para la Innovación Agraria) was published, a document that gathers information and defines needs and actions for innovation for a group of 15 productive chains and key matters for agriculture in Chile (MINAGRI, 2006). One of these topics is water resources, in which guidelines to be dealt with and issues to be focused on to increase the availability and quality of the water resources for agriculture, and to improve the technological level of irrigation and drainage, were defined. This was done with the ultimate purpose of supporting productivity and competence of the Chilean agricultural sector. Particularly, the following guidelines stand out: a) Promoting an integrated vision of water resources at the basin; b) Strengthen the management ability of the users organizations; c) Strengthen the management and institutional operation of the extra-property irrigation infrastructure; d) Generate the coordination to improve the market of water resources for irrigation; e) Control environment pollution caused by irrigation; f) Strengthen the intra-property land management of irrigation.

In summary, irrigation is one of the bases for agricultural development in Chile. At the same time, it has become one of the more efficient instruments for the achievement of the two determining program guidelines on the Agro-food Policy, which are: a) To modernize and make more competitive the national forest and agricultural sector, and b) To promote the opportunities of development of the Medium-size Agriculture and the Rural and Native Family Agriculture.

From this perspective, the central ideas of the program defined by the State of Chile regarding irrigation are:

- Giving structure and order to the irrigation development through the formulation of a National Program of Irrigation and Drainage, based on the National Policy.
- Readjustment, enlargement and focalization of the instruments for the development of irrigation, especially the Law for Irrigation Promotion, to benefit Rural and Native Family Agriculture.
- Restructuring and rehabilitation of the system of promotion and development of rural irrigation from INDAP (National Institute for Agriculture Development), which supports the enforcement of the Law for Irrigation Promotion towards Rural Family Agriculture.

One aspect that outstands from this analysis is related to the 18.450 law or “Law for the Promotion of Private Investment in Irrigation and Drainage Structure”. It is important to mention the characteristics of this legal instrument and its influence over the development of the agricultural area under irrigation in Chile to understand the current context of the water use in the Chilean agriculture. The Law for the Promotion of Irrigation and Drainage grants agricultural financial assistance to irrigation and drainage projects with a top cost of UF 12.000, in the case of individual projects, and with a top cost of UF 24.000, in the case of projects presented by farmer organizations (UF stands for Unidad de Fomento[1]. At the time of writing this chapter, 1UF ≈ US$35). The maximum rebate amount to which a determined project can apply corresponds to 75% of the total cost. Projects that can be rebated include a) building and repairing irrigation and drainage installations, b) execution of intra-property such as wells, technified irrigation systems, and electrification, c) execution of extra-property land buildings, such as water intakes, starting frames, and different art works.

Its original enforcement period was of eight years, but it was modified in 1994 to be in force until December 31st, 1999 and, later on, until January 1st, 2010. However, there is currently an active discussion for an extension of the enforcement. The reason for this responds to the important benefit that its existence has brought, in terms of modernizing and improving the irrigation and drainage infrastructure. For example, for the 2000-2006, the existence of the law allowed for annual average investments over the $M 30.000 (US$ M 60), of which around $M 20.000 (US$ M 40) was rebated by the State. The largest part of these investments, ca. 75%, was concentrated on the area between the regions of Coquimbo and Bio Bio. Only 3% of the investment was destined to drainage works, therefore almost all investments were destined to civil works (51%) and irrigation technification (46%). Finally, it

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[1] The Unidad de Fomento (UF) is a count unit which adjusts to the inflation rate, used in Chile. It was created by Decree Nº 40 from January 20th, 1967. Originally its main use was for mortgage loans. Later on it was widely used for bank or financial loans for private or individuals, investment, contracts and in some case, fees.

is important to point out that the exercise of this law has favored middle-sized entrepreneurs (47%) and small producers (32%) and user organizations (19%).

It is also important to mention, as a complement to the existence of the 18.540 Law, the program for middle-sized and major water reservoirs (dams) motivated by the Chilean State in the last 30 years, represented by the PROMM Program, the Executive Order Law 1123 and the DS 900 of the Department of Public Works Concessions. The PROMM Program finances the building and restoration of middle-sized irrigation structures, that is, those that cost over 24.000 UF but under 600.000 UF. Finally, the 1981 Executive Order Law 1123, modified in 1995, establishes regulations for the execution of irrigation works by the State, while the 1996 DS 900, modified in 2006, corresponds to the Concession Act of Public Works, which includes dams. Both instrument represent the most important financing mechanisms currently available for big irrigation works, that is, those that cost over 600.000 UF (ca. US$ 20M). The main differences between both mechanisms are explained by the fact that in the Executive Order Law 1123 the works are executed and subsidized by the State, and there is a commitment of privates (farmers with water use rights) to reimburse part of the investment, and, therefore, becoming both the reservoir and water rights property of privates. In contrast, for the case of the DS 900, a contract is established between the State and a single private, being the latter a concessionaire. The concessionaire finances the construction, maintenance and operation of the work in exchange for the right to exploit it for a determined period (20 to 25 years) during which the water users (farmers with water rights) must pay a fee to the concessionaire. An "allowance" is set that corresponds to a percentage of the amount the State pays in an agreed period. The remainder of the investment is recovered by the concessionaire with the fare charged to the users. At the end of the concession period the structure becomes property of the State. Under the frame of the first instrument, in the last fifteen years, the Santa Juana (Atacama Region), and Puclaro and Corrales (Coquimbo Region) reservoirs were built, which significantly benefit the development of the agricultural activity in the Central North area of Chile (Torres, 2006). Currently, there is a group of 7 works in project that will be built towards 2013 by means of the 1123 Executive Order Law and the 900 DS, favoring 124.000 and 87.000 has respectively, including new irrigation surface and improved irrigated surface.

Factors that Determine the Use of Water in the Chilean Agriculture

In the following section a brief characterization of the climatic, physiographic and organizational factors existing in Chile is presented and the relation among these factors and the use of water for agriculture in the main areas of agricultural production is established. Thus, this is done for the area comprising the regions between Atacama and Los Lagos (26-41º S).

Soils: As opposed to the situation existing northern of latitude 26º S and southern of latitude 33º S, where the territory is organized into clearly defined longitudinal strips N-S, the middle segment between 26º-33º S corresponds to an almost continuous mountainous landscape interrupted by narrow cross river valleys and by some basins on the south (Endlicher and Weischet, 1986). Also, this geomorphologic difference coincides with the absence of quaternary volcanism, due to geodynamic conditions specific for this realm. On this area of transverse, E-W valleys, agriculture soil is set up as alluvial terraces formed by moderately thick sediment (blocks, cobbles, and sand) as result of erosion of the Andean range. The main lithology is intermediate volcanic and plutonic, with a minor participation of sedimentary rocks (Rivano and Sepúlveda, 1991; Paskoff, 1993). The soil presents a moderate degree of development, and it is classified mainly as aridisol and as alfisol (Luzio and Alcayaga, 1992; Oyarzún and Alvarez, 2001).

In the Central South and South areas, the Central or Longitudinal Valley is located, where the major part of Chilean agriculture is carried on, because of a more favorable water availability pattern and soil with better agricultural conditions (34-37º S). The filling deposit includes a larger participation of materials of fluvioglacial and limnic origin, as well as soil horizons formed by ashes and other materials coming from the quaternary volcanism (Borgell, 1983). Also, thick and long laharic fan-shaped deposits were formed, as well as pyroclastic flow (ignimbritic) and ash deposits due to the volcanic activity (Moreno and Varela, 1985). This causes the existence on the soil of horizons of low permeability, and, as a consequence, the presence of perched aquifers with shallow water levels.

The significance of the volcanic material in the origin and development of the Central Valley is evident when considering that nearly 50 to 60% of the arable surface of the country (5.400.000 ha) corresponds to volcanic soil (Arumi and Oyarzún, 2006). The volcanic soil gives rise, in the central-south area, to soils of inceptisol order, and in the south area, to soils of the order andisol order, following to the USDA Soil Taxonomy (Besoain, 1985). They are located, mainly, between the Santiago area (33º30’ S) and Temuco (38º30’ S), and 60% of them correspond to the type locally known as “Trumao”. These soils are characterized, among other aspects, for its moderately fine texture and for the existence of an intense biological activity, and also for an abundant presence of organic carbon, at least in the first meter depth, corresponding to the A and B horizons. Mineralogically, the clays correspond to allophane, imogolite and varied silicate in different proportion (Besoain, 1985). Also, it is possible to find Mollisols in the Central Valley, which proves a higher degree of evolution and a larger accumulation of organic matter (Luzio and Alcayaga, 1992). In fact, the levels of organic matter considerably increase from N to S, with levels of 1,3 to 5% around 34ºS, 3 to 8% between 35º to 37ºS, reaching values from 10 to 20% between 38º and 42ºS (Honorato, 1994).

Weather: Regarding weather, the most important variations in the Chilean territory occur mainly as a result of latitude and, secondary, as a result of altitude; this is essentially reflected in the rainfall pattern existing throughout the country (Figure 3). This is not the same for temperatures, since there is a relative thermal uniformity along the country, because of the moderating influence of the ocean, the action of the Humboldt Current and the movement of air masses (DGA, 1987).

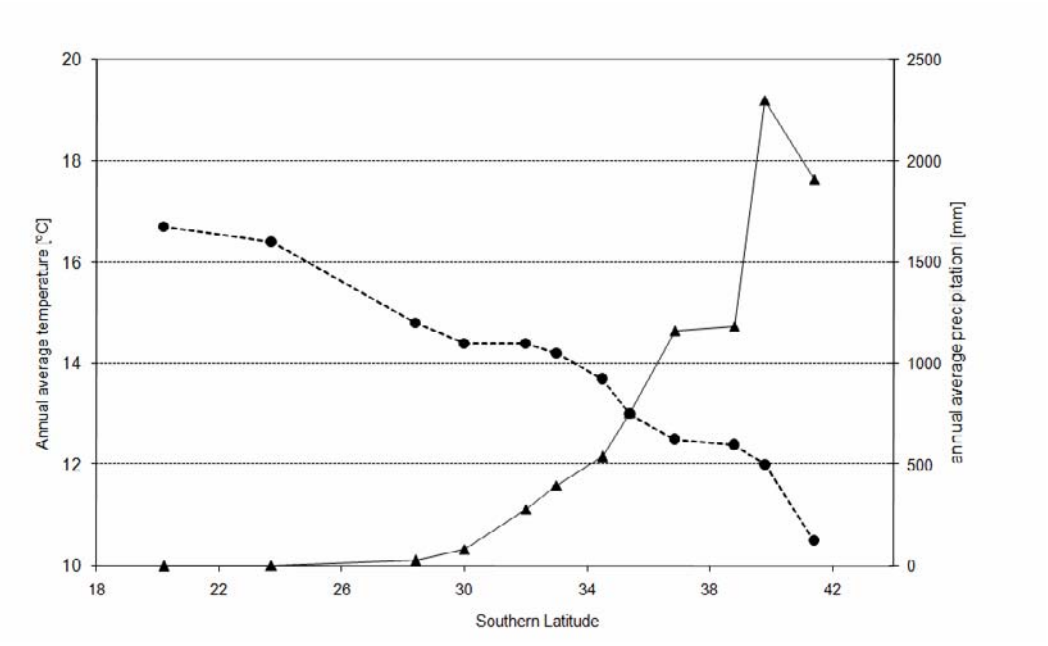

Figure 3: Territorial distribution of rainfall in Chile (own elaboration based on data from DGA, 1987).

Rainfall pattern in Chile is strongly affected by the behavior of the Oriental South Pacific anticyclone and by the superficial temperature of the Pacific Ocean (Santibañez, 1986). The Pacific Anticyclone keeps close to the continent during summer, reducing the entrance of fronts coming from the south. During winter, the anticyclone moves away heading northwest leaving a “passageway” for the passing of front systems towards the centre and north of Chile. In the same way, the summer descent of this anticyclone towards higher latitudes causes the scarce precipitation to be distributed almost exclusively during winter months (Santibañez, 1986). At the same time, the ocean temperatures have influence over the position of the anticyclone, in such way that cold water promotes the stagnation of the center of high pressure in the central area resulting in droughts, specially during summer months. Finally, the effect of the uneven topography of the region favors the formation of several micro-weathers, with different meteorological characteristics.

In the north area the deficit of rain with regard to accumulated potential evapotranspiration during the dry season, stressed by the relief of the inner areas, can reach up to 1.000 to 1.400 mm. Under this scenario, irrigation becomes an essential practice during virtually the whole year, especially for the case of permanent crops. In the case of the Central and Central-South areas, although the water balance presents values closer to precipitation and evapotranspiration, the seasonality of these variables, that reach their peaks in different seasons of the year, makes irrigation essential at least during summer time.

Water Users Organizations: In Chile there is a strong tradition in the distribution and managing of water resources, which goes back to the beginning of the Republic during the first years of the XIX century. It could be said that the main role of user organizations is the distribution of water based on the right and maintenance of the installations for intake and conduction. However, some of these organizations play an important social role bringing together farmers around a channel and throughout the catchment.

These are non-profit institutions since they have no special right for use or benefit from the rights of exploitation belonging to its members, therefore its administrative and accountant structure is designed to manage the services that allow the distribution of the water and the maintenance of the installations. A strength of the organizations of water users is that, given the nature of the resource they are sharing, they keep territorially integrated the whole basin. However, a limiting factor for its development as promoters of the productive fomenting and the appropriate use of water, in addition to the preservation of its quality, is that they cannot apply by themselves for instruments of productive investment fomentation because of their own legal nature.

Supply of irrigation water: Nationally, it is important to consider that from the Metropolitana Region (33º30' S) towards North the rights for surface water exploitation are in an over-allocation condition (Universidad de Chile, 2006), which means that rights have been granted for the use of all the available surface water. Thus, it can be envisioned that there will be a larger demand for the exploitation rights of groundwater in the next years. Estimations made by the DGA indicate that the renewable availability of groundwater in Chile, in the area located north from Santiago, rises up to 65 m^3/sec; for the same area the water use rights requested in the year 2000 were 300 m^3/ sec (Muñoz, 2000). From the region of O'Higgins (34º S) to the south, the rights requested in the year 2000 were 20 m^3/sec (Muñoz, 2000), which implies a smaller pressure over the exploitation of groundwater. In this aspect it is worth to mention that the market of water rights works a lot better in the north area of the country than in the south. Because of the water shortage, initiatives are being developed, such as the desalinization of sea water in the north of Chile and a study of the artificial recharge on water is beginning to be carried out, even though his practice has not been used in Chile (Brown, 2002). Finally, the increase of irrigated surface for permanent crops (fruits) in recent years creates a total dependence on the water supply. Thus, the dependence of agricultural irrigation systems is highly related with regard to the operation of dams. In addition, the incorporation of numerous hectares of orchards of ever green fruit trees has affected particularly the original curves of demand and supply, in which winter water distribution used to be minimal.

NEEDS FOR RESEARCH

Next, some topics for the management of water in the Chilean agriculture that, in the authors's opinion, require further investigation in the near future, will be proposed. In general case, these topics are consistent with some of the guidelines defined by the "Agenda for Agricultural Innovation", that were mentioned earlier. These examples mainly focus on the Limarí Basin (Coquimbo Region, 30º30' S) and the Valley of Peumo (O'higgins Region, 34º S), which are representative of the conditions where agricultural irrigation activity is developed in the Chilean Central North and Central South areas, and where part of the research work of the authors has been carried out. However, it is important to clearly state that the analyzed situations are equally relevant, applicable, and valid for other areas of agricultural importance in Chile.

Soil-Plant-Water Interaction

Soil interacts with water and therefore its characteristics are a reflection of, and sometimes the reason for agronomical decisions. However, in some areas of the country the information on soil and the effects of the irrigation techniques over them is scarce. An interesting case corresponds to the “new” irrigation area in the Limarí Basin, Coquimbo Region, where an important increase of the irrigation surface over land traditionally considered “marginal”, that is, areas above channel location and with important slopes, that sometimes rise over 30%, has occurred in the last years (Figure 4).

Along with the explosive and sustained agricultural development that have taken place in the last decades, it is important to mention that most of the existing soil surveys in the region are rather old (60´s or 70´s), and that they are concentrated on the at-the–time irrigated area. Although they are complete in terms of morphological descriptions, they are at the same time incomplete in terms of physical and chemical analysis. For instance, the La Paloma soil survey, for the Limarí Province, was carried out in 1967 (Alvarez, 2005; SAG-DICORA 1967). Also, the referred study was developed with the objective of the assessment of the soil limiting factors, in terms of their morphology, regarding surface irrigation methods typically used by that time such as furrow and flood irrigation. Thus, limitations were determined as a function of runoff and erosion, issues that should not be as important as other hydrological processes such as infiltration and redistribution when technified irrigation methods such as drip and sprinkle irrigation are used. Even more, the mentioned soil study covered areas that are currently under water (because of the construction of reservoirs) and also did not consider areas that are currently cultivated. In that sense, although the La Paloma system reservoirs (La Paloma, Recoleta, Cogotí) has been functioning for over 30 years, there is no updated database with records to guide the management of the irrigation. This situation, in association with the overall lack of detailed physical and chemical analysis, highly difficult the decision making progress oriented to a sustainable irrigation agriculture.

For instance, as described by Oyarzun and Alvarez (2001) and Alvarez (2005), it is rather common to find in these historically non-irrigated areas soils with fine textures and at the same time relatively very well structures of prismatic type. Thus, a hybrid hydrological behavior is faced: at low water contents (high tension), water circulates through the aggregates matrix, whereas at high water contents (lower tension), water tends to circulate through the between-aggregates spaces. This kind of behavior will affect also root aeration and distribution. Given the fact that roots are the places where growth promoter hormones such as Cytokinines are produced (Kramer, 1983), this should be finally related with above-ground growth (shoots and fruits).

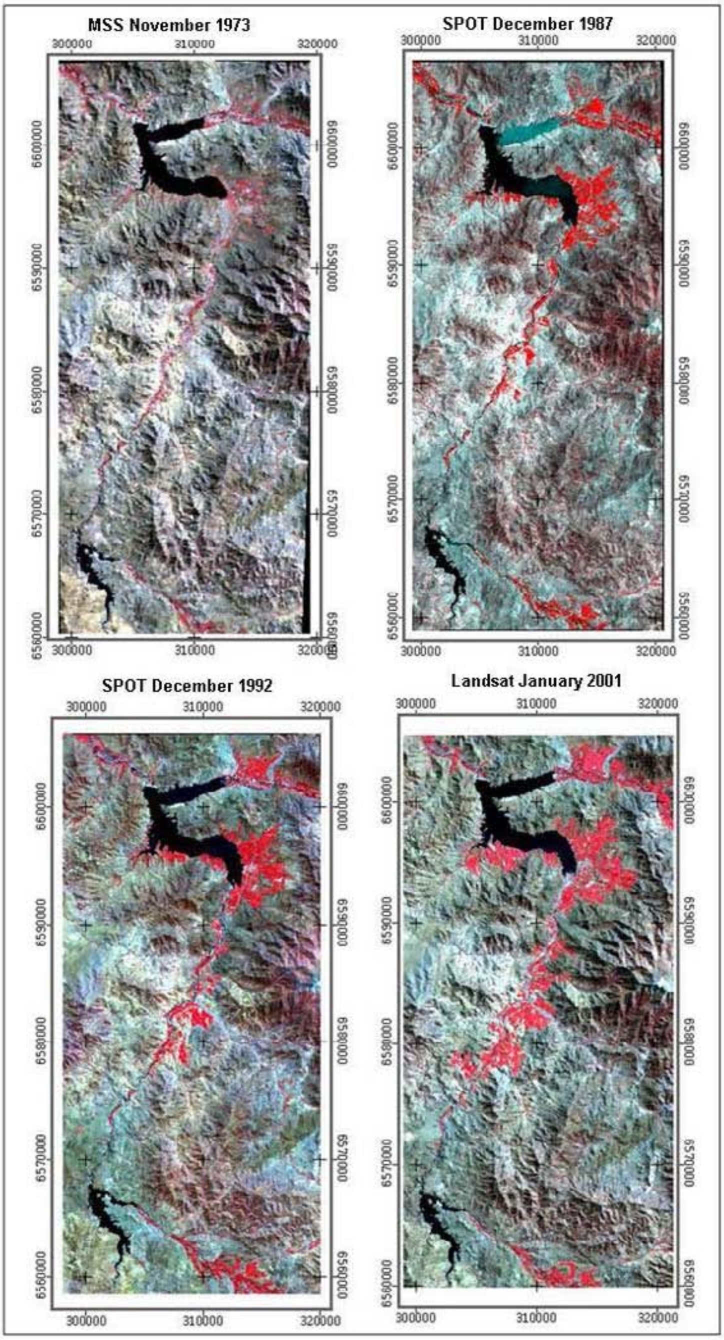

Figure 4: Satellite images (false color) showing the evolution of agricultural land patterns (irrigated areas, in red) in sloped terrains of the Huatulame sub-basin, Coquimbo Region.

As a consequence of the discussed aspects, several questions arise, such as: What happens with the irrigation water movement in the soil?; What is the shape and distribution of the wet bulb and nutrients?; Which are the water accumulation zones?; Are irrigation design and management schemes considering these situations or just practices for flat terrains are followed?; What is the spatial and temporal variability of soil moisture?; When man-made soil ridges are developed, what are the physical properties of this mixed soil where trees are growing? Moreover, this subject becomes more complex when considering clayed soils, in particular regarding sensible species, such as avocado, in terms of water excess and soil oxygen levels.

The effects of situations such as those mentioned should be taken into account when irrigation systems and orchards are designed and planned in these new irrigated areas in sloped terrains. However, it is common to find irrigation systems that have been designed and installed following “standardized guidelines” developed in other regions and with other conditions, without any consideration of the local characteristics. Moreover, the effects of both cropping and irrigation practices in these highly intensive systems over the soil properties and behavior have not been extensively studied. Preliminary characterization on the sector of the Huatulame sub-basin, Limarí catchment (Alvarez, 2005) allow us to mention several effects on the soil such as the beheading of the surface soil horizon, the modification of the stoniness distribution, and the modification of the slope configuration as three important changes induced by irrigated agriculture practices (Figure 5).

Figure 5: Soil surface and profile traits in the Huatulame irrigated area, Limari Province.

Likewise, it has been observed that the excessive labor over the inner rows determines the presence of a secondary compact horizon with scarce roots. In this case, the humidity – machinery use combination generates a flowerpot effect that limits the root useful volume, from the water and nutritional perspective. Another morphological trait of the soils cultivated with vines is the displacement of the original A horizon towards a central ridge. This has caused a different radicular distribution between the plant row (ridge of furrow) and the space between rows. In this case the “A” horizon from the inner row is moved from its original place towards the upper row generating an “Anthropic” profile with an “Ap” horizon with a higher exponent than the original.

Also, it must be considered that irrigation practices, i.e. water application, affect clay swelling/shrinkage processes and the temporal pattern of these oscillations in the soils. Along with this, another aspect that has been observed has to do with the effect of irrigation over the natural saline balance of the soil, adding dissolved salts to the water in addition to that of the fertilizers. Thus, with a larger contribution of fertilizers the salinity should increase in the root area, except that the washing rate applied with irrigation keep the original saline balance.

Evidence of accumulation of salts at the level of the third horizon has been observed, for some of the analyzed soils, probably due to the surface flow and the slow percolation occurring associated to the amount and type of clay, in particular smectites. The salt-leaching washing rate can, undoubtedly, be managed with irrigation, but it’s limited by mineralogy and content of clays. The salt-leaching practice without control could generate anoxic problems (saturation) in addition to an increment in the water use. Finally, traces of eluviation (leached), illuviation (deposit) and the existence of primary and secondary minerals with a particular spatial arrangement have been found through micromorphologic analyses. The eluviation traces indicate that there is an important water dynamic in the soil, and that the inner flows mobilize clays from the superficial horizons towards the lower horizons. Eluviation is itself an evidence of fertility loss because of water (Alvarez, 2005). In summary, there are several components that have not studied yet and that we envision as strategic developing lines for the irrigated agriculture under similar conditions. Considering all these elements, it is possible to state that a proper understanding of these processes, at a local level, is currently required for a successful and sustainable irrigation management and the planning and application of related agricultural practices such as fertilization or soil salt leaching.

Part of this aspects, having a better understanding of soil hydrological processes and their implications in irrigation systems design and management, have begun to be taken into consideration in recently started projects such as the Project SIAR-Limarí (http://www.siar.cl/). The SIAR project is a three years initiative financed by CORFO (Corporación de Fomento de la Producción) through its Innova Program, and its general objective is “to technically assist producers in the programmed and controlled application of the resource, in order to adjust in real time, the dose and frequency of irrigation for the real water requirements of the different species of vegetables during their development”. The aforementioned project considers different aspects of the agronomic system, being one of them the characteristics of soil (hydrologic behavior, depth, texture, density, salinity and physical chemistry composition in general). Even though this is the first year of the SIAR project, it has already been able to generate interesting soil information that will make possible to regulate the water applications made by agriculturists of the basin.

Change of Irrigation Practices an Increase of Irrigated Surface

Along with the soil-plant-water relationships at the orchard level discussed above, the current national trends in the increase of the irrigated agricultural surface, mainly on sloped terrains, with high efficiency systems (drip or sprinklers) have an uncertain hydrological effect at the watershed level (Figure 6). Indeed, from the hydrological point of view, previously in a watershed we have an agriculture area (let say X) that use an amount of water (let say Y) with an irrigation efficient of approximately 30%; that means that an important volume of water return to the watershed (about 70% of Y). In the future scenery we will have in the same watershed an agriculture area of 2X, with an irrigation efficiency of 90%, so the return of water to the watershed will be only a 10% of Y. That will means less water recovery of the rivers.

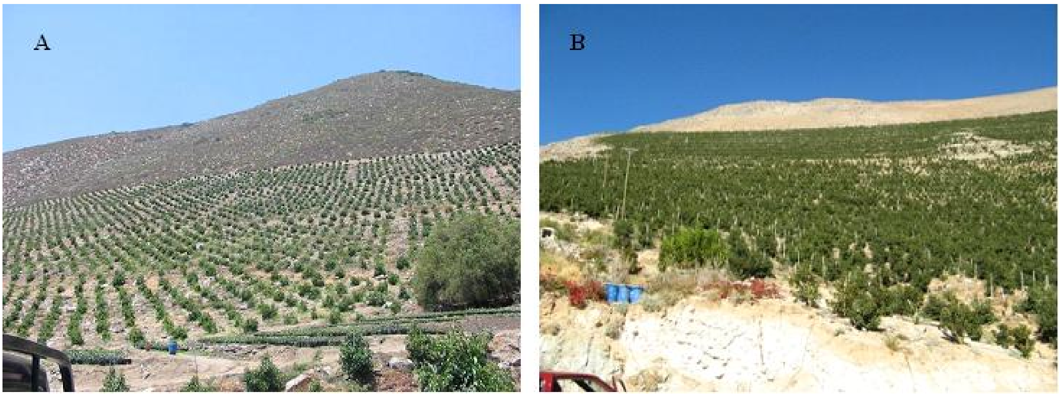

Figure 6: Newly established avocados on hillslope at the Aconcagua Valley (33º S) (Panel A) and the Elqui Valley (30º S) (Panel B)

Now that analysis takes us to the following research questions: What will be the effect of the change on agricultural and irrigation practices on the hydrological regime of the watersheds?; What will be the effect on water rights of the changes on water recuperation of the rivers?

To fully answer the previous questions there are some key issues that must be addressed: a) To develop of monitoring techniques that may work under Chilean reality. That means to considerer in the design aspects such as: i) relative low cost to make affordable the monitoring program; ii) reliability (and accuracy) of the data to be obtained, and iii) Safety and robustness in operation (simple to use and easy to camouflage to avoid vandalism); b) To develop hydrological models which can operate with sparse data. That development should focus on a robust conceptualization and integrated knowledge where scale will be an important issue.

Operation of the Water Market

Along with the expansion of the irrigation surface, another factor to be considered regarding the agricultural development under irrigation in Chile, refers to the declaration of over-allocation of the basins. Due to these situations, which prevents the constitution of new permanent exploitation rights of surface water, it is reasonable to think that a steady increase of the planted surface will require more water resources, which should come from the market (need for transparency, that will be discussed later on) or from the exploitation of new sources such as groundwater (need for regulation and control). Actually, access to the rights can be gained generally through four ways: inheritance, rental, buying, and constitution and inscription of a new right. For example, in the case of the Limarí Basin there is a declaration of over-allocation since February 2005, currently in force and that the DGA uses as a base not to authorize the constitution of new superficial exploitation water rights. Therefore, to gain access there is only the ways of the market or the exploration and application for the constitution of groundwater rights.

Related to the first, market and rights transference (need for transparency), it is worth mentioning that organizations such as the Junta de Vigilancia del Rio Grande-Limarí y sus

Afluentes and the Asociación de Canalistas del embalse Recoleta (both of the Limari Province) have regulated through meetings and directories the transference of rights intra and inter organization. Beyond details, what's important is the structural vision of the system so as to minimize the potential negative effects (external issues) derived from the mobility of the rights. What has been described has evident territorial implications, since the most rigid areas on their water demand sustain their development on the internal agreements of the La Paloma System, aspect that requires maximum transparency. Beyond the economic settlement and public-private negotiations, the System is expected to be fully operated, in the short-term, by privates represented by nine irrigation organizations. Under this context, and considering the responsibility that the private actors are willing to assume, it is possible to wonder how they will develop the controls tools that give feasibility and sustainability to the System, considering that these aspects are the basis of the integration of the basin through the water management and the rights related to it. In the same sense, the operation of the local irrigation organizations has incorporated the volumetric management of the rights but lacks of qualitative monitoring of it, as well as they lack of effective controls of transference and mobility of the rights, state of the installations, and the assessment of the whole efficiency of the System. So, how could the operational management of the basin and of the organizations be preserved and guaranteed, and that can be proven transparent and sustainable?

In particular, transparency on the operation of the basin must be transversal to the organizations allowing transferring to the bases, that is "the irrigation organizations", and finally farmer with water rights, the state of the management. For this reason, the generation of a base protocol for operation of the organizations and of the system as a whole is required. Besides, competent professionals must be trained to develop this function and, finally, constant information of the status of the management at the level of the water communities must be delivered and made public. In this way, the farmers with water use rights will themselves control quantitative and qualitative the integrated management of the basin.

For the above mentioned reasons, it seems important to propose the development of a specialized process of management tools, such as water audits, that ensure transparency and generates an integrated control of the water resources management in basins such as the Limarí. An initiative of this kind was recently submitted (January 2007) as a project to CORFO under the name of "System of Water Audits". The importance of the concept behind this idea is that on the regulatory and politic system that rules the water management in Chile, it is required the creation of supervision and control systems over the operation of the dams and installations of hydrological systems, especially when these will be managed by privates.

As to the second aspect, the use of groundwater, it is worth mentioning that several basins in the Central North area of Chile, area characterized by narrow valleys E-W oriented, with aquifers on porous materials of small dimension in the headwaters of the basin and of middle-size area in the middle and low parts of it, restricted to the recent alluvial deposits. In this restrictive hydrogeological context the legal and technical aspects discussed on the previous sections become relevant. Thus, the interaction of surface water – groundwater subject emerges as a relevant aspect. Despite the current legal separation, the interaction between surface water and groundwater is usually very active. It is particularly important to understand the participation of the surface and groundwater on the supply of the water needs of the basin. Systematic studies of the relations of interaction river-aquifers are essential to provide the DGA and privates with the necessary tools that allow a correct volumetric management of the water in the basins. One option involves the use of analytic expressions like the Jenkins method for the estimation of the river-aquifer interference, and for example it has been used by the organizations of users of the Limari basin to oppose the constitution of underground exploitation rights. Indeed, in the last 6 years irrigation organizations have opposed the constitution of underground exploitation rights for a total of 285 l/s, in 7 localities of the Limarí basin. Another option is to use numeric models and/or stable isotopes analysis. However, the use of any tool depends on the availability of field information with respect to the hydrogeological characteristics of the system, which remains quite limited yet and in a rather coarse scale in several zones of the country.

Lixiviation of Agrochemicals in Orchards

Modern agriculture depends largely on agrochemicals, especially fertilizers and pesticides, in increasing amounts. Because of this, agrochemicals that are not assimilated by crops and those which are not degraded within the vadose area, become a source for potential pollution in groundwater, even when the improvement on the irrigation efficiency allows a decrease in the deep percolation. However, as Lovejoy et al. (1999) point out, the timing and spatial distribution of the application, the crop, soil, slope, hydrogeology, irrigation method, weather and management practice patterns are as important as or more important than the amount of fertilizer applied. Also, Troiano et al. (1993) carried on a study of tracers where it was shown that the distribution of atrazine in the soil profile depends on the amount of percolated water, establishing that gravitational irrigation, used in the valley in study, is the method that percolates the largest amount of water, while localized irrigation methods, like microsprinklers, lixiviate the smallest amount of pollutes. However, the prior does not imply that the election of an irrigation method can decrease in itself the risk of pollution, since the percolated water volumes depend on the operation and management of the irrigation systems.

On studies carried on the Valle de Peumo (O'Higgins Region) in orchards with pressurized irrigation (droppers, microjet), it was confirmed that irrigation generates a relatively constant humid area during the season, where fertilizers accumulate (Rivera et al., 2005 and 2007; Arumi et al., 2006). The areas of temporary storage can be explained by the non saturated mobility of water on soil and unevenness in the humidity-conductivity relation. During summer, under irrigation conditions, because of humidity differences and the bulb stability of the humid area, hydraulic conductivity K_1 inside the bulb is higher than the hydraulic conductivity K_2 in the area surrounding the humid bulb, generating an area of accumulation (Figure 7). During winter, pollutes on these accumulation areas could be transported nearby or under the phreatic level by the effect of rain pulses.

The previously exposed issues allow us to explicit some questions for work: how do the practices of fertirrigation affect the overload of contaminants to groundwater?; how should fertilizers be applied if you take into consideration aspects such as weather and phenological states of the crops or orchards?

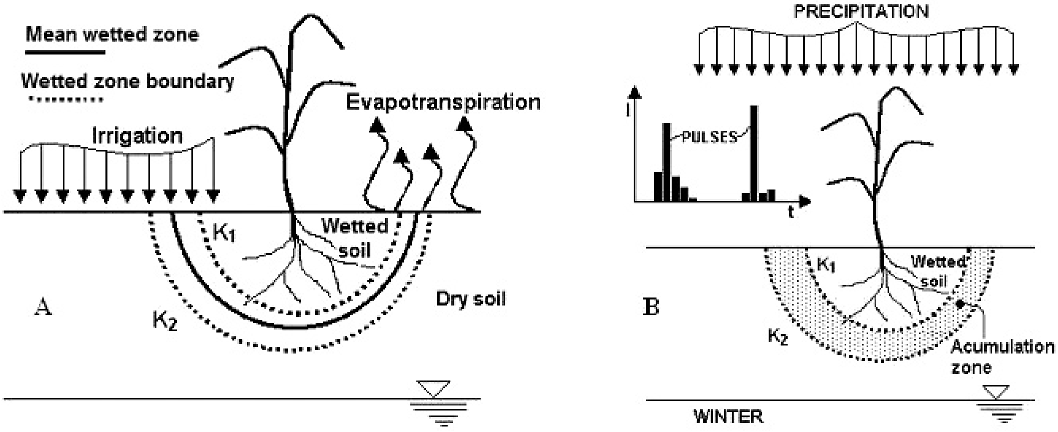

Figure 7: Process of accumulation and transport of pollutes in the humid bulb under localized irrigation and precipitation conditions.

The modeling of the water and fertilizers balance in orchardds must be improved. Currently there are models like Cropsyst or Hydrus that allow for a study of the subject, but these models must be perfected, especially regarding the simulation of the dynamic of water and nutrient extraction from the roots by orchards.

Effect of the Distribution Network of Irrigation Water

Studies of the hydrological effects of seepage from irrigation canals have shown that seepage can be an important source of recharge to shallow groundwater in specific situations. Groundwater recharge from irrigation canals was shown to cause groundwater mounds directly beneath canals (Maurer, 2002), though larger valley aquifer effects were not documented. At the farm, canal and field seepage were shown to increase water tables during the irrigation season in northern New Mexico (Fernald et al., 2007). Larger valley effects have only been documented in few situations. In the North Platte River Valley, for example, stable isotope studies confirmed the irrigation canal seepage origin of recharge that caused a rise in local groundwater levels (Harvey and Sibray, 2001). Lining irrigation canals was shown to reduce the availability of shallow groundwater that supplied wells to irrigate cropland (Calleros, 1991). Modeling studies have illustrated the effect of canal seepage on shallow alluvial aquifers (Youngs, 1977; Yussuff et al., 1994; Ram et al., 1994). If lining canals reduces seepage rates, there may be less recharge to shallow groundwater. In terms of the scientific and technical literature, there is a need to fill gaps in the understanding of the effects of canal seepage on shallow groundwater and larger spatial scales (like the river valley) over longer temporal scales (like the full irrigation season). There is an acute need for improved hydrologic understanding particular to producers in Chile contemplating changed land and water use management.

In the Peumo Valley, irrigation seepage and groundwater recharge patterns were consistent throughout the valley and are illustrated with examples from an upper valley wine grape field well and a central valley observation well. After dropping during the winter, water tables increase by 40 cm three to four weeks after the beginning of irrigation channel operations in September (Figure 8a). Around late spring and early summer, water levels drop again. More detailed information on groundwater response to irrigation seepage was observed with the automated sampling locations in the upper valley wine grape field (Figure 7b). Both wells showed a 35 cm water table increase after the opening of irrigation diversions (usually after September 20th), with the timing of the increase related to their distance from the irrigation canal. Well 1 was located 110 m from the irrigation canal and the water table peak was observed 22 days after the opening of irrigation diversions. Well 2 was located 390 m from the irrigation canal and the water table peak was observed 28 days after the opening of irrigation diversions.

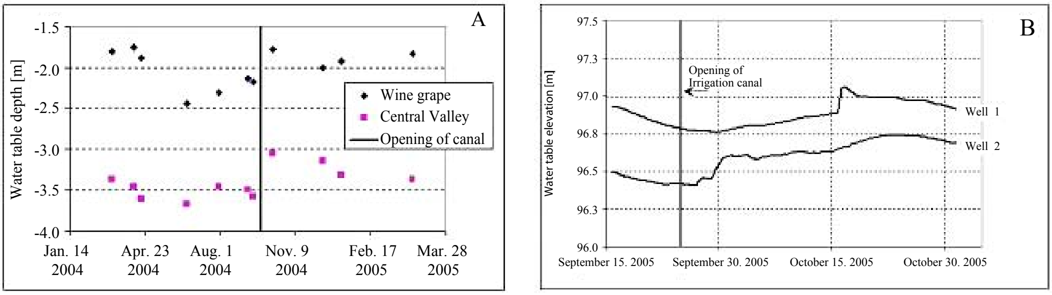

Figure 8: Irrigation seepage and groundwater recharge patterns.

Ongoing process-level study (Arumi, unpublished data) combined with basic water balance concepts lead to the following interpretations of these seepage and groundwater patterns. At the annual scale, water levels drop until June because there is not recharge from precipitation or runoff. There is a delay in water table rise after the beginning of the irrigation season corresponding to the time required to replenish soil available water capacity. Water table declines in spring and early summer correspond to the period of increased plant evapotranspiration demand. For the detailed period before and after the opening of irrigation diversions, the delay of about 5 days from the water table peaks in well 2 to well 1 is a function of the travel time of the pulse of seepage water moving from the irrigation canal under crop lands. Both wells lie on the same line perpendicular to the irrigation canal. Though the peaks (Fig 8b) represent different travel times of seepage pulses, the water table decline corresponds to the exact same period at different locations because it is caused by the evapotranspiration demand.

In the absence of a complex irrigation network, the recharge processes in the Peumo Valley and similar valleys in the region would involve winter wet season surface and subsurface runoff from the Coastal Range uplands into the valley floor. This runoff would recharge groundwater in winter, leading to higher water tables. In the summer dry season, plant evapotranspiration demand and lack of precipitation or upland runoff would lead to lowered water tables. However, in the Peumo valley where there is now a highly developed irrigation canal network, the large main irrigation canals bound the edge of the valley, intercept upland runoff, and transport the water to the river at the lower end of the valley. This runoff interception by canals greatly reduces valley aquifer recharge by upland runoff. The irrigation canal seepage serves to recharge the shallow aquifer in summer, unlike natural recharge that would take place in winter, leading to higher water tables in late spring (Figure 9).

With land and water managers considering lining irrigation canals, it is important to consider how interactions between surface water and groundwater may be affected by reducing or removing canal seepage. In the current water balance of the valley, shallow groundwater levels depend on recharge from irrigation canal seepage. Modifications to the canals, such as lining with impermeable materials, could lead to a reduction of groundwater recharge and changes in crop production patterns due to lowered groundwater levels.

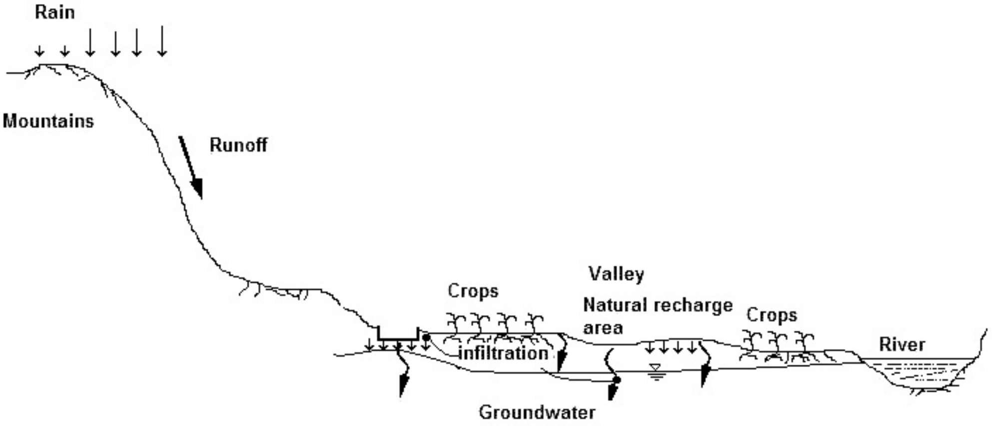

Figure 9: Conceptual scheme of rainfall-runoff-recharge processes

With land and water managers considering lining irrigation canals, it is important to consider how interactions between surface water and groundwater may be affected by reducing or removing canal seepage. In the current water balance of the valley, shallow groundwater levels depend on recharge from irrigation canal seepage. Modifications to the canals, such as lining with impermeable materials, could lead to a reduction of groundwater recharge and changes in crop production patterns due to lowered groundwater levels.

Also, in terms of ecological functions supported by this agricultural landscape, riparian vegetation along the irrigation canals play an important role in diffuse source pollution control and wildlife habitat, both aquatic and terrestrial (Cey et al., 1999; Cirmo & McDonnell, 1997). Field campaigns identified high riparian vegetation production along irrigation canals in the Peumo Valley, and foliar analysis of this riparian vegetation showed high nitrogen concentrations (1000 mg kg^{-1}) similar to local fertilized wine grapes (Arumi, unpublished data). Accordingly, the riparian vegetation acts as a biofilter that naturally contributes to maintenance of lowered nitrogen concentrations in surface waters. It is likely that the riparian vegetation contributes to improved water quality by reducing turbidity and conductivity, important for agricultural management and aquatic habitat, though further studies are necessary to fully characterize these functions.

NEED FOR AN INTEGRATED MANAGEMENT

The concept of integrated development of basins considers that every action carried out on a delimited physical territory will affect the surroundings, and therefore the growth and development of a territory must be harmonic with natural resources. Whether it is an industrial, municipal or agricultural demand, it must necessarily be evaluated by the actors and users of the basin. Here are included, among others, technical, legal, juridical and administrative organisms. Therefore, development of the agricultural activity under irrigation in Chile, and the associated investigations, will require a holistic approach on a Basin level, so that it can be internalized that the agricultural activity is not developed individually, but linked to a series of technical, commercial, legal and environmental elements, both internal (local and national) and external (international). In relation to this, Chile is the Latin American country with the largest number of free trade treaties. The major chains of food distribution of commercial partners in Chile are the ones that increasingly demand health, innocuousness and quality measures. Consequently, it is important to end this chapter briefly mentioning the current situation of the integrated management of basins in Chile and of the scenarios foreseen on short and middle term.

Integrated management of basins is a group of actions that determine the management of a basin, originated from the base of the territory in question through the multi-participative work of users to protect, for example, the water quality and the natural balance of water ecosystems. The concept of integrated management is born with a strong decentralization and local valorization component since every basin is specific.

Even though basin integral management is a new concept in Chile, such concept still lacks of a constitutional and legal frame, and it is addressed, for the time being, in an extremely sectorial way, with legislative adjustments only through the water code. The possibility to apply this discipline not only would allow to achieve territorial planning and zoning, but also to comply with the international compromises and demands acquired by the country. Thus, even if there is not a clear legislation about this issue in Chile, there are some initiatives and debates around the integral management of water resources at the level of hydrographic basin, especially after the 90’s. Nevertheless, in practice, evidence and experience are rather scarce. The DGA is the State organism that has implemented the most important actions towards this goal since 1994, starting with the Bío-Bío Basin (37^o S), in the homonym region, then in the Arica Basin ($18^o30'$ S), Arica-Parinacota Region; Aconcagua Basin (33^o S), in the Valparaíso Region and, recently, on the Choapa Basin ($31^o30'$ S), in the Coquimbo Region. The instruments developed and used include the Directive Guidelines (Planes Directores), for the period 1997-2003, and the support of the basin organisms and the public institutions. However, these initiatives remain as proposals without making significant progress, with partial or sectorial achievements that are far away from the concept of integrated basin management, mainly because of financing problems and lack of the companying legislation. Recently, the National Environmental Agency (Comisión Nacional del Medio Ambiente), CONAMA has been also addressing the subject of basin management initiating a National Integrated Basin Management Strategy, which is currently on a design stage and evaluation of the legal, economical, social, environmental feasibility. Regardless the results of this specific initiative, it is clear that according to the internal political interests and to the demands of external markets, Chilean agriculture and the development of irrigation will have to consider elements beyond purely technical aspects. Surely, these issues will have to be addressed by the new lines of investigation and development policies that will have to be implemented bearing in mind irrigation agriculture.

CONCLUSION

In Chile there is a shared vision by the State and the private sector, which is to become an agricultural food power. This vision generates needs for research that have been partially addressed by the national scientific community. However, this investigation brings forth new questions on the interactions among agriculture-water resources, society and environment. This leads us to affirm that investigation on agricultural water management is actually an open field full of questions and opportunities, and this investigation must consider local, national and international aspects, on a highly dynamic scenario.

AKNOWLEDGEMENTS

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Chapter 6

DEFICIT IRRIGATION AS A TOOL FOR MANIPULATING FLOWERING DATE IN LOQUAT (*ERIOBOTRYA JAPONICA* LINDL.)

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ABSTRACT

A frequent response of fruit trees to deficit irrigation (DI) is a promotion of flowering. This response is often explained because of a lesser competition with exuberant vegetative growth. Here, we report the effects of regulated DI on loquat shoot growth and flowering and discuss the possible mechanisms involved in the promotion of flowering in water-stressed trees. Loquat is a subtropical tree crop that bloom in autumn after a period of summer dormancy. Loquat flowers develop in panicles formed at the apex of the new shoots, therefore shoot growth has to cease before flower initiation can take place. In our experiments, the flowering of fully irrigated trees of 'Algerie' loquat was compared with the bloom in trees undergoing three different levels of DI implemented at post-harvest from mid-June to the end of July. DI levels during these six weeks were: light (50% of the water applied to controls), moderate (25% of the water applied to controls) and severe (no watering). Minor effects due to DI were found on flowering intensity. In contrast, water-stressed trees reached bloom before controls (between 10 and 27 days, depending on treatment). The more severe the water stress was, the earlier the blooming resulted. Blooming advancement was produced despite final shoot length and leaf number remained essentially the same. On the contrary, DI profoundly altered the pattern of shoot growth that changed from a single sigmoid to a double sigmoid. This shift was the result of water stress causing an early, but transitory, cease of growth, which was reassumed up to the length of controls when water deficit ended. Observations carried out under scanning electron and conventional microscopy indicate that panicle initiation occurred days before the fully establishment of summer dormancy, when growth rate in the apical meristem slowed down. The advancements of summer dormancy and panicle initiation correlates well with blooming date advancement. Our results question the hypothesis of resource competition between flowering and vegetative growth and suggest that flowering promotion is the result of a diminished growth rate in the apical meristem due to hormonal changes that favour the process of flower induction. This theory is coherent with the promotion of flowering in response to growth inhibitors and with the negative effects that gibberellins have on tree blooming. The modification of reproductive phenology by the management of the agricultural water may represent a new avenue for improving profitability in tropical and subtropical fruit crops.

INTRODUCTION

A frequent response of fruit trees to deficit irrigation (DI) is the promotion of flowering. This flowering promotion is often explained in terms of a lesser resource competition with vegetative growth effectively restrained by water deficit in evergreen and deciduous fruit trees (Chaikiattiyos et al., 1994; Behboudian and Mills, 1997). This tree response to DI has been successfully exploited to induce out of season blooming and to increase the levels of flowering in many tropical and subtropical fruit crops (Barbera et al., 1985; Crane, 2004; Grierson et al., 1982; Whiley, 1993; Stern et al., 1998; Bally et al., 2000), among them loquat (Cuevas et al., 2007).

Loquat (*Eriobotrya japonica* Lindl.) is a subtropical evergreen fruit tree of the family Rosaceae, subfamily Maloideae that presents an annual cycle reverse to that of the well-known temperate fruit crops. Loquat rests during summer, blooms in autumn, develops its fruit through winter and ripens them in early spring. Its unusual phenology allows growers to obtain high prices for its fruits, especially for early-season harvests. In previous experiences, we have demonstrated that deficit irrigation is a useful strategy to advance harvest date making the crop more profitable (Hueso and Cuevas, 2007).

As occurred in other pomes, loquat blooms apical; in this species forming terminal panicles in current year wood. Apical flowering requires the end of shoot growth before panicle initiation can take place. This occurs in some moment after a period of summer dormancy poorly characterized. New shoot growth become then both support and competitor of flowering. Same flowering habit applies to others tropical and subtropical fruit crops where the management of shoot growth using different techniques has resulted in increasing levels of flowering (Davenport, 2003; Salazar-García and Vázquez-Valdivia, 1997; Stern and Gazit, 1993). Here, we report the effects of different levels of water deficits on shoot growth and flowering and discuss the possible mechanisms involved in the promotion of flowering in response to the imposed water deficit.

MATERIAL AND METHODS

This experience was carried out in season 2005/06 in an experimental orchard of ‘Algerie’ loquat trees located at the Experimental Station of Cajamar Foundation “Las Palmerillas”, in Almería (SE, Spain). The area presents a semi-arid subtropical climate with an average rainfall of 231 mm and evaporation from an “A” pan (Epan) of 1922 mm per year. Mean annual temperature and humidity is 18ºC and 68%, respectively. Orchard soil is a well-aerated sandy-loam (72.4% sand, 14.6% loam, and 13.0% clay), pH 7.8. Field capacity is 13.4%, while wilting point is 5.1%.

Adult ‘Algerie’ trees grafted on ‘Provence’ quince were used for the experiments. The trees are vase-trained and 5 x 5 m spaced. Four irrigation treatments were applied to these trees. First treatment was a control in which trees were fully irrigated with about 40% of Epan measured with a Class A pan placed in the orchard. Next three treatments were different DI strategies in which trees received a 50%, a 25% or 0% of the water applied to controls (treatments W50%, W25%, and W0%, respectively) during a period of six weeks, from mid-June (around 8 weeks after the end of previous harvest) to the end of July. Soil water content in response to treatments was monitored using Watermark (Irrometer Co. Inc.) electrical-resistance blocks. The changes in soil moisture were followed using three sets of sensors, one set per block and treatment, placed at 30, 60 and 90 cm depth. Plant water status in response to the treatments was monitored by measuring stem water potential (Ψst) during the period of deficit irrigation using a Scholander pressure chamber. Six mature leaves per treatment were sampled from the outer part of the canopy at 1.75 m height.

Effects of DI treatments on flowering date, length and intensity, and on shoot growth were analyzed following a randomized complete-block design with three replications per treatment. Each replication consisted of one row of trees hydraulically isolated by placing a plastic film 1 m deep, where most quince roots are restricted. The two central trees of the row were chosen for measurements. Tree phenology was followed on these trees from summer rest to bloom using phenological stages described by Cuevas et al. (1997). Flowering date and length and advancement of full bloom with respect to controls were calculated based on observations carried out twice per week. Bloom intensity was estimated on main shoots and secondary late-formed shoots by the percentage of them forming a terminal panicle in ten randomly chosen shoots of each type per tree. The number of flowers per panicle in main and secondary shoots was counted on four panicles per tree.

New growth was followed by counting the new leaves formed from mid-June to the end of September every five days in ten main shoots per tree. Shoot length was also measured with the same periodicity. Plastochron (i.e. days needed between the formation of two consecutive nodes) was calculated along the growing season.

Flower initiation was dated in the most extreme treatments (control versus W0%) by scanning electron and conventional microscopy. To do so, twenty four terminal buds (four per tree) were sampled weekly from mid-July to mid-November. With the aim to process the most representative and uniform samples for each date, the buds once collected at random were taken to the lab and ordered by size. Then, the four intermediate-sized buds were selected for SEM studies and fixed in 3% glutaraldehyde in phosphate buffer, pH 7.2. Before observation, the buds were partially dissected removing most external bracts under binocular, and subsequently dehydrated, critical point dried, sputter-coated with 20 nm gold, and finally observed under a Hitachi S-3000N Scanning Electron Microscopy, mostly operated at 15-20 kV. The remaining twenty buds, also partially dissected, were fixed in a mixture of formalin-glacial acetic acid-alcohol (FAA), dehydrated in tertiary butyl alcohol and ethanol series, and embedded in paraffin wax. The embedded buds were then sectioned at 10 µm using a Leica RM 2125RT microtome. Finally, preferred sections were stained with safranin, crystal violet and light green (Gerlach, 1969).

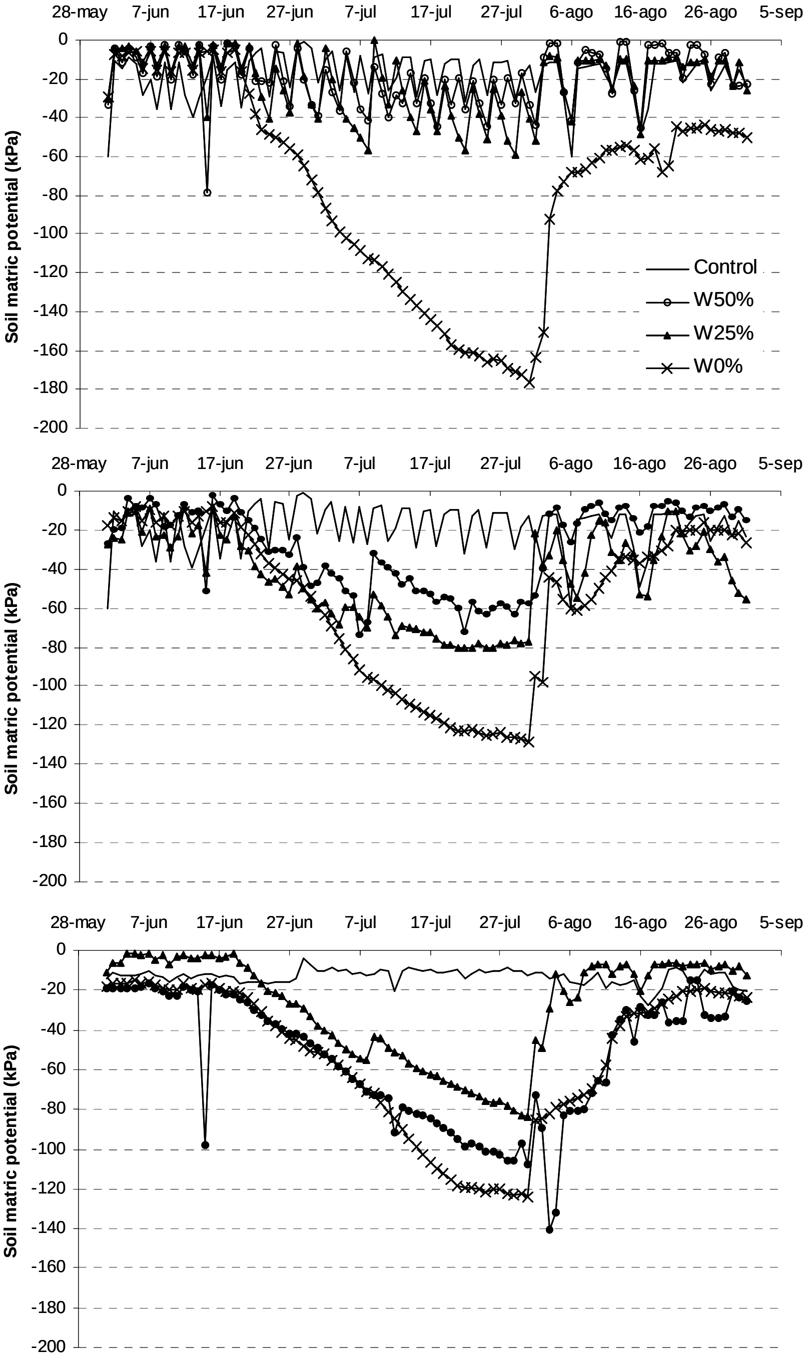

Figure 1: Soil matric potential at 0.3 m (top), 0.6 m (center) and 0.9 m depth (bottom) during the six week experimental period in control full irrigated trees and trees suffering different levels of water deficits.

RESULTS

Deficit Irrigation Effects on Soil and Plant Water Content

Controls trees received circa of 6800 m^3 per ha of water along the season; 990 of them applied during the six-week experimental period. During this time, W50%, W25% trees 450 and 259 m^3 per ha, respectively, while W0% trees were not irrigated at all. Rainfall during the season accounted for a total of 229 mm; there was no rain during the DI period. DI treatments progressively diminished soil water content during this period (Figure 1). The rest of the year water soil content did not differ among treatments (data not shown). At the end of the period of water shortage, soil around W0% trees had Ψm values of -172 kPa, -127 kPa and -123 kPa at 30, 60 and 90 cm depth, respectively while in W25% soil reached Ψm values of -26 kPa at 30 cm, -57 kPa at 60 cm and -83 kPa at 90 cm. Water content of soil around W50% trees was kind of similar to that observed for W25% (-17 kPa, -77 kPa and -97 kPa, for 30, 60 and 90 cm depth, respectively). In contrast, soil around control fully irrigated trees was close of field capacity showing Ψm records between -10 and -20 kPa, along the season. The reduction of soil water moisture in moderate and severe DI treatments translated into the plant, but seemed not to affect to W50% trees. Controls and W50% presented similar Ψst values at the end of July (Ψst=-1.07 MPa for controls versus -1.37 for W50%). More negative records were reached at the end of the water shortage period in W25% and W0% (Ψst=-1.74 and -2.07 MPa, respectively). Differences were significant between these two groups.

Deficit Irrigation Effects on Flowering

The alteration of soil and plant water status modified reproductive phenology of ‘Algerie’ loquat. At this regard, all deficit irrigation treatments promoted earlier flowering. However, the more severe the water stress was, the earlier the blooming resulted. Therefore, the earliest blooming took place in W0% trees (October 22nd, 27 days ahead of control trees). A noticeable advancement in full bloom also occurred in W25% trees, which flowered on October 28th, 21 days before than controls. W50% reached full bloom on November 8th, ten days before control trees (Figure 2). Control trees bloomed on November 18th. The average full bloom date of these trees is November 23rd (9 years controlled). Water-stressed trees not only reach full bloom date earlier than control trees, but they also opened their first flowers before (Figure 2).

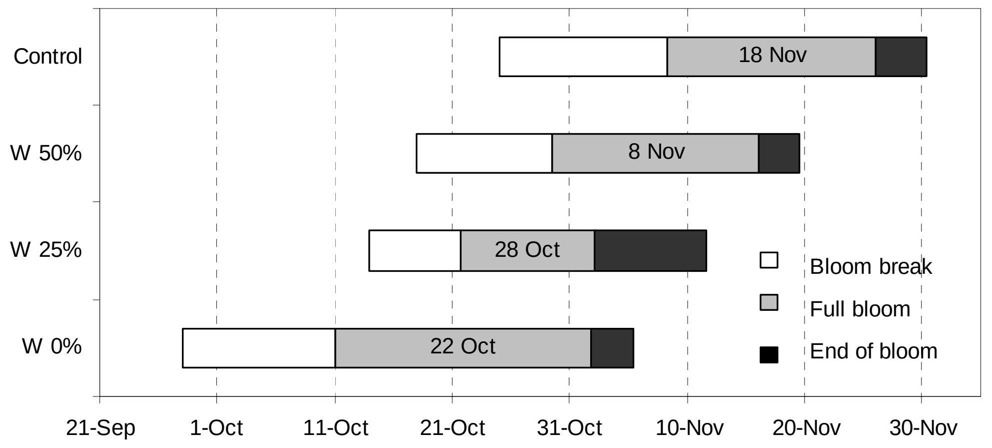

Figure 2: Blooming course of control full irrigated trees and trees suffering different levels of water deficits.

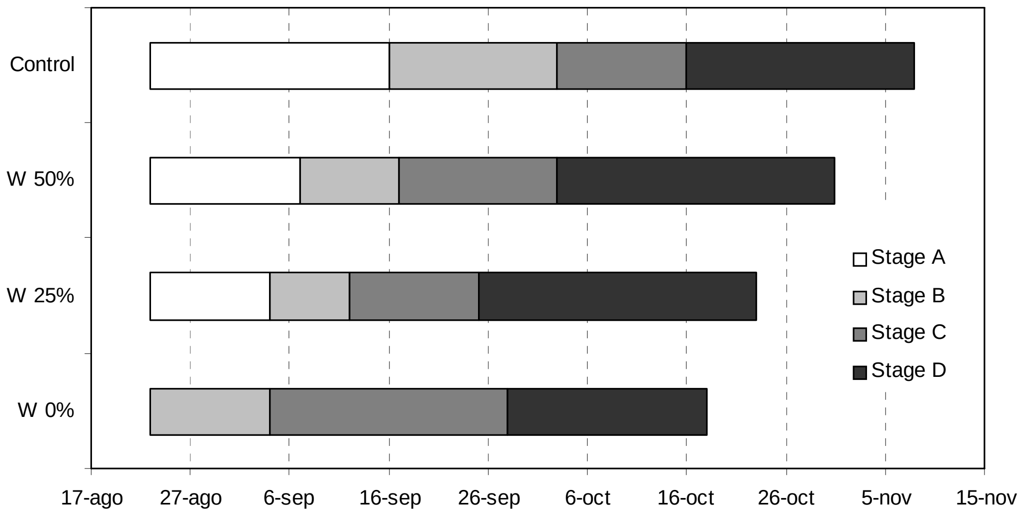

Figure 3: Loquat phenology from dormancy to visible floral buds in control full irrigated trees and trees suffering different levels of water deficits.

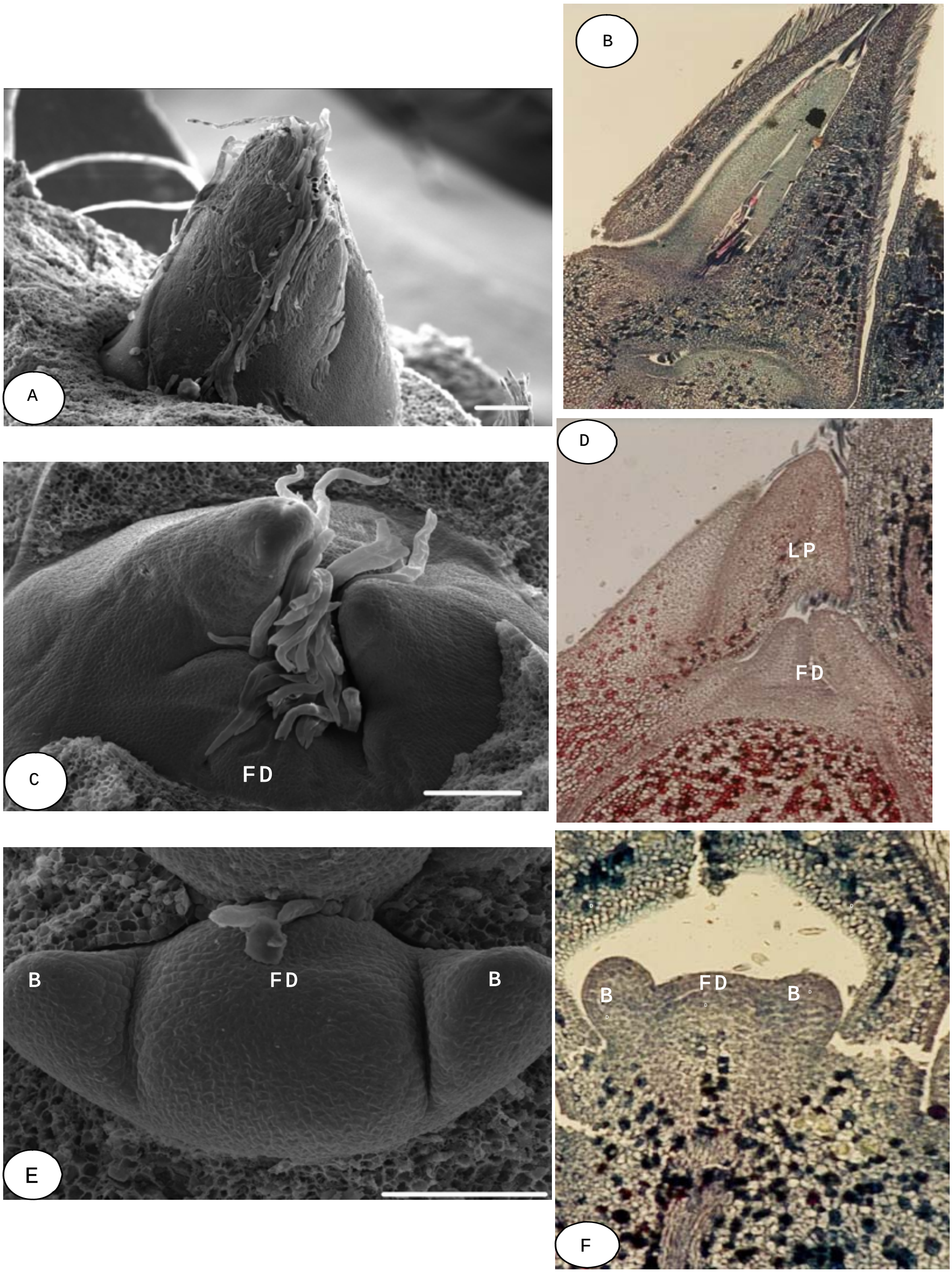

Figure. 4. First stages of panicle initiation and development. A and B. Vegetative meristem. C and D. Panicle raising. E and F. Bracteoles formation. FD: Floral dome. LP: leaf primordia. B: bracteole.

The advancement in full bloom and bloom break dates for water-stressed trees basically coincided with the advancement observed in prior-to-bloom phenophases. In effect, bud dormancy release and panicle differentiation phenophases occurred before in W0% trees followed by W25% and W50% trees (Figure 3). Furthermore, flower initiation date determined by scanning electron and conventional microscopy confirmed that the changes within the bud associated to flower initiation occurred before in samples of water-stressed trees (Figure 4). In these samples, anatomical changes compatible with the initiation of the panicle were recognizable on July 7th in water-stressed trees, while similar stage of development was reached by well-watered trees three weeks later (25th July). The subsequent stages of panicle elongation and individual flower bud initiation were seen in control trees samples during the first weeks of August, and between 12 and 18 days before in water-stressed trees (Figure 4).

On the other hand, no clear pattern in the duration of the phenophases can be inferred from the comparison of treatments. In control trees, 36 days were needed to take a bud from dormancy release to anthesis, while 33 days passed in W50% trees between bud break and bloom, and no less than 39 days in W0% trees (Figure 3). Only W25% trees exhibited a little faster developmental rate during panicle formation phenophases (30 days), also expressed in a more compact blooming period.

Finally, DI only caused minor effects on flowering intensity. The percentage of bearing shoots was slightly enhanced by DI (Table 1). The differences were not significant in main shoots. However, the differences in secondary late-formed shoots, although small, reached statistical significance. No differences were observed in the number of flower per panicle in main shoots, while in secondary shoots the most severe DI treatments (W0%) had a reduced number of flowers per panicle (Table 1).

Table 1: Effects of Regulated Deficit Irrigation treatments on bloom intensity and shoot growth

	Bearing shoots (%)		Flowers/panicle		Main shoots	
Treatments	Main shoots	Secondary shoots	Main shoots	Secondary shoots	Leaf Number	Shoot length (cm)
Control	90 a[1]	74 b	265 a	164 ab	17 a	14.3 a
W50%	97 a	89 a	232 a	182 a	16 a	12.2 a
W25%	100 a	98 a	237 a	175 a	17 a	11.1 a
W0%	98 a	93 a	230 a	138 bc	17 a	12.4 a
P	NS	0.05	NS	0.005	NS	NS

[1] Different letters in each column indicate significant differences according to the p-value. NS, not significant ($P>0.05$). Percentage data were previously arc-sin transformed. Duncan test.

Deficit Irrigation Effects on Shoot Growth

Shoot growth in control well-irrigated trees fitted a sigmoid pattern (Figure 5). New growth started immediately after harvest and kept a regular pace until early August, when summer rest was imposed in apical buds (August 10th). Plastochron length was very regular during the first weeks, but was greatly enlarged as summer rest approached. Control trees abandoned dormancy in early September forming the terminal panicle. Final length of main shoots in control trees reached 14.3 cm. Seventeen new leaves were formed in these main shoots. DI did not diminish the length or the number of leaves per shoot (Table 1). However, DI profoundly altered the pattern of shoot growth that changed from a single sigmoid to a double sigmoid (Figure 5). This shift was the result of water stress causing an early, but transitory, cease of growth, which was reassumed up to the length of controls when water deficit ended. Modification of shoot growth pattern was more acute in trees where irrigation was completely suspended (W0%) and less noticeable in trees where water irrigation was cut by half (W50%). No new nodes were formed in W0% trees since the beginning of July and summer rest was already established two weeks after water withholding. The onset of summer rest occurred last week of July in W25% trees, while it could be dated at the beginning of August in W50% trees. The release of rest in apical buds was almost immediate in all DI treatments after the resumption of full irrigation. On mid-August just a few days after the end of water deficit, the trees responded forming new leaves below the differentiating terminal panicle (Figure 5). The variations in shoot growth rate along the experimental period expressed in large changes in plastochron length of W0% trees from more than 40 days to scarcely 2, when bud dormancy release and rapid growth occurred. Less marked changes took place in W50% and W25% trees.

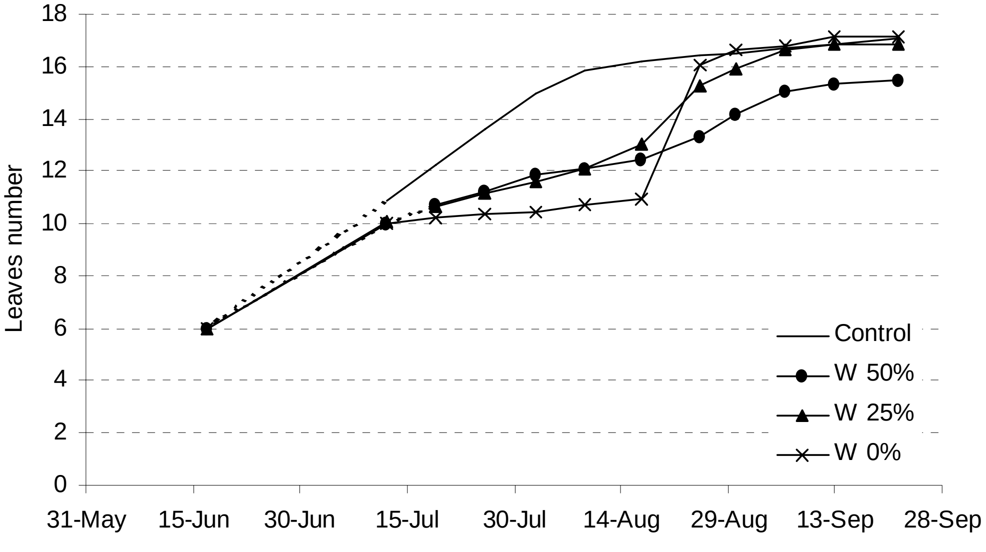

Figure 5: Shoot growth in control full irrigated trees and trees suffering different levels of water deficits.

DISCUSSION

Proximate Causes of Flowering Promotion in Water-Stressed Loquats

Previous experiments have demonstrated that posharvest DI is a useful strategy to advance bloom and harvest dates in loquat, making the crop more profitable (Hueso and Cuevas, 2007). However, the causes determining bloom earliness could not be explored in that experience. Shoot growth involvement in early flowering has been now specifically addressed. The correlation found among the advancements in terminal bud dormancy, panicle development and bloom dates informs that loquat earliness in response to DI is due to a complete displacement of the reproductive cycle, from flower initiation to full bloom and harvest.

This phenological displacement can be explained by DI effects on shoot growth and rest. Our results show that DI treatments progressively reduced soil water content, effect that in turn was translated into the plant. The reduction of water availability determined an earlier suspension of shoot growth in water-stressed trees, allowing terminal buds to differentiate into panicles before. SEM and conventional microscopy images confirm that the first anatomical changes in the apical meristem leading to the formation of the panicle occurred three weeks earlier in W0% trees. This transition to flowering occurred days before the full establishment of dormancy in the apical bud, when the formation of new leaves slowed down (i.e. increasing plastochron length). Panicle initiation preceding bud dormancy has been observed in avocado indicating that rest is not a prerequisite for the transition to flowering (Salazar-García et al., 1998). Certain growth of buds during the exposure to cool inductive temperatures also appears to be necessary for panicle initiation in mango (Núñez-Elisea and Davenport, 1995). In apple, hand-defoliation soon after harvest makes possible a second annual crop in Indonesia, by preventing dormancy entrance in a time in which flowers are already initiated (Edwards, 1985).

After panicle initiation, flower development will continue if water deficit does not prevent it. At this regard, bud break and panicle development phenophases also proceed first in water-stressed trees, because the timely resumption of full irrigation. On the contrary, a prolongation of DI during August has been proven detrimental for bloom earliness because water stress delays the last steps of panicle elongation (Cuevas et al., 2007). In contrast to the success of moderate and severe DI treatments, pulses of water shortages as those caused by W50% advanced flowering date in a minor extent because they were not able to make buds to enter in dormancy long before controls. Light water-stress caused by a 20% reduction in watering along the season has also failed to substantially modify flowering date in previous experiments (Hueso and Cuevas, 2007). Work in progress is trying to determine the optimum levels of water stress that more rapidly activates the flowering process in loquat. The hypothesis is that a moderate water stress switches on the flowering program without restraining panicle development. A severe stress may serve, however, to extend the positive effect to the whole bud population making blooming season more compact and uniform. The gradual modification of loquat phenology from panicle initiation to bloom in response to increasing water deficits demonstrates that bloom earliness under DI is due to an advancement of the flower induction process and not due to a higher developmental rate in water-stressed trees, as it has been argued in mango (Núñez-Elisea and Davenport, 1994). Bringing first discernible response to DI to summer can be useful to farmers since provides an early indication of success.

Flowering advancement in water-stressed loquats coincides with observations carried out in citrus and mango. Out of season flowering in response to water withholding is a well-known strategy for citrus producers (Barbera et al., 1985). In several species of genus Citrus, a severe water stress imposed in summer provokes, after rewatering, a second bloom that sets a more valuable crop next summer (Maranto and Hake, 1985). In mango, water stress also advance bloom date (Núñez-Elisea and Davenport, 1994; Lu and Chacko, 2000). Because fully irrigated mangoes bloom profusely (as our control trees), Núñez-Elisea and Davenport (1994) conclude that water stress is not essential for induction of floral morphogenesis in mango grown the subtropics, where cool temperatures have been identified as the main flowering stimulus. In the tropics, however, night temperatures remain too high for induction and a dry period is proposed as the environmental cue for flower induction (Lu and Chacko, 2000).

It is worthwhile to mention that although the onset of summer rest took place before in DI treatments, the number of phytomers, structural segments composed of a leaf, bud, node and internode, was not modified by water deficit. From our results is deduced that the last phytomers were initiated and its founder cells recruited at the time water stress was imposed. At this moment, a number of leaves may still expand, but others remain as undifferentiated foliar primordia below the differentiating terminal bud, until the recovery of plant water status. In lychee, a tropical species with terminal panicles, the same levels of DI here applied (50%, 25% and 0%) greatly reduce postharvest shoot growth and increase flowering and yield. This results made to the authors conclude that resource competition among vegetative and reproductive growth operate in lychee. In loquat, same shoot leaf number and similar length in fully irrigated and water-stressed loquats suggests that the amount of resources allocated to vegetative versus reproductive growth scarcely changed in response to DI.

Ultimate Reasons behind Flowering Promotion in Water-Stressed Fruit Trees

A model for explaining flowering promotion in water-stressed trees is then alternatively proposed. From Arabidopsis studies, we have learned that the transition to flowering in annuals may be regulated by multiple signals and multiple pathways. In Arabidopsis, flowering is controlled by four pathways. All these pathways converge to regulate the meristem identity gene *LEAFY* (Soltis et al., 2002). A *LEAFY-like* gene has been recently isolated in six species of *Maloideae* including loquat, where the highest levels of transcription are expressed at bud break (Esumi et al., 2005; Liu et al., 2007). One of the floral pathways identified in Arabidopsis is GA dependent, but whereas GA is a floral promoter in long-day annuals, it inhibits flowering in fruit trees (Sedgley and Griffin, 1989). This fundamental difference in the role of GA has to be taking into account when proposing a model for flowering in fruit trees. In annuals, an increase in GA activates floral pathways integrators that regulate the formation of flowers (Ausin et al., 2005; Percy, 2005). The situation must be reverse in fruit trees where fast shoot growth as that provided by GA cancel the chance of bud dormancy and flower initiation in fruit trees. For this reason, flower initiation in Angiosperm woody plants is not only compatible but it may require bud dormancy.

In our model, drought promotes abscisic acid (ABA) synthesis and transport to the leaves to induce rapid stomata closure (Beardsell and Cohen, 1975). ABA antagonism with growth promoters hormones, noticeably gibberellins (GA), may eventually lead to a hormonal balance favourable to the onset of terminal bud dormancy (Wareing, 1978; Michalczuk, 2005), allowing flowering program to be expressed. This is not to say that ABA plays a role of floral promoter but that its antagonism with the floral inhibitor (GA) indirectly promotes flowering in water-stressed trees. Goldschmidt and Samach (2004) argue that woody perennials may be constantly induced, but the flowering is repressed by a floral inhibitor (GA in our model) which would act in a similar manner as FLOWERING LOCUS C gene represses flowering transition in Arabidopsis. No need of floral promoter in fruit trees is deduced from this approximation. GA involvement in shoot growth is well documented in annuals and woody plants, where low GA content reduces growth, especially internode elongation. ABA, formerly known as "dormin" (Eagles and Wareing, 1963), specifically inhibits GA biosynthesis and blocks the formation of enzymes as α-amylase that are stimulated by GA to obtain energy for maintenance and growth. Furthermore, GA and ABA are both terpenoids that share the same promoter, the mevalonate, allowing competition for substrate to take place. Common tree flowering promotion in response to triazoles application and ABA may respond to the antagonism of both molecules to GA biosynthesis.

Note that in this model, new leaves as a source of flower inhibitors are not required for explaining lack of flowering in active growing shoots. Rather on the contrary, the presence of new leaves is the negation of the conditions required for flowering transition to occur. Reduced activity in the apical meristem (i.e. increased plastochron) due to water stress is the only switch needed for the activation of the flowering program that includes bud competence and flower initiation during summer. Some kind of citokinins (CK) involvement in bud dormancy onset and release seems likely since its synthesis in roots and delivery to the leaves is usually decreased in water-stressed plants (Pospíšilová, 2003). Low CK levels during dormancy and an increase during dormancy release suggest to CK may reinforce the role of GA in bud break. This theory is coherent with the promotion of flowering in response to growth inhibitors and with the negative effects that gibberellins have on tree blooming and fits a series of field observations including tree response to pruning, watering and nitrogen overfertilization.

Many others tropical and subtropical fruit crops seem to require reduced vegetative activity for flowering transition. In lychee, a period of vegetative dormancy is needed to initiate floral buds. This dormancy can be induced by low temperatures, water stress, withholding fertilizers, cincturing and auxin sprays (Menzel, 1993). Whiley and Schaffer (1994) have also noted that flower induction in woody subtropical and tropical evergreen species usually follows a period of quiescence in the canopy caused by environmental conditions (temperature and drought). Bower et al. (1990) propose a simple model to explain flowering in avocado in response to low temperatures that also relays on vegetative growth stops and low GA content. In this model lack of shoot growth (low GA) would conduce to a reduction in available carbohydrates and to an increase in CK and ABA synthesis by new roots. In avocado, CK would increase the number of sprouting buds while ABA would regulate the transition to flowering in apical buds. This scenario coincides with Ben-Tal (1986) inhibitory theory, in which vegetative growth end is marked as a necessary step for flowering to take place in fruit trees. Ben-Tal (1986) emphasizes that vegetative growth disturbance is the general rule that explains tree flowering in response to many different inductive factors such as day length, temperature, hormones, plant size and, as in water-stressed loquats, drought.

Although the previous model for flowering promotion in water-stressed loquats seems plausible, an identification of the environmental factors stimulating terminal bud dormancy and flower initiation in well-irrigated loquats is still needed. This floral stimulus must be naturally produced and must be responsive to water-stress. Two different possibilities arise: correlative inhibition (paradormancy) exerted by competing organs and an environmentally induced dormancy (ecodormancy). In temperate-zone trees, paradormancy develops as days shorten in late summer (Faust et al., 1997). During this period, ABA content increases, although dormancy is still relatively shallow. In late fall, dormancy becomes more intense as dehydrins accumulate in the bud triggered by ABA and decreasing air temperatures (Faust et al., 1997). Arora et al. (2003) acknowledge the difficulty delinking the functions of ABA in cold hardiness versus dormancy in the buds of temperate-zone fruit trees. Different results make the authors yet to assign a major role of ABA in cold acclimation. However, this function does not fit into loquat characteristics since its terminal buds are formed in summer and do not exhibit cold resistance (loquats bloom on November). Although the literature commonly infers that the short day length of late summer is responsible of the cessation of shoot growth, many temperate-zone woody plants, as well as loquat, form terminal buds in early summer with long day periods (Powell, 1987). Shoot growth cessation at this time may be due to the competition of numerous metabolic sinks for essential metabolites (Powell, 1987). Whatever the final reason and exact time may be, shot elongation ceases and apical bud dormancy is established. Correlative inhibition of the apex by mature leaves operate in apple as it has been shown in hand-defoliation experiments (Faust et al., 1997). Interestingly, an ABA decrease, a GA increase and small changes in CK take place in these apple floral buds forced to break paradormancy (Edwards, 1985). Mango apical buds also exhibit foliar paradormancy (Núñez-Elisea and Davenport, 1995). Apical bud paradormancy triggered by an early increase of ABA in mature leaves is compatible with the flowering advancements achieved under DI.

On the other hand, the analysis of loquat phenology has shown that in control trees terminal bud enters in dormancy in August when the evapotranspirative demand and temperatures are high (Cuevas et al., 1997). Water soil content and plant water status in fully irrigated trees negate, however, a situation of water stress, leaving high temperature as the only relevant environmental factor. In this situation the great similarities between seed and bud dormancy (Powell, 1987) may be of help. Seed dormancy induced by high temperature is known as thermodormancy. Thermodormancy inhibits seed germination in late summer in many important crops. ABA and other GA inhibitors cause seed thermodormancy, while chilling and GA release seeds from dormancy. Same situation may apply to loquat buds. This mechanism for inducing ecodormancy is compatible too with the flowering advancement observed under DI. At this regard, it is well known that drought increases leaf temperature which indirectly may advance bud thermodormancy. Rewatering, on the contrary, reduces leaf temperature. Environmental effects on bud dormancy maintenance can be deduced by comparison of loquat behaviour in contrasting climates. In the tropics (San Juan del Obispo, Guatemala), with constant moderate temperatures (25/15ºC) along the year, loquat has modified its annual cycle at high altitudes and forms panicles during a dry period in spring (the usual time for harvest), reaching bloom during the wet summer. This shift suggests a favourable effect of water shortages on flowering transition, but disregards temperatures as main dormancy inducers (B. Sercu, com. pers.). The effects of defoliation and high temperatures on potted loquats are now in study trying to elucidate the factors causing the onset and release of terminal bud dormancy in this species.

CONCLUSION

In conclusion, our results shown that postharvest DI advances loquat bloom dates thru an effect on shoot growth and dormancy onset and release. Apical bud dormancy is briefly preceded by panicle initiation indicating that a large plastochron length (i.e. reduced meristem activity) is the switch that activates the flowering program in loquat. The advancement in harvest date in response to DI and the consumers' appreciation for early season loquats clearly demonstrate that the modification of reproductive phenology by means of the management of the agricultural water is profitable in this species. We also expect from these studies to bring some insight into the endogenous factors controlling flowering in other tree crops. The unusual phenology of loquat makes it a suitable model to explore the role of water stress, bud rest, and hormonal changes in the flowering of fruit crops, more economically important as apple and pear. A major difference with these closely related species is that loquat bud break follows summer rest and no fruits are present at this time. Although water deficit causes an early rest too in these temperate-zone tree crops (and the prolongation of the watering a delay that increases frost risks), the confounding effects of chilling requirements for bud break makes them less amenable for experimentation. Finally, a model for flowering promotion under DI is proposed and the environmental and endogenous factors leading to flower induction in loquat discussed.

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Chapter 7

DEVELOPING A CLASSIFICATION SYSTEM OF WATER ENTITLEMENTS FOR SUSTAINABLE WATER MANAGEMENT IN THE MURRAY-DARLING BASIN, AUSTRALIA

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ABSTRACT

It is increasingly realized that water resource management has played a vital role in Australia’s economic, environmental and social sustainable development. However, many water-related issues face growing scrutiny and policy debate. A major part of the Council of Australian Governments (COAG) water reforms was the development and implementation of consistent and tradable water entitlements, which represent key attempts to standardize approaches to water resource management at a national scale. As part of this process, the Murray-Darling Basin (MDB) has faced a number of challenges in designing a robust system of water entitlements that jointly meet the needs of entitlement-holders, community and the environment. This chapter aims to identify the features of different water entitlements arrangements and develop a classification system. First, the chapter outlines an overview of water management in the MDB. Next, it provides a property rights analysis of existing water entitlements arrangements and the broad directions that governments may take in the light of water entitlements system reforms. Then, a water entitlements classification system is proposed and its policy implications are discussed. The chapter concludes that significant challenges remain to be overcome before implementing a consistent and tradable water entitlements system in the MDB.

1. INTRODUCTION

The Murray-Darling Basin (MDB) is the biggest catchment in Australia. It covers 1,072,000 square kilometres and encompasses roughly three-quarters of New South Wales (NSW), half of Victoria, a substantial portion of southern Queensland, and a small part of eastern South Australia (SA) (see Figure 1). Although the MDB receives only 6% of Australia's rainfall, it is the scene of 70% of Australia's irrigation. It contains 42% of Australia's farmland and produces 40% of the nation's food. The diverse legislative, geographic, economic, environmental and political history of water use and management in the MDB has left us with a plethora of water entitlement systems for different purposes (e.g., for irrigation, industrial use, and domestic supply). Currently, there are 22 categories and 438 types of surface water entitlements throughout three jurisdictions (i.e., NSW, Victoria and SA) in southern MDB. Among them, nine categories and 183 types of entitlements are for irrigation purposes (Shi 2005, 2006). The variety of forms and structures of water entitlements reflect the differing approaches by the states to partitioning and dealing with a range of water users. The Council of Australian Governments [1] (COAG), the Murray-Darling Basin Ministerial Council (MDBMC), industry, politicians and conservation organizations are all calling for improvements in the way water entitlement systems are defined and administered.

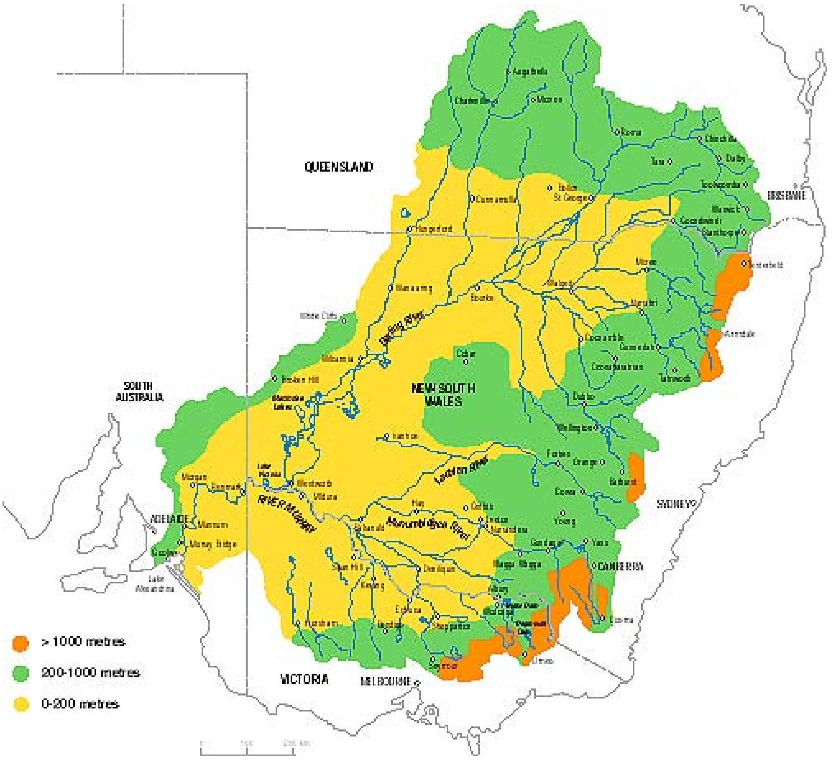

Figure 1: The Murray-Darling Basin

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[1] COAG comprises the Premiers of the various sovereign states, together with the Prime Minister of the Commonwealth of Australia. It debates matters of national significance.

Water resource management is complex and evolving because of the different physical characteristics of water systems and the various super-imposed institutional and cultural frameworks. Water entitlement systems occur at incompatible scales of analysis and are classified differently by different states. The absence of appropriate exchange rates [2] has further created impediments to entitlements trading due to variability in the entitlement attributes. Exchange among different water entitlements creates opportunities for arbitrage, administrative error and potentially is highly restrictive, costly and inefficient. Therefore, water entitlement systems should be defined in a consistent manner as an antecedent to trade proceeding at both the intrastate and interstate level to reduce the likelihood of an inefficient allocation of water resources. The COAG Water Resources Policy 1994 and the National Water Initiative 2004 represent strategic attempts to standardize approaches to water resource management at a national scale. However, there is no consensus about the most appropriate way to establish a well-defined system of tradable water entitlements.

1.1 Coag Water Reform

In Australia, water illustrates most of the difficulties in specifying property rights for natural resources. One of the most important reforms endorsed at the February 1994 COAG meeting was for states to develop and implement a comprehensive system of water allocations or entitlements backed by separation of water entitlements from land title and clear specification of entitlements in terms of ownership, volume, reliability, transferability and, if appropriate, quality (COAG 1994). Government policies have also identified establishing competitive markets for tradable water property rights as the most appropriate instrument for allocating scarce water between different commercial uses. In implementing a national water market, the discrepancies between the different entitlement systems in each state need to be addressed.

Most water entitlement arrangements are based on the water acts (e.g., NSW *Water Act 1912*, Victoria *Water Act 1905*, SA *Water Resources Act 1976*) written in a time when water was plentiful and focused on encouraging water development rather than water allocation. As Young & McColl (2002) state, the existing plethora of water entitlement systems in the legislation has been derived piecemeal over time and has not been built for trading – in effect, trading has been “bolted on”. The entitlement systems and legislative arrangements therefore do not adequately consider the potential environmental, social and economic implications of entitlement arrangements and associated water use activities. The water reforms have recognized the need for thorough examination of the entitlement systems to ensure the effectiveness and to align them more closely with water management requirements under the COAG water reform framework.

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[2] Exchange rates provide a methodical accounting of the variable attributes of water entitlements, and within infrastructure constraints, they enable the predictable supply and delivery of water.

1.2 National Water Initiative

Effective water management requires collaboration between researchers, policy makers and the community. These integration concepts have been reflected most recently in the National Water Initiative[3] (NWI), which is attempting to achieve equitable access to and sustainable use of water resources by all stakeholders (including environment), while maintaining the characteristics and integrity of water resources within sustainable limits. In this inter-government agreement, water access entitlements are defined as open-ended or perpetual access to a share of the water resource that is available for consumption as specified in water plans. The consumptive use of water (i.e., irrigation, industry, urban, and stock and domestic use) will require a water access entitlement separate from the land, be enforceable, and will indicate the responsibilities and obligations of entitlement holders (COAG 2004).

It is increasingly acknowledged that current water entitlements are not well defined and this undermines the certainty of entitlement holders (Crase *et al.* 2000). It is important to identify the difference between what is stated in each entitlement and the way this is (and has been) translated into on ground commitments and opportunities (Young & McColl 2002, 2003; Productivity Commission 2003). In order to minimize the transaction costs and maximize the benefits, it is imperative to simplify the array of existing water entitlement systems and develop a coherent and consistent framework for alternative water entitlements arrangements.

2. WATER MANAGEMENT IN THE MDB

2.1 A Brief History of Water Rights

A water right is a legal authorization to take water from a water source. However, the terminology used for defining water rights varies significantly in all the jurisdictions in the MDB; they may be locally referred to as rights, licenses, permits, allocations or entitlements. Water rights are granted for specific users (e.g., irrigators), for specific purposes (e.g., stock and household consumption, environmental flows), for an individual (e.g., diversion licences), or for a group of users (e.g., bulk licenses). Australia inherited its water laws from English common law in the early days of colony. Landowners have an unrestricted right of access to the surface and groundwater for all ordinary and domestic purposes (Tan 2002). The common law property right in surface water is framed in terms of a right of access and use, not a right of ownership of the water resource. Over time, common law rights to access water have been progressively restricted or replaced by statute. As a legacy of Alfred Deakin’s Victorian *Irrigation Act* of 1886, the right to own or to control and use water is vested in the Crown or State (Fisher 2000). The right to access and use water is granted to users, most of them have to be registered and licensed, and they should pay for this right. This is mainly because the states or the public (e.g., irrigation district) built and maintained the large

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[3] At the COAG meeting of 25 June 2004, the Commonwealth, the Australian Capital Territory, Queensland, New South Wales, Victoria, South Australia and the Northern Territory agreed to participate in an intergovernmental agreement on water allocation and management.

infrastructures (e.g., dams and channels) that enable the reliable supply of water resources. Gradually, water rights systems in Australia have been moving from a customary system to accommodate the common use rights (not necessarily transferable) of multiple parties toward nominally simpler systems that accord full (and transferable) ownership rights to individuals.

Originally, when water was relatively abundant, water licenses were defined to permit irrigation on the basis of an authorized land area, and generally free of extraction limits. These access entitlements to use water were permanently attached to land and thus could not be traded or freely exchanged. This prevented farmers from responding to new market opportunities, impeded productivity, and prevented water moving from low-value to high-value uses (e.g., from irrigated pasture to vineyards). In addition, the growth in the volume of access entitlements was not capped. The recognition of increasing scarcity in water resource has led to changes in irrigation license conditions by putting a cap [4] on the exploitation of water by existing users. The cap did not solve the problem of new demands for water, of which the answer lies in setting embargoes on issuing new irrigation licenses. As the cap on the volume of water extracted for consumptive use being put in place and no new licences being issued, new development can only take place by reallocating water from existing entitlement holders to new water users.

2.2 A Paradigm Shift in Water Management

Water supply in the MDB has been complex because it embraces many different types of water use, consumption and delivery. These factors have been compounded by highly episodic climatic variability and a general mismatch between seasonal water availability and demand. The need to allocate, manage and use water, in a way that balances consumptive and non-consumptive requirements, has only been recognized since the late 1980s. Water scarcity is the bottleneck restricting economic growth when existing supplies are institutionally tied to historical uses, with little possibility of reallocation (where institutions have been slow to adapt to changing water supply and demand conditions). Such conditions preclude the development of active water markets.

In general, water scarcity originates more from use inefficiency and poor management than from the physical constraints of its supply (Young & McColl 2003). The paradigmatic shift from water development to water allocation requires a radical reorientation of water institutions. Institutional change is not a one-time event but rather a continuum that moves in line with changing resource realities, socio-economic needs, and political power structure. On contrast to the development era, characterized by a bureaucratic and closed-loop decision structure where political and engineering considerations predominate, the allocation era demands an open and participatory decision process where economic issues take priority and a premium is set for consensual procedures and outcomes (Saleth & Dinar 2004).

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[4] The cap set the use of water for consumptive purposes (e.g., for irrigated agriculture, stock and domestic and urban needs) to a level reflecting the 1993/1994 levels of development.

2.3 Current Water Resource Management

Current water resource management consists of two separate yet closely interdependent activities: the water sharing plans and licensing of individual water users. Water sharing plans provide the legal policy framework for the allocation, use and transfer of water that is consistent with the COAG's principles for water reform. A water sharing plan needs to define both consumptive and non-consumptive entitlements. The main objectives of a water sharing plan are to describe water availability from the source, to protect or reserve a sufficient amount of water for important unlicensed uses (e.g., domestic and stock needs, wetlands, aquatic life), and to make remaining water available, at a reasonable assurance level, to licensed users (DLWC 2001). During the water allocation planning process, water for the environment is set aside and cannot be allocated to any other user if this would compromise the environmental health of the catchment in question. Once the balance of water is allocated, users may then trade.

Water sharing arrangements are backed up by a consistent licensing system. The licensing system under the water act is the mechanism by which the government permits access to water and regulates the security of access. Water licensing ascribes the rights and responsibilities of a specific water user operating specific works at a specific location. License categories define the priorities and conditions of access to water. A share component is the core of the license, which specifies the holder's right to extract a share of the water available from a certain water source. Water access licenses are subject to any conditions and obligations imposed by the water sharing plans. For example, license holders will not be able to pump water until a minimum environmental flow level is reached.

3. PROPERTY RIGHTS AS INSTITUTIONAL ARRANGEMENTS

3.1 The Issues of Property Rights

Property rights are the formal and informal institutions and arrangements that govern access to water and other resources, as well as the resulting claims that individuals hold on those resources and on the benefits they generate (Bromley 1997). A property right is best defined as a tripartite social relationship giving those granted resource access, power (enforced by the state) over other individuals, and restrictions of others control or use of the resource (Macpherson 1978). "The establishment of such a set of property rights will then allow individuals in highly complex interdependent situations to be able to have confidence in their dealings with individuals of whom they have no personal knowledge and with whom they have no reciprocal and ongoing exchange relationships" (North 1989, p. 1320). Coase (1993) argues that the best solution, if transaction costs are present and low, is to give property rights to the players such that incentives are established for them to use the production factors in the most productive manner. A system of property rights forms the basis for all market exchange and the allocation of property rights in society affects the efficiency of resource use. Cole & Grossman (2002) argue that ultimately, the only way for efficiency-enhancing exchange to take place is for enforceable property rights and duties to be established.

Property rights in water are difficult to define. Changes in any characteristic of water property rights could potentially affect other water users. The institution of property rights is dependent on support by the state and requires a working legal system that can define, allocate and enforce property rights. From a historical perspective, four types of property rights have been described in relation to water resources, which reflect the evolving nature of water from a plentiful resource to a scarce one (Bromley 1989; Schlager & Ostrom 1992):

- *Open-access* refers to situations in which property rights have not been defined, i.e. nobody holds exclusive title to the resource;
- *State-ownership* refers to situations in which the state holds the exclusive title to a resource and controls access to the resource;
- *Common property* generally refers to resources for which the exclusive title is in the hands of a group of individuals; and
- *Private property* exists when the exclusive title to the resource is held by individuals or corporations.

Private property rights are sufficient for the production of private goods, while public goods have to be safeguarded by state intervention. The rights holders of common property regimes use water resources for the production of both private and public goods. Common property rights are private property rights shared by a group of people according to agreed rules. Common property is seen as a way of promoting notions of community and reducing conflict in some complex systems, and as an equitable and efficient way of achieving sustainable resource use, especially under uncertainty (Quiggin 1988). The state property regime has the advantage that it is flexible regarding adaptation to changing values of the society (Glück 2002). The private water rights system, collective action institutions, and state management organizations are complementary institutional components of a new governance structure for water resources (Saleth & Dinar 2004).

Water is a non-exclusive resource – more than one party may own rights to use different attributes of the same resource. If property rights are treated as bundles of rights to different attributes of water resources, it becomes clear that individuals rarely own rights to all attributes of the resource. A higher level of government intervention means that the government holds rights to more attributes of a resource. Government intervention in property rights can improve the potential for water management by protecting attributes of water resources most threatened by the pursuit of private economic gain. “Given that the existence of “transaction costs” means that the necessary changes cannot be achieved by voluntary exchange alone, the efficiency gains from optimal rights structures can be achieved only if the state intervenes to change the structure of property rights” (Quiggin 1988, p. 1076). Historically, and at present, water in the MDB is subject to a state property regime. Legal property rights to water attributes are restricted to government agencies. While this continues, water users must rely on definition and enforcement of government water allocations rather than on their own legal rights.

Table 1: A comparison of priority and proportional entitlement systems

	Priority entitlements	*Proportional entitlements*
Advantage	Different levels of supply reliability can be purchased	Entitlements are homogeneous, easier to establish market, i.e., lower transaction costs
Disadvantage	Entitlements are heterogeneous, more difficult to organize market	Different levels of reliability can be created by holding extra shares [a]
Tradability	Difficult to trade	Easy to trade
When water supply is highly variable	Protects investments but results in some short-term inefficiencies	Difficult to protect investments but equates marginal values where users are alike
Risk distribution	A fixed risk allocation that prefers high to general security entitlement holders in dry years	Equally sharing risk and capable of managing new risks created by new demands on the system

Note: While purchasing more proportional entitlements would increase the volume of water available in a season, this 'reliability' is not what is normally referred to as the reliability of an entitlement.

3.2 Class-Based or Share-Based Entitlements

Two options are available when governments face escalating demands and increasing water scarcity: (1) continue to permit users to consume water on a first-come-first-served basis. This would have resulted in some low-value users enjoying supply priority based on historical precedent and at the expense of potential high-value users; and (2) regulate the consumption of water resources by allocating water among different competing needs (Sturgess & Wright 1993). Priority entitlements and proportional entitlements are two main types of rights in water quantity that have evolved under an appropriations doctrine (see Table 1). Since water entitlements are typically defined as proportional shares rather than fixed quantities, the only way to have secure supplies during a drought is to hold excess water entitlements in reserve in the absence of the ability to trade. This is especially critical for citrus and other permanent crops, where the investment at stake is much higher than losing a single year's production.

3.3 Tradable Water Entitlements

Water entitlements supplied by schemes owned by state governments are generally volumetric allocations. These entitlements are in the most part 'statutory entitlements' rather than proprietary rights in the legal sense (Tan 2002). These traditional statutory rights to water provided limited security and were not divisible or transferable (ACIL Tasman 2004). Individuals in environments with such insecure property rights will choose to engage only in self-enforcing contracts, which provide less potential for the society to realize gains from trade and build a foundation for economic growth (Fuchs 2003). These water entitlement arrangements limit transactions to spot sales of water or to the lease of water for a single year rather than to permanent sales of water entitlements. The lack of long-term secure access to water under such a system also discourages investment in activities that require access to large amounts of water.

Over the last two decades, a sustained shift has been observed, in the literature as well as in reality, from a preference for centralized allocation of scarce resources to the belief that private ownership and decentralized allocation is more appropriate (Raymond 2003). The consumptive use of water will generally require a water access entitlement, separate from land, and described as a perpetual or open-ended share of the consumptive pool of a specified water resource. Entitlements will have characteristics that allow free and open trade, and will be cancelled by governments only in the case of water users not meeting their conditions of entitlement. The separation of the water access entitlements from the water use approvals will streamline the process for water trading, as it is the water access entitlement and its components that are the tradable commodities. The trading of water access entitlements will be the major means by which new developers can obtain water and existing developers can expand their production.

Table 2: Existing 22 categories of entitlements in regulated surface water system in three states

NSW	*Victoria*	*SA*
Domestic & stock access licence	Domestic & stock right	Stock & domestic licence
Local water utility access licence	Town water supply	Metropolitan water licence
High security access licence	Supply by agreement	Country town water licence
Conveyance access licence	Water right	Industrial licence
Environmental water access licence	Diversion licence	Recreational & environmental licence
Indigenous cultural access licence	Sales water [a]	Wetlands licence
General security access licence		Water taking licence
Supplementary water access licence		Water holding licence [b]

Notes: a) Under current arrangement, sales water is not a formal entitlement. It is attached to water right or diversion licence and cannot be traded separately. As the Victorian Government White Paper (2004) has proposed to unbundle sales water into a separate, legally recognised and independently tradable entitlement, in this study, sales water is identified as a separate category of water entitlement. b) A highly reliable entitlement that allows holder to access water in prescribed sources indefinitely but the water cannot be used until it is transferred to a water taking licence.

Water access entitlements provide ongoing rights to a share of the resource. The access entitlement itself – the share of available resource – does not need to change at all. They are firm entitlements held by and traded between individuals and other interests, even though the volume of water associated with them may vary each year. Quiggin (1988) argues that tradable water entitlements establish a basis for the operation of common property subsystems within large water resource systems. They are designed to be more perpetual and stable than the kinds of access granted under the command-and-control model. There are a number of advantages associated with a tradable water entitlements scheme:

- Provided that the market for entitlements is competitive (i.e., perfect information, single good, sufficient number of trades so that each is unable to individually influence the market outcome), tradable entitlements minimize the costs of restricting use of the resource;
- Resource users can enter the industry without increasing the overall level of water diversion/use;
- Non-consumptive resource users, such as government, environmental or community groups, can purchase entitlements on the market;
- A tradable entitlements scheme is flexible enough to allow production processes of resource users to adapt over time in response to changes in economic and technological conditions; and
- Trade may take place on a large scale, such as at a basin or national level, or within a local region.

Table 3: A summary of state approaches to irrigation water allocation

State	*Entitlement*	*Allocation policy*	*Supply reliability* [a]
NSW	High security access licence	Specified as a maximum volume and expected to be available in all but the worst droughts; unused allocations are surrendered at the end of the season (i.e., no carry over)	95% (Murrumbidgee) 97% (Murray & Lower Darling)
	General security access licence	Varies according to the water available in the general security allocation pool, after allocating to higher priority pools (e.g., water utilities, the environment, stock and domestic uses, high security access licence holders, etc); allow to carry over or overdraw in some years	70% on average
	Supplementary water access licence	Available after meeting the needs of high and general security licences and when flows are surplus to in-stream requirements; varies from year to year	Opportunistic
Victoria	Water right	Specified as a maximum volume and expected to be available in all but the worst droughts; no carry over	96-99%
	Diversion licence	Usually allow a maximum diversion rate; no carry over	96-99%
	Sales water attached to water right	Only available after meeting the needs of water rights and the volume of water required to supply the next season's water rights is secure in the dam; varies from year to year; no carry over	68% [b] (Murray) 43% [b] (Goulburn)
	Sales water attached to diversion licence	Same as above	48% [b] (Murray) 30% [b] (Goulburn)

Table 3: Continued

State	*Entitlement*	*Allocation policy*	*Supply reliability* [a]
SA	Water (holding) licence	Allocations do not vary from year to year and expected to be potentially available in all but the worst droughts	Almost 100% [c]
	Water (taking) licence	Specified as a maximum volume and expected to be available in all but the worst droughts; taking allocations include permission to use water at a specific location; no carry over	Almost 100% [c]

Notes: a) Data were derived from Ballard (2003). b) Data are approximate and reflect the probability of receiving full sales water allocation. c) In 2003-04 and 2004-05, for the first time, SA water licence holders did not receive their full allocation.

4. AN ANALYSIS OF EXISTING WATER ENTITLEMNETS ARRANGEMENTS

In the past 50 years, the number and type of water access entitlements has grown dramatically in the MDB. Shi (2005, 2006) has identified 22 categories of surface water entitlements currently in existence throughout three jurisdictions in Southern MDB (see Table 2). Among them nine entitlement categories are for irrigation purposes and their allocation policies are summarised in Table 3. Typically, an irrigation license holder has a specific type of entitlement for nominal volume of water. The actual volume that can be ordered is governed by an allocation, announced by the local managing authority at the beginning of a season and revised throughout the season, based on available supplies. Given the frequency of changes in seasonal rainfall and other conditions, it needs to be flexible in the allocation of existing water supplies.

In this study, four attributes are considered as important in specifying a water entitlement:

- *Supply reliability* is defined in terms of the number of years in 100 when entitlement holders can expect to receive their maximum entitlement volume;
- *Entitlement and allocation tradability* refer to the ability to trade among states (***), within the state (**), only within the region (*) or un-tradable (0);
- *Tenure* describes whether the licence is issued for a number of years or perpetual (∞); and
- *Access priority* describes the order in which water is taken from pools of the system (In general, there is a close correlation between access priority and supply reliability).

Table 4 summarises the characteristics of 22 surface water entitlement categories in terms of supply reliability, tradability, tenure and access priority arrangements.

Table 4: Existing 22 entitlement categories and the feature of their attributes

State	*Entitlement category*	**Attributes**				
		Supply reliability (%)	*Entitlement tradability*	*Allocation tradability*	*Tenure (year)*	*Access priority* [b]
NSW (8)	Domestic & stock access licence	100	0	0	∞	1
	Local water utility access	100	0	A*	20	1
	High security access licence [a]	>95/97	E***	A***	∞	1
	Environmental water access	100	0	0	∞	1
	General security access licence [a]	70 [b]	E**	A***	∞	2
	Supplementary water access	50 [b]	0	A*	2	3
	Conveyance access licence	50 [b]	0	A*	∞	2
	Indigenous cultural access	100	0	0	∞	1
Victoria (6)	Domestic & stock right	100	0	0	∞	1
	Town water supply	100	0	A*	∞	1
	Supply by agreement	100	0	A*	∞	1
	Water right [a]	96	E**	A***	∞	2
	Diversion licence [a]	70 [b]/96	E***	A***	5/15	2
	Sales water [a]	30-70	0	A**	1	3
SA (8)	Stock & domestic licence [a, c]	100	E***	A***	∞	1
	Country town water licence	100	0	A*	∞	1
	Industrial licence	100	0	0	∞	1
	Recreational & environmental	>97	0	0	∞	1
	Water taking licence [a]	>97	E***	A***	∞	1
	Wetlands licence	>97	0	0	2-5	1
	Water holding licence [a]	>97	E***	A***	∞	1
	Metropolitan water licence	100	0	A*	∞	1

Notes: E - entitlement; A - allocation; *** - trade among states; ** - trade within the state; * - trade within the region; 0 - not tradable; ∞ - perpetual. a) Assigned for irrigation purpose. b) Figure is estimated and indicative of the average supply reliability. c) In general, stock and domestic licences are not tradable. The exception applies to SA stock & domestic licences, which are separated from land title and can be traded independently.

5. A CLASSIFICATION FRAMEWORK FOR WATER ENTITLEMENTS

5.1 Developing a Classification System for all Water Access Entitlements

In the past 50 years, the number and variety of water access entitlements has risen dramatically in all jurisdictions of the MDB. This has often resulted in overlap and lack of coordination between states and territories. A comprehensive classification system of water access entitlements is needed to adequately reflect and account for the variety of attributes and management intent of water access entitlements across different scales (e.g., national, basin, catchment, river valley). In general, the 22 statutory water rights that are granted administratively to water users by the states across the MDB can be classified into six broad categories: (I) irrigation water rights; (II) stock and domestic rights; (III) urban water supply rights; (IV) industrial use rights; (V) indigenous water rights; and (VI) environmental water rights. The proposed classification system of all water access entitlements is presented in Table 5.

Table 5: Six categories of water access entitlements

Category	*Water Access Entitlement*
I *Irrigation*	High security access licence, General security access licence, Supplementary water access licence, Water right, Diversion licence, Sales water, Irrigation licence
II *Stock and domestic*	Domestic & stock access licence, Domestic & stock right, Stock & domestic licence
III *Urban supply*	Local water utility access licence, Town water supply, Metropolitan water licence, Country town water licence
IV *Mining and industrial use*	Supply by agreement, Industrial licence,
V *Indigenous culture and others*	Indigenous cultural access licence, Water (holding) licence
VI *Environment and recreation*	Conveyance access licence, Environmental water access licence, Recreational & environmental licence, Wetlands licence

In this proposed classification framework, the categories are deliberately broad to account for the variety of different water access entitlements. The new classification recognizes the real differences in terms of management requirements, ability and responsibility that exist between holders of these various water access entitlements. Such a classification system not only would benefit water resource planning, but also would allow for more informed policy discussion on the current and future roles that the various entitlement categories may have in a region. However, the proposed classification does not suggest that existing on-ground jurisdictional water access entitlement names should be altered. Water access entitlement Category I is usually separated from Categories II-VI as the former generally involves greater intervention and modification, and is usually allowed for trading (see Figure 2).

Nature of Entitlement	← *Longer* *Tenure*	*Shorter* →
↑ *Higher* *Tradability* *Lower* ↓	I	I
	II, V, VI	III, IV

Figure 2: Relative tradability and tenure of six entitlement categories

5.2 Implications for Compatible Water Entitlements Arrangements

This chapter has outlined the characteristics of existing water access entitlements and proposed a new classification system to rationalize water access entitlements arrangements. It is envisaged that the water entitlements classification system has the potential to substantially improve the compatibility of all water access entitlements at a water authority jurisdiction or basin scale. The categories described in the water entitlements classification system are intended to stimulate discussion about the means of classifying and accounting for the ever-increasing array of water access entitlements. It is not a definitive statement on a new classification system at this stage. Furthermore, as the use and management of water resources can be closely linked to the form of tenure and rights held over them, the application of the classification framework to situations where, for example, customary water rights predominate, warrants further research.

6. CHALLENGES FOR A CONSISTENT ENTITLEMENT SYSTEM

An important part of a policy reform process is the development of a mechanism that adequately addresses negative impacts of the reform on various sectors (e.g., compensation), or that allows a fair share of the reform benefits (Williamson 1994). Current water entitlements systems are complicated by overlapping (and sometimes conflicting) statutory and customary rights, many of which are not subject to market transfer, or which may be transferable only under certain restrictive circumstances. A tradable water entitlements system is reliant on a non-attenuated property rights structure, with a clear definition of who is entitled to a certain percentage of water resources. It promotes the efficient allocation of water when some water rights are privately held (e.g., irrigation licences) and some are held in common (e.g., environmental water trust). The socially optimum allocation of water may require moving water from current commercial consumptive uses, in particular from irrigation, to increase environmental flows. Not surprisingly, farmers will seek compensation for what they perceive to be a loss of historical property rights. Tan (2002) argues that compensation may not legally binding on the state, but government buying of water property rights for environmental flows effectively compensates current right holders.

Water property rights reform creates an exchange situation that is constrained by transaction costs and formal rights distributed to resources. Since water resource is characterised by interdependent and jointly produced values, it is impossible to completely internalise externalities by property rights alone. Transfer of water entitlements cause third party effects, such as volumetric reliability (i.e., reduce the value of existing entitlements), delivery reliability (i.e., decrease system reliability) and water quality effects (i.e., harm ecosystems). In other words, markets may not maximize the collective outcome in terms of social equity, ecological sustainability and economic efficiency. The introduction of trade in water property rights without charging users the marginal cost of water conveyance and reticulation (including losses) may not necessarily lead to more efficient water use.

Existing water entitlements can be regarded as property rights of sorts in that state legislation backs an entitlement holder’s right to the exclusive use of an allocation or diversion of water. However, the emphasis of the existing system is on regulatory and administrative control of entitlements rather than on a market-based system of tradable rights. This is called inflexibility, that is, once a dominant property right begins to emerge it becomes progressively ‘locked in’ (Arthur 1989). The current practice of issuing licenses for specified terms will continue and the conditions under which licenses can be changed should be carefully defined in legislation. Long-term licenses will be issued where it can be shown that there is little risk to the resource or other users. In other areas, where the risks are higher, licenses will be issued for shorter periods to allow periodic review. Early renewal of licenses will be possible if the license holder wants extra security before investing in new development or offering the license for sale.

The definition of property rights is a contested ground, resulting in a lively debate with little agreement on what a property right might be. In addition, informal institutions change more slowly than formal institutions. As a result, there is always tension between altered formal rules and persisting informal rules (North 1990). Policies shape property rights by intervening in specific parts of the bundle of rights held by the right holder. “Different degrees of policy intervention in private property rights, thus, may require different actions by government, and therefore different levels of political will and capacity depending on the constitutional framework” (Fuchs 2003, p. 91). Water use is comprised of both public interest and private/commercial interests, and government intervention should be confined in the area related to public interest, and not be involved in commercial activities.

7. CONCLUSION

Tradable water entitlements exist only when the benefits and costs associated with the entitlements are well defined and there are regimes that facilitate entitlement transfers with appropriate constraints. In general, the greater the heterogeneity among entitlements the greater buyers’ searching costs and other transaction costs, since markets operate most efficiently when the commodity being allocated is homogeneous (Howe *et al.* 1986). The non-uniformity of entitlements arrangements within and across jurisdictional boundaries will lead to market distortions, which may result in undesirable social, economic and ecological outcomes.

Markets increase economic efficiency by allocating resources to the most valuable uses. For market forces to work, property rights to water must be legally defined as enforceable, fully specified, exclusive, and transferable. Trading is only one way to provide incentives to right holders, and not all licensed property rights encourage trading to the same degree (Raymond 2003). “Water problems involve such diverse interests, uses, and values that sorting them out relies on legal and political institutions more than markets” (Bauer 1997, p. 640). Markets cannot substitute for overtly legal and political processes. The key difference/inconsistency between the legal frameworks of water managing jurisdictions has impeded the ability of the government to change the structure of existing water property rights. It seems unlikely that unified forms of property rights and governance arrangements would evolve without first passing through a comprehensive system of water access entitlements in a society that shares the same water resources.

An essential component of sustainable water resource planning and policy is a comprehensive classification framework for water access entitlements that accurately accounts for different water uses/users for consumptive and non-consumptive purposes. It is envisaged that this classification framework has the potential to significantly improve the compatibility of existing water access entitlements arrangements across all water use types at a variety of scales in the MDB. Due to the risk-averting behaviour of individual farmers, future water resource planning must incorporate a comprehensive approach to integrating social, environmental and economic dimensions, and must guarantee greater levels of local involvement and transparency.

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Chapter 8

EFFECT OF SOIL TEXTURE ON WATER RELATIONSHIP AND RADIATION USE EFFICIENCY OF SIX CULTIVATED SPECIES

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ABSTRACT

Potato, maize, sunflower, sugar beet, soy-bean, and tomato were cultivated in a lysimeter set-up on two soil types, loam and clay, simultaneously during the same season Crops were grown under the same conditions of climate, mineral nutrition and plant density and were well-watered during the whole crop cycle.

As for potato, sunflower and sugar beet, stomatal conductance, evapotranspiration, leaf area, yield, and radiation use efficiency (RUE) were systematically lower on clay than on loam. The other three species were not sensitive to soil texture, excepted for the yield of maize.

The results cast doubt on RUE's values being independent from soil texture, as is commonly hypothesized by models simulating the productivity under well-watered conditions.

Keywords: plant water relationship, productivity model, Radiation Use Efficiency, soil texture.

1. INTRODUCTION

To characterize the biomass growth, Monteith (1972) proposed a simple method. It was obtained by analyzing the relationship between the dry matter increase and the amount of solar radiation intercepted by the crop. Generally, under non-limiting conditions of water and mineral nutrition (Monteith, 1978), this relationship is represented by a linear function. The slope of the function stands for the radiation use efficiency (RUE), characteristic for each species. RUE is supposed to be constant during the vegetative cycle (Gallagher and Biscoe 1978; Gosse et al., 1986; Kiniry et al., 1989). This simplified approach is largely used for simulating crop growth and yield. Effectively it is commonly adopted in crop production models, such as CERES (Ritchie et al., 1994). CROPSYST (Stockle and Nelson, 1997), EPIC (Sharpley and Williams, 1990), STICS (Brisson et al., 2002).

The analysis of RUE values published in literature (Sinclair and Muchow, 1999) shows that the RUE of each species responds to different sources of variability.

Genetics is the first source of variability. As an example, maize (Tollenaar and Aguilera, 1992) or sugar beet (Damay and Le Gouis, 1993) are characterized by RUE values changing with the genotype.

Plant density is a second source of variability (Giauffret et al., 1991; Beguè et al., 1991). The RUE values increase with plant density till a threshold and decrease afterwards.

The third source of variability is caused by environmental factors, among which the ratio between diffuse and solar radiation (Sinclair et al., 1992; Hammer and Wright, 1994), the daily minimum or mean air temperature (Bell et al., 1992; Andrade et al., 1993) and the vapour pressure deficit (Stockle and Kiniry, 1990; Goyne et al., 1993; Kiniry et al., 1989; Kemanian et al., 2004).

Finally, the soil water and nitrogen deficit (Muchow, 1992; Muchow and Davids, 1998; Whitfield, 1993; Wright et al., 1993), or excess (Ceotto and Castelli, 2002) significantly modify the RUE values.

In analyzing the possible sources of RUE variation, soil texture has never been considered as an environmental factor susceptible of modifying the RUE (i.a., see the detailed revue by Sinclair and Muchow, 1999). However, this omission is not supported by experimental evidence. On the contrary, a number of results reported in literature emphasizes the role of soil properties in satisfying crop water requirements (Ozier-Lafontaine et al., 1998). The following considerations merit attention:

- Soil water movement and available water, which depend on the soil hydrodynamic properties and therefore on soil texture (Gardner, 1988);
- Root system capacity for water uptake, which depends on root density and distribution, affected in turn by physical soil properties (Tardieu and Pellerin, 1991).

Taking these considerations into account, it is clear that the plant water requirements cannot be satisfied to the same degree in every soil type, even under well-watered conditions, (Gardner, 1988). Both models (Bruckler et al., 1991; Tardieu et al., 1992) and field surveys of plant water status and biomass growth (Tardieu et al., 1992; Bethenod et al., 1996) confirm this point. RUE values should necessarily be affected by soil type.

To the best of our knowledge, the effect of soil type on the RUE has never been reported in literature. In this paper we compare RUE values determined on six species (potato, sugar beet, maize, sunflower, soy-bean, and tomato) grown under the same conditions of weather, water and mineral nutrition, and simultaneously on two soil types (loam and clay). The objective was to answer the following questions:

- Under well-watered conditions, does soil type significantly modify crop water use?
- If so, can the observed modifications in evapotranspiration change the biomass accumulation, and, in turn, the RUE?

In the conclusion, the practical consequences derived from this study will be discussed.

2. MATERIALS AND METHODS

The experiments were carried out, between 1992 and 1998, at CIHEAM – Mediterranean Agronomic Institute (Bari, Italy), in the frame of a long-term experiment to study the crop response to soil salinity. Species behaviour of the species in saline environment was analyzed in previous studies by van Hoorn et al. (1993) and by Katerji et al. (1996, 1997, 1998a and b). The experimental data in this paper synthesize the observations obtained on the control treatments that were kept in well-watered condition with fresh water. Such a synthesis was never approached before. The Bari climate is Mediterranean. It is characterized by warm dry summers, with maximum air temperature sometimes higher than 40°C, and minimum relative humidity often less than 20%.

2.1. Set-Up

For each species, the set-up consisted of 10 cylindrical lysimeters of reinforced fibre glass with an internal diameter of 1.2 m and a depth of 1.2 m. A layer of coarse sand and gravel, 0.10 m thick, was overlain by a repacked soil profile of 1 m. At the bottom of the lysimeter, a pipe serving as a drainage outlet connected the lysimeter to a drainage reservoir. The set-up was covered at a height of 4 m by a sheet of transparent plastic. This sheeting excluded any rain, but attenuated the solar radiation up to 10 %. This maximum value was derived from radiation measurements taken above and below the sheeting, at different hours and seasons. A 5-lysimeter block was filled with loam, and a second block with clay. Table 1 presents physical properties of the soil after filling the lysimeters. The lysimeters were irrigated with fresh water in order to maintain well-watered conditions during the whole crop cycle.

Table 1. Soil properties

Soil type	Particle size of mineral parts (%)			$CaCO_3$ (%)	% Water (v/v)		Bulk density (kg dm^{-3})
	< 2 μm	2 ÷50 μm	> 50μm		pF 2.0	pF 4.2	
loam	19	49	32	25	36.3	20.4	1.45
clay	47	37	16	5	42.0	24.0	1.45

At each irrigation, water was supplied in excess of about 20% for restoring field capacity. Irrigation water was supplied simultaneously to the two lysimeter series (5 lysimeters containing clay soil, and 5 with loam) whenever the accumulated daily evaporation of the class “A” pan, located in the standard agro-meteorological station nearby the lysimeter set-up, had attained the threshold of about 65 mm. In the Mediterranean region, actual crop evapotranspiration is systematically lower than the class “A” evaporation (see the review published by Rana and Katerji, 2000). If evaporation and evapotranspiration were the same, 65 mm correspond to 34% of the total amount of the available soil water for clay and to 40 % for loam. Under these soil water conditions, crops can be considered well-watered (Tardieu and Katerji, 1991). This hypothesis was tested by measuring the plant water status during the growth cycle.

2.2. Crops

Table 2 presents the crops grown during 6 seasons, the cultivars, and the reference publications with detailed information concerning crop density and fertilization. The table shows that the crops grew in different seasons: sugar beet from late autumn to early summer, potato in spring, and maize, sunflower, tomato, and soy-bean in summer. For each crop the cultivar, the sowing date, the plant density and the fertilization were the same in this study.

Table 2. Crop, variety, growth period, final density (plant m^{-2}), and reference

Potato (*Solanum tuberosum* L.)			
Spunta	3/2/1992- 7/6/1992	5.3	Van Hoorn et al., 1993
Corn (*Zea mays* L.)			
Hybr. Asgrow 88	27/7/1993- 2/11/1993	4.4	Katerji et al., 1996
Sunflower (*Helianthus annuus* L.)			
Hybr. ISA	22/4/1994- 2/9/1994	4.4	Katerji et al., 1996
Sugar beet (*Beta vulgaris* L.)			
Suprema	25/11/1994- 2/6/1995	4.4	Katerji et al., 1997
Soybean (*Glicine max* L.)			
Talon	18/7/1995- 16/9/1995	22	Katerji et al., 1998a
Tomato (*Lycopersicon esculentum* L.)			
Elko 190	28/6/1996- 10/9/1996	3.5	Katerji et al., 1998b

2.3. Crop Water Status

Three parameters were used to characterize the crop water status:

- The pre-dawn leaf water potential. This parameter is measured when the equilibrium between soil and plant is approached (Katerji and Hallaire, 1984). It is determined at dawn, before sunrise, on leaves of the upper part of the canopy. At each determination, 5 leaves per treatment, equally distributed over the 5 lysimeters, were taken and the potential was immediately measured in a pressure chamber (Sholander type) at the experimental set-up.
- The stomatal conductance was always determined at midday, when the hourly transpiration attains its maximum value (Katerji et al., 1988). At each determination, 10 leaves per treatment, from the top of the vegetation, and equally distributed over the 5 lysimeters, were measured by means of a diffusive porometer (Licor 1600).
- The actual evapotranspiration was measured for each lysimeter as the difference between the amounts of irrigation and drainage water. Soil moisture sampling during the first experimental year showed almost the same moisture content, after each irrigation, corresponding to the field capacity. No infiltration or water logging problems were observed.

2.4. Growth and Yield

The leaf area and the above ground dry matter were determined at the successive main phenological stages of each species, on 5 plants (one per each lysimeter) chosen from the central part of each lysimeter, in order to avoid the edge effect. The leaf surface was determined by means of "LAI-Licor 1300". Dry matter was measured, on the same plant samples, after oven drying for 48 hours at 80°C. In the cases of potato and sugar-beet DM included the main yielding organs.

2.5. Determination of Radiation Use Efficiency (Monteith's Model)

The radiation use efficiency (RUE) is derived by the following equation (Monteith, 1993):

$$RUE = \frac{DM}{\Sigma PAR_a}$$

Where DM is the dry matter and ΣPAR_a equals the total of the photosynthetically active radiation (between 400 and 700μ) intercepted during the crop cycle.

The daily estimate of PAR_a was made according to the following model (Varlet-Grancher, 1982):

$$PAR_a = \varepsilon_i \cdot PAR_i$$

Where PAR_i is incoming PAR estimated as:

$$PAR_i = 0.48 \cdot Rg$$

and Rg is daily total incoming solar radiation (MJ m^{-2} d^{-1}) measured with an Epply pyranometer, and reduced by 10 % for taking into account the plastic sheeting; ε_i, the proportion of light absorbed, declines roughly exponentially with the leaf area index (LAI). Following Varlet-Grancher et al. (1982), ε_i could be calculated as:

$$\varepsilon_i = \varepsilon_{\max} \cdot (1 - e^{-K \cdot LAI})$$

Where $\varepsilon_{\max}$ is the maximum value of interception efficiency; it is quite close to 0.95 for most of the agricultural conditions; K is PAR extinction coefficient.

The K value is specific for each species. As for the studied crops, Varlet-Grancher et al. (1989). K values have been retained: 0.65 sugar beet; 0.42 potato; 0.70 maize, 0.97 sunflower, 0.50 tomato, 0.88 soy-bean.

For each year, DM was plotted versus accumulated PAR_a. Linear regressions forced through origin, were not significantly different from zero. The slope of these regressions (α) is an estimate of the Radiation Use Efficiency (RUE).

3. RESULTS

3.1. Soil Type Effect on Crop Water Status and Evapotranspiration

Figure 1 shows for the six studied crops the evolution in time of the pre-dawn leaf water potential in clay and loam soil. All crops showed a similar trend of an increase after irrigation, followed by a decrease during the irrigation interval. According to the species, the pre-dawn leaf water potential decreased from a maximum value, between -0.1 to -0.3 MPa, to a minimum value, between -0.4 to -0.6 MPa.

Values of maximum stomatal conductance (Figure 2) observed immediately after irrigation depend on the species. The differences among species indicate the role of the stomatal density, pore length and relative (respect to the total) pore area (de Parcevaux, 1972). The decrease in the maximum stomatal conductance with time, observed especially in sunflower and, to a lesser extent, in sugar beet may be attributed to the increasing air saturation deficit during the growing period (Fereira and Katerji, 1992).

The soil type significantly affected the stomatal conductance values of potato, sunflower, and sugar beet. These values are statistically lower on clay than on loam. In contrast, the soil type did not affect the stomatal conductance in the case of maize and tomato. Soybean behaviour was intermediate: the soil type effect being significant only in the case of maximum values of stomatal conductance, measured just after an irrigation.

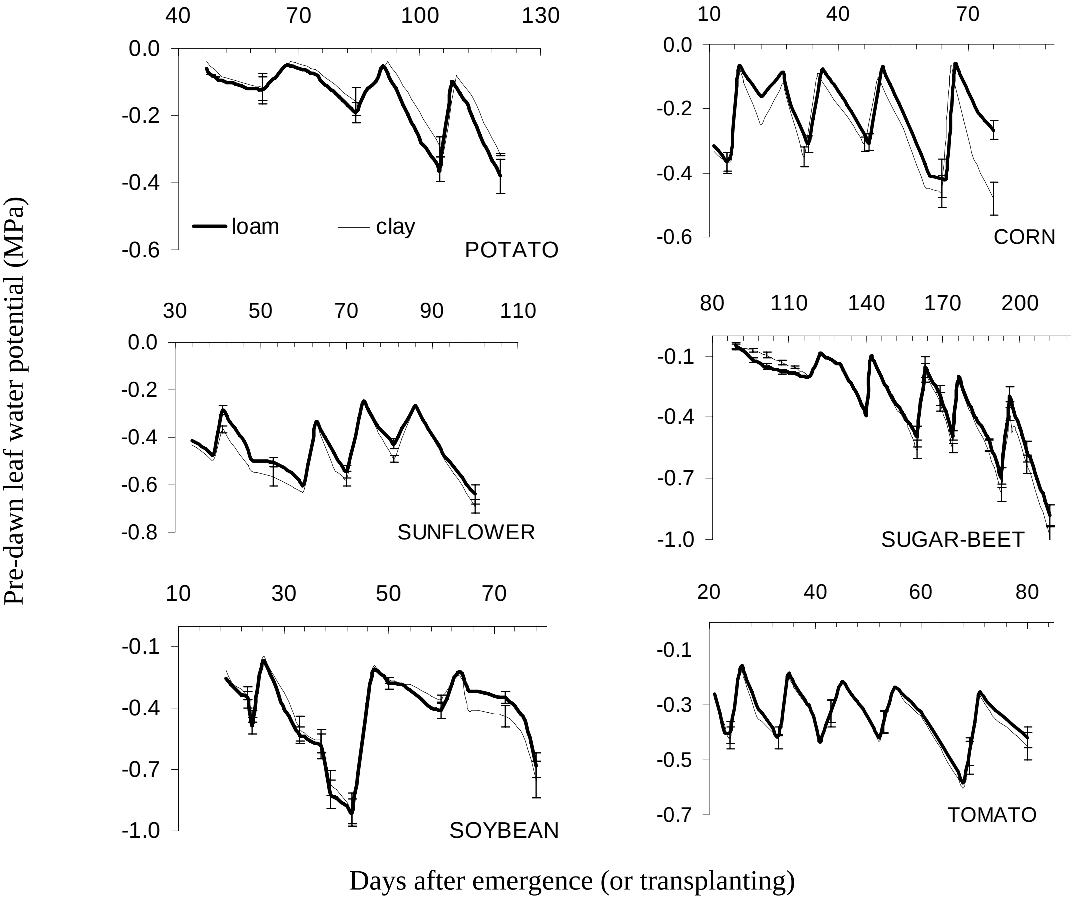

Figure. 1. Evolution in time (days after emergence) of pre-dawn leaf water potential (MPa) of six species grown on loam and clay soils.

Table 3 shows the accumulated evapotranspiration during the crop cycle. In the case of potato, sunflower and sugar beet, the values on clay are significantly lower than those observed on loam. These differences in accumulated evapotranspiration appear (Figure 3) only during a part of the vegetative cycle, when the leaf area attains the maximum value (see paragraph 3.2).

3.2. Soil Type Effect on Growth and Yield

Figure 4 shows the evolution of the leaf area index (LAI) measured in the six species. As for potato, sunflower, and sugar beet, the leaf area measured on clay was significantly lower than that on loam. In contrast, no soil type effect was observed in tomato and maize. As for soybean, the value observed on clay was significantly higher only when LAI attained its maximum value. The observed reduction in accumulated evapotranspiration (Figure3) in potato, sunflower and sugar beet on clay originated from both LAI and stomatal conductance reduction.

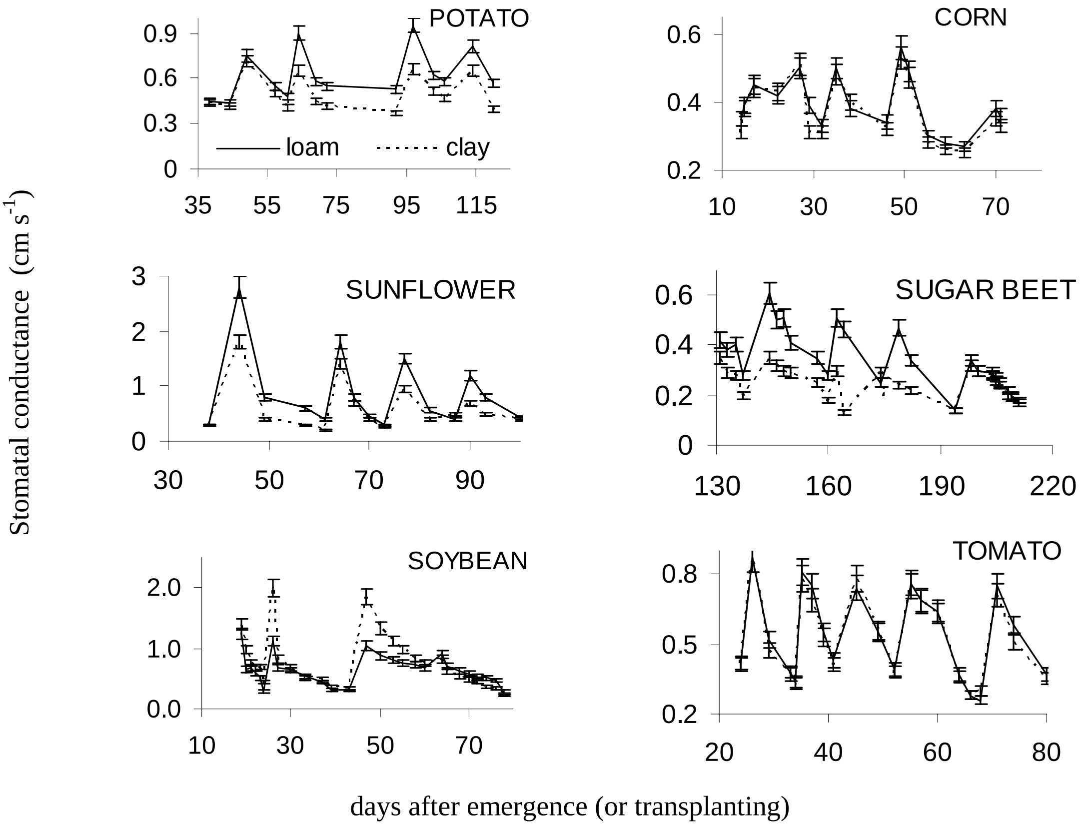

Figure 2. Evolution in time (days after emergence or transplanting) of stomatal conductance during the crop cycle of 6 species grown on loam and clay soils. Vertical bars indicate the standard deviation of each measurement.

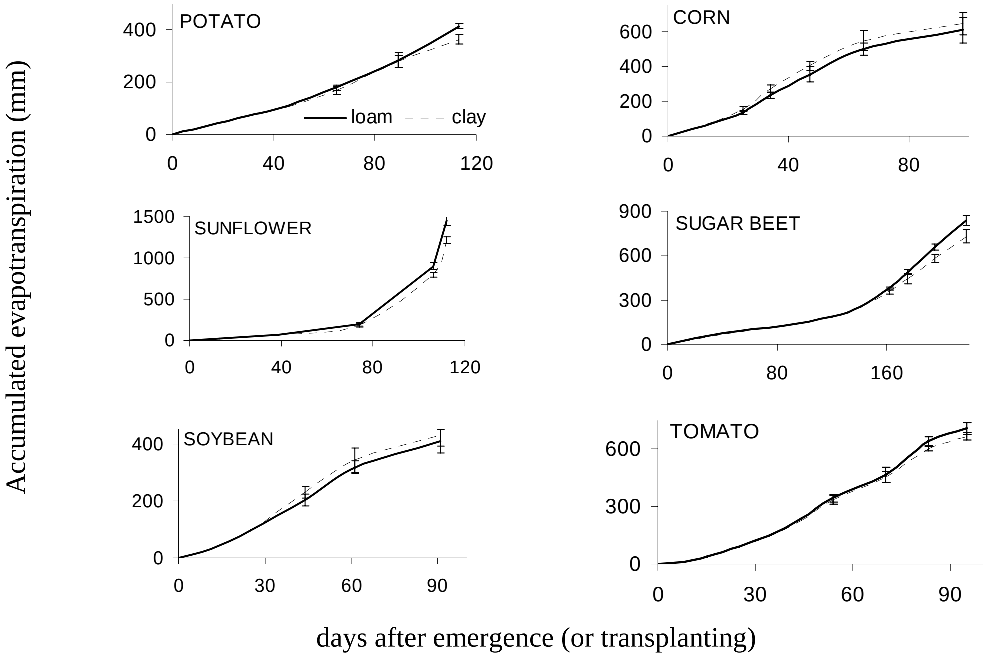

Figure 3. Evolution in time (days after emergence or transplanting) of accumulated evapotranspiration during the crop cycle of 6 species grown on loam and clay soils. Vertical bars indicate the standard deviation of each measurement.

Table 3. Accumulated evapotranspiration (mm) of the six species. Figures (in columns) followed by the same letter are not statistically different ($p < 0.05$) based on SNK's mean range test.

	Potato	Corn	Sunflower
loam	415 a	607 a	1450 a
clay	363 b	644 a	1215 b
	Sugar beet	Soybean	Tomato
loam	836 a	410 a	708 a
clay	731 b	430 a	667 a

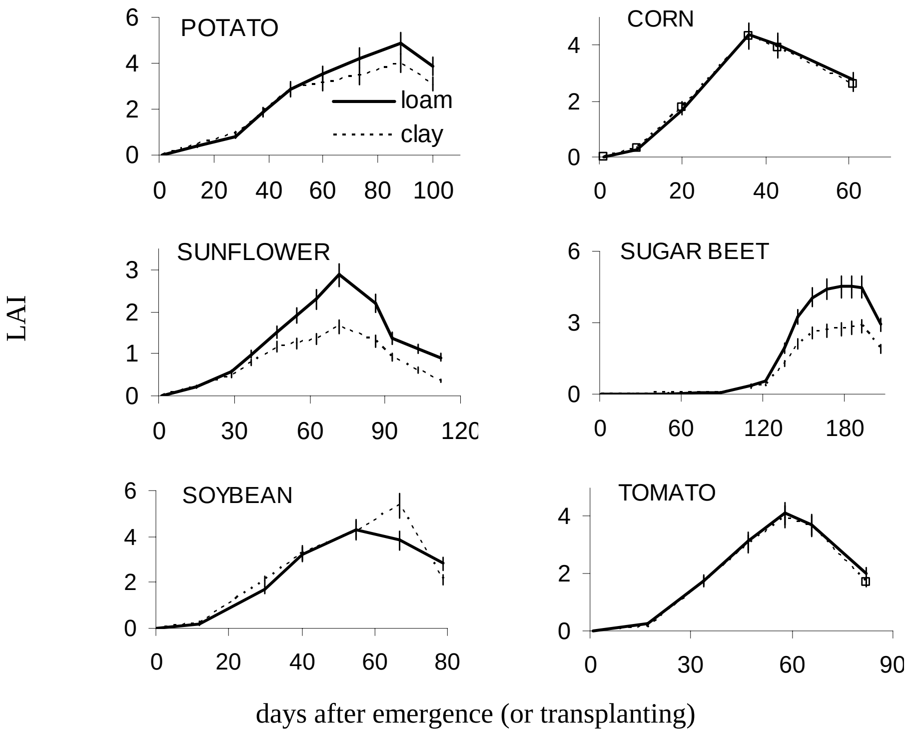

Figure 4. Evolution in time (days after emergence or transplanting) of LAI during the crop cycle of 6 species grown on loam and clay soils. Vertical bars indicate the standard deviation of each measurement.

Figure 5 shows the evolution of the dry matter measured on the same plant samples used for determining the LAI values. Also for dry matter, a significant reduction was observed during the crop cycles of potato, sunflower and sugar beet, on clay.

The commercial production in grain, tubers, or fruit is presented in Table 4. Potato, sunflower, sugar beet, and maize yields obtained on clay were significantly lower than those harvested on loam. The difference in maize between clay and loam is less than half the difference observed on the other three crops.

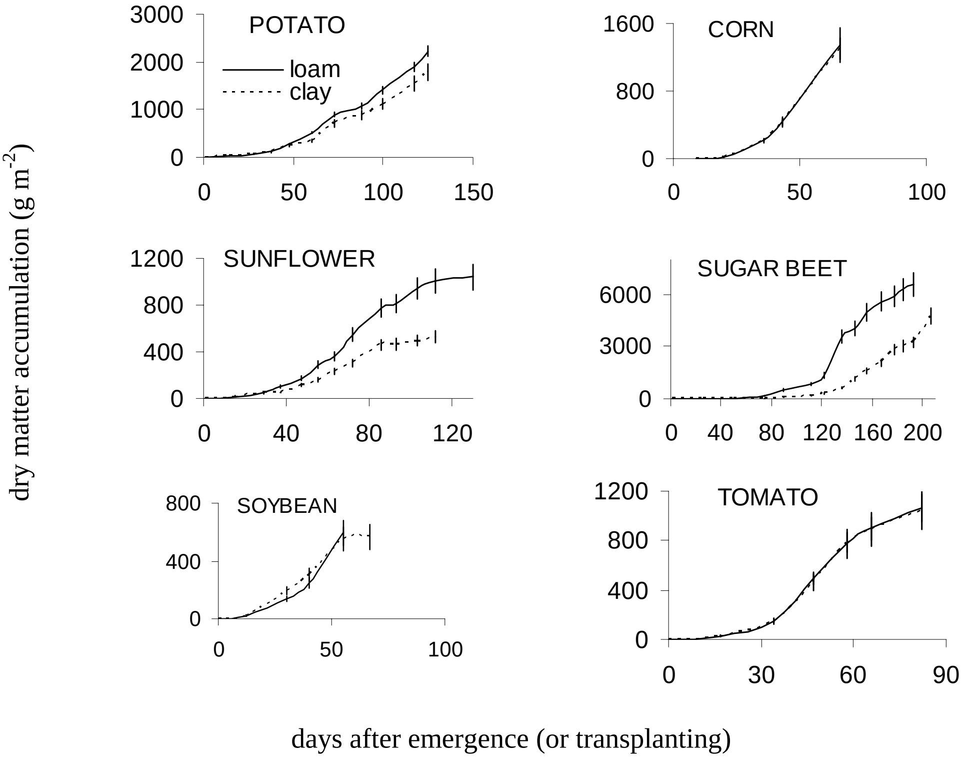

Figure 5. Evolution in time (days after emergence or transplanting) of dry matter accumulation (g m-2) during the crop cycle of 6 species on loam and clay soils. Vertical bars indicate the standard deviation of each measurement.

Table 4. Yield in kg m-^{2}. Figures (in columns) followed by the same letter are not statistically different ($p < 0.05$).

	Potato (tubers)	Corn (grain)	Sunflower (grain)
loam	8.62 a	0.68 a	0.35 a
clay	5.80 b	0.55 b	0.22 b
	Sugar beet (beet)	Soybean (grain)	Tomato (fruit)
loam	1.02 a	0.33 a	6.12 a
clay	0.64 b	0.31 a	5.31 a

3.3. Soil Type Effect on Radiation Use Efficiency

Figure 6 shows the relationships between dry matter and absorbed radiation. The RUE values, calculated from the previous relationships, are reported in Table 5.

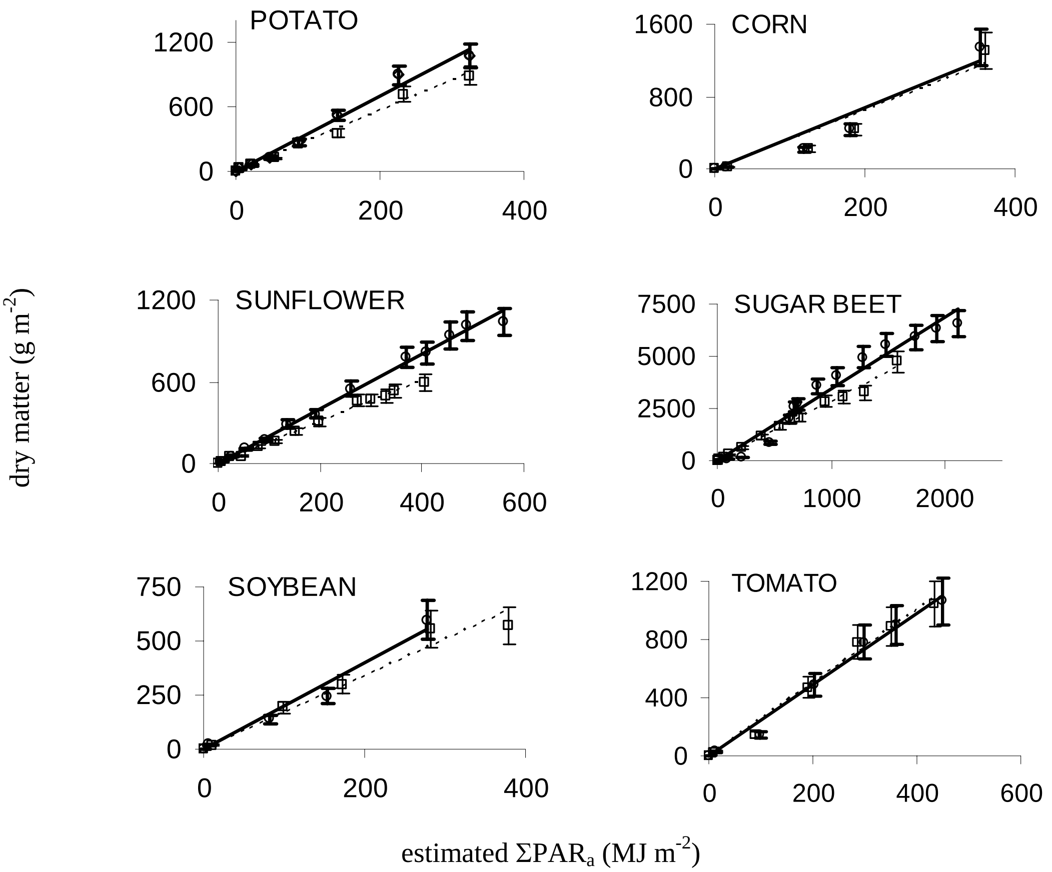

Figure 6. Dry matter accumulation (g m^{-2}) as a function of the estimated absorbed PAR (MJ m^{-2}) during the crop cycle (ΣPAR_a) of 6 species grown on loam (solid line) and clay (dashed line) soil. The standard deviation of each measurement is represented by the vertical bar.

Table 5. Radiation Use Efficiency in g MJ^{-1}. Values from literature were provided by Sinclair and Muchow (1999) and for tomato RUE by Cavero et al. (1998). Figures followed by the same letter are not statistically different ($p < 0.05$).

	Potato	Corn	Sunflower
loam	3.51 a	3.38 a	2.01 a
clay	2.83 b	3.22 a	1.53 b
literature	3.2÷3.5	2.6÷3.4	2.54
	Sugar beet	Soybean	Tomato
loam	3.43 a	2.00 a	2.44 a
clay	2.83 b	1.62 a	2.49 a
literature	2.5÷3.0	2.04	2.4

Generally, RUE values observed on loam were systematically higher than those determined on clay, with the exception of tomato. The statistical analysis revealed that the differences are significant for potato, sunflower and sugar beet.

Table 5 shows that the RUE values determined in this experiment are consistent with those reported in literature. Sunflower showed lower values than those published, both on clay and on loam.

4. DISCUSSION

The small pre-dawn leaf-water potential variations, observed on the six species grown on clay or loam, indicate that in the present study the crop water status corresponded to well-watered conditions. Indeed, before senescence, the pre-dawn leaf water potential for tomato, soybean, maize and corn varied in a range which was 5 to 6 times smaller than the range measured on the same species grown in soils whose available water varied between field capacity and wilting point (Katerji et al., 1988; Mastrorilli et al., 1993; Rana et al., 2004).

With regard to leaf surface, dry matter growth, yield and RUE, potato, sunflower and sugar beet systematically show their sensitivity to soil type by lower values on clay than on loam. The yield sensitivity of potato and the indifference of tomato to soil type agree with results reported in literature (Chapman and Carter, 1976; Fisher and Neil, 1990).

The observations of this experiment do not validate the hypothesis that soil type does not affect RUE under well-watered conditions. Since half of the species examined show an effect of soil type on RUE, the hypothesis commonly reported in literature has no a general validity. In the present study, RUE was determined in small plots. Monteith (1978) found that several reports of high maximum growth rate were associated with significant amounts of lateral radiation interception on small plots. Consequently the values of RUE were overestimated. Such hypothesis does not seem verified in this study. Table 5 shows that the RUE values determined in this experimental set up are consistent with those reported in literature and supported by field experiments. Sunflower showed lower values, both on clay and on loam. This could be attributed to the high air saturation deficit (Stockle and Kinery, 1990), already mentioned with regard to the behaviour of the maximum stomatal conductance of sunflower.

The sensitivity is closely linked to plant water relationships, which are less favourable on clay. The three sensitive species show a soil type effect on the punctual measurements of the stomatal conductance and on the global measurements of the accumulated evapotranspiration. The convergent observations clearly underline that the water status of plants growing on clay is less favourable than the water status of plants growing on loam. The physiologic mechanisms regulating gas exchanges and growth on clay probably originated by root signals (Davies and Zhang, 1991; Tardieu et al., 1991) transmitted to the aerial plant portion for reducing leaf growth and stomatal conductance. These signals, indeed, represent the reaction to mechanical (Masle and Passioura, 1987) or water (Tardieu et al., 1992) constraints exerted by soil on the roots. However, in reaction to the same environmental constraint, root signal concentration in sap flow varies according to the species (Tardieu and Dreyer, 1997). This different reaction to a certain extent could explain why some species demonstrate higher sensitivity than others to soil constraints.

5. CONCLUSION

Main conclusions of this study are addressed to agronomy, in general, and to crop modeling, in particular:

- As for the agronomic issues, it is clear that, to obtain the potential production, non-limiting water and mineral nutrition are not enough for some cultivated species (potato, sugar-beet, and sunflower). Soil type, its physical proprieties and soil management improving its physical proprieties play a determinant role in crop productivity.
- As for the crop productivity models, under non-limiting conditions of water and mineral soil nutrition, existing models simulate the biomass increase as a function of the absorbed radiation and of the RUE value characteristic of each crop. The validity of this hypothesis is restricted by the conclusions of the present work. Our result explains at least one of the possible reasons why predictions, provided by simulation models, do not always fit the observed data. Since some species demonstrate the RUE sensitivity to soil type, RUE values should be simulated accordingly.

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INDEX