Irrigation-management decision system (IMDS) for vineyards (Regions VI and VII of Chile)

INTRODUCTION

In Chile, most barriers to more efficient irrigation management are associated with poor estimations of vineyard water use. Crop coefficients reported in the literature are not adapted to the local conditions. Moreover, growers generally use non-quantitative observations of canopy and soil conditions to determine whether water availability is low or not. Current approaches are unlikely to optimize irrigation timing and the amount of irrigation application. For this reason, in 1998, the Research and Extension Centre for Irrigation and Agroclimatology (CITRA) established an irrigation-management decision system (IMDS) for grape-growers in Regions VI and VII of Chile. This system requires input data on: soil properties (texture, field capacity, wilting point, bulk density, wetting pattern, and effective rooting depth); weather variables (air temperature, relative humidity, wind speed, solar radiation, and precipitation); and vineyard characteristics (cultivars, vine vigour, irrigation system, and yield target). Soil characteristics are used to calculate the available waterholding capacity, and weather data are used to compute vine evapotranspiration (ET_{vine}). Because of the uncertainty of the crop coefficient values (Kc), the irrigation schedule is designed using soil-water content measurements in the effective rooting depth (ERD) for each growing season. Using the weather information in combination with soil-water measurements, Kc values are calibrated for each specific soil, climate, and vineyard condition, according to yield and quality targets. The ET_{vine} can then be used to estimate irrigation needs on a daily basis. Once a general irrigation plan is in place for a given vineyard, more refinements can be made to manage zones differentially within a vineyard.

The main steps required to establish irrigation management zones are (Ortega-Farias *et al.*, 2003):

1. Determine the spatial variability of available waterholding capacity (AWHC).
2. Define the spatial variability of vineyard vigour and fruit quality.

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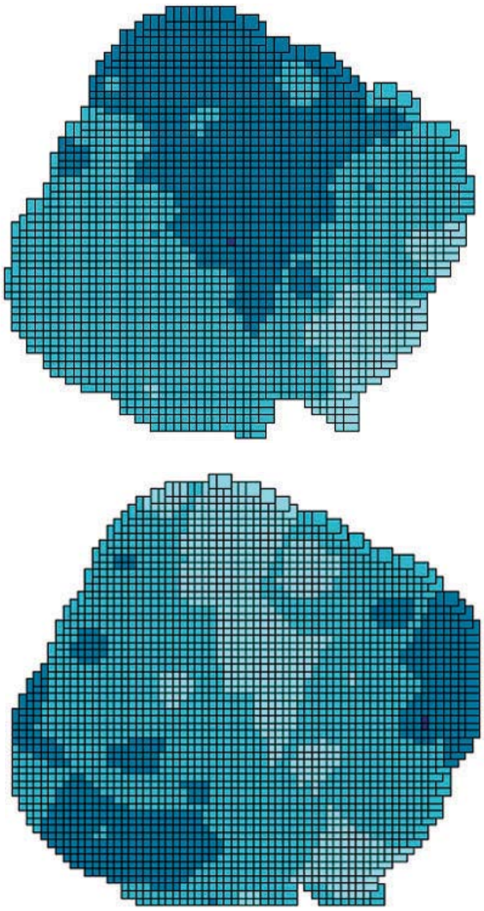
FIGURE 1
Spatial variability of available water (a) and soil water content at the rooting depth (b), increasing relative values from light to dark



3. Define spatial and temporal variability of microclimate.
4. Site-specific calibration of irrigation scheduling.

Step 1. Determining the spatial variability of AWHC

This step is required to measure field capacity (FC), wilting point (WP), bulk density (BD), available water (AW = FC –WP), and effective rooting depth (ERD). The evaluation of the spatial variability of AWCH can be done using a global positioning system (GPS) and geographical information system (GIS) to generate the maps of homogeneous soil sectors, which enable the proper sectoring of irrigation (Figure 1). Data is sometimes difficult to interpret because differences in vine size can be caused by differences in available water, while at the same time small vines consume less water. Small vines cannot possibly consume as much water as large vines when irrigation is uniformly applied. Furthermore, an irrigation regime designed to stress a vineyard moderately may stress large vines more than small ones. Therefore, a combination of measurements of vine vigour (discussed below) and soil characteristics is required in order to define management zones.

Step 2. Defining the spatial variability of vineyard vigour and fruit quality

This involves the establishment of sampling stations to measure: vegetative growth (trunk cross-section, shoot length, weight of pruning, and Ravaz Index), yield components (yield, weight of cluster, number of berries, and berry diameter), and quality components (skin-to-pulp ratio, soluble solids, total acidity, pH, total anthocyanins, and total polyphenols) (Figures 2 and 3). As quality is difficult to define, combining several quality components and making a map of a quality index is sometimes helpful. This information can be used to map homogeneous sectors of vigour and quality within the vineyard. Knowing which areas have undesirable quality or excessive vigour can help to guide irrigation decisions.

Step 3. Defining spatial and temporal variability of microclimate

Climate variables are essential for estimating the vineyard water consumption (or ET_{vine}), which is computed using a reference evapotranspiration (ETo) and Kc. The Penman-Monteith equation calculates the ETo based on solar radiation, air temperature, relative humidity and wind velocity. The following steps must be examined when evaluating the variability of ETo:

- The temporal variability of atmospheric conditions can be evaluated using an automatic weather station (AWS), which measures solar radiation, air temperature, relative humidity, and wind velocity at hourly intervals.
- The spatial variability of atmospheric conditions will define the optimal number of AWSs and the best locations for placement.

Step 4. Site-specific calibrating of irrigation scheduling

The effect of the phenological stage on vineyard water consumption is represented by changes in Kc, which depends upon understanding the non-linear interactions among soil, climate, and vineyard conditions. Evaluating these interactions is very important for the practical application of regulated deficit irrigation (RDI), which is used to increase the must quality, especially for red wines (McCarthy, 1997; Peterlunger *et al.*, 2002). For this reason, the CITRA is implementing a methodology to develop specific irrigation coefficients (Kr) for each cultivar and vineyard condition. This local calibration is performed measuring soil-water content at the rooting depth during the growing season. The location and

FIGURE 2
Spatial variability of trunk cross-section area (a) and number of clusters (b), increasing relative values from light to dark

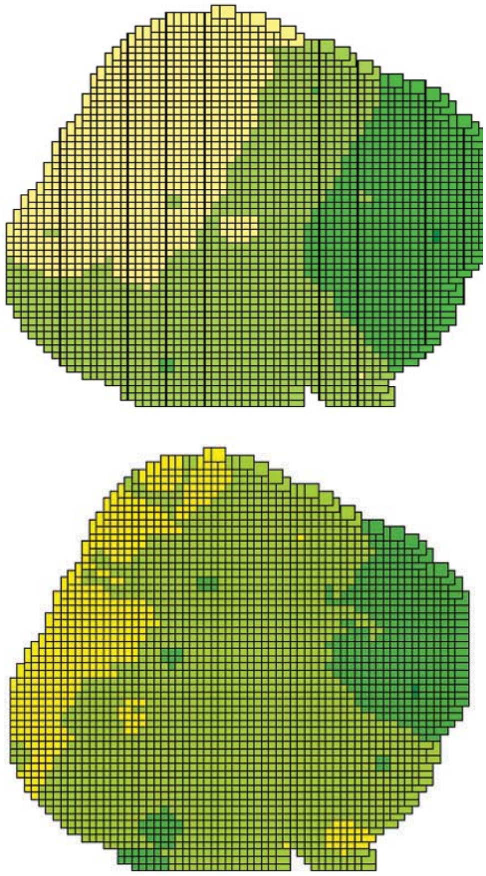


FIGURE 3
Spatial variability of total polyphenols (a) and anthocyanins (b), increasing relative values from light to dark

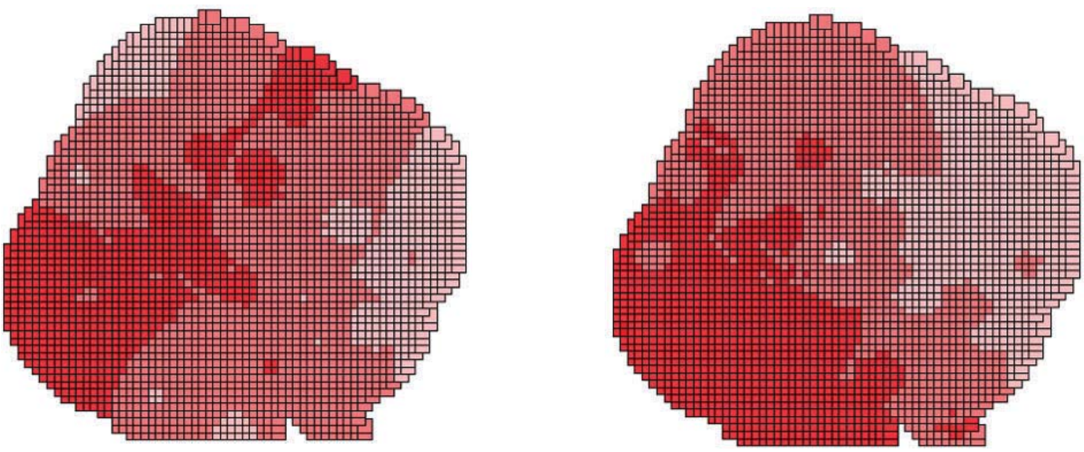
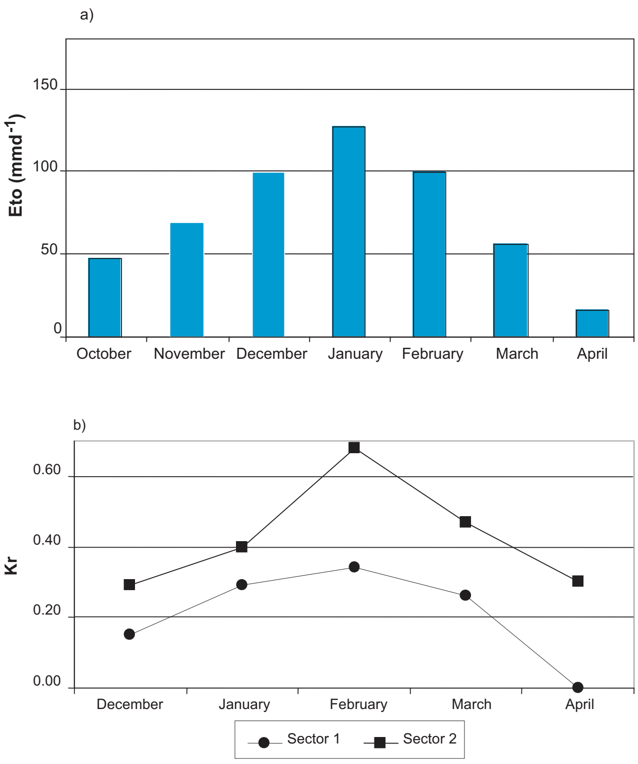


FIGURE 4
Reference evapotranspiration (ETo) and irrigation coefficient (Kr) for a Cabernet Sauvignon vineyard under a drip irrigation system, Molina Valley



number of sampling stations to measure soil moisture content are determined according to the identification of homogenous sectors described above.

Three or four years are required to calibrate the grape water consumption for each vineyard. As an example, use of the IMDS model from 1998 has facilitated a reduction in water application of 20–60 percent and has increased wine quality by 20–30 percent, especially in commercial Cabernet Sauvignon vineyards located in the Regions VI and VII.

APPLICATION OF THE IMDS

The IMDS was applied to a commercial Cabernet Sauvignon vineyard located in Molina, Maule Region, Chile (35° 6' S; 71° 16' W), during 2002/03. The climate of the area is Mediterranean with a mean annual rainfall of 540 mm, with 474 mm falling between April and September. January is the warmest month with the greatest values of ETo (Figure 4). According to soil type (Table 1) and yield target, the vineyard was separated into two homogeneous sectors in order to manage the water application differentially. In this example, the vineyard manager wanted to maximize quality in Sector 1, while producing high yields with the best quality possible in Sector 2. Table 2 presents yields and quality evaluations.

Vines were trained in a vertical positional system and were irrigated using 4 litres/h drippers spaced at intervals of 1 m. The irrigation interval was 2–3 days according to the ERD, soil texture and wetting pattern of the vineyards. The irrigation timing (IT) on a daily basis was calculated as follows:

$$IT = \frac{ET_{vine} A}{N_d q_a E}$$

TABLE 1
Soil characteristics for two homogeneous sectors, Molina Valley

Sector	Texture	Field capacity (cm³/cm³)	Wilting point (cm³/cm³)	Bulk density (g/cm³)	Maximum allowed depletion (mm)
1	Sandy-loam	33.4	16.7	1.52	99
2	Clay	42.2	23.0	1.28	150

TABLE 2
Yield, berry diameter and must colour for two homogeneous sectors Molina Valley

Sector	Yield (tonnes/ha)	Berry diameter (mm)	Total phenols (mg/litre)	Total anthocyanin (mg/litre)
1	8.5	10.9	2 852	1 729
2	16.8	12.0	1 934	1 530

where IT and ET_{vine} are expressed in hours and millimetres per day, respectively; A is the area of the vine (3 m^2); N_d is the number of emitters per vine; q_a is the emitter discharge (litres per hour), and E is the efficiency of the drip irrigation system (0.95). Daily values of ET_{vine} can be defined as (FAO, 1998):

$$ET_{vine} = ETo\ Kc\ Ks \text{ or } ET_{vine} = ETo\ Kr$$

where ETo (millimetres per day) was calculated using the Penman-Monteith equation (Ortega-Farias, Acevedo and Fuentes, 2000); Ks is a stress coefficient; and Kr is an irrigation coefficient.

To compute ETo, hourly weather data were collected from an AWS installed over a well-irrigated grass, which was located next to the vineyard. Because of the uncertainty of the Kc and Ks values, the irrigation timing was corrected by measuring the volumetric soil-water content in the effective rooting depth (60 cm). For each homogeneous sector, the volumetric soil-water content was measured twice per week with a portable TDR unit (TRASE, Soil Moisture Corp., the United States of America) during the growing season. Values of maximum allowed depletion (MAD) of 55 and 50 percent were used for Sectors 1 and 2, respectively.

Values of Kr for each homogeneous sector (site-specific) are illustrated in Figure 4, which indicates that the greatest Kr values for both sectors occurred in February. Moreover, Kr values for Sector 2 were greater than those for Sector 1 during the whole season. Maximum values of IT were observed in January and February for Sectors 1 and 2, respectively (Figure 5). For the 2002/03 season, values of IT were 93 h for Sector 1 and 231 h for Sector 2. In the case of Sector 1, the vineyard manager applied the RDI between fruit set (late November) and veraison (late January) with the objective of reducing berry diameter and increasing the must colour (Table 2). In this case, the total water application was 3.1 Mlitres/ha and 1.2 Mlitres/ha for the Sectors 1 and 2, respectively (Figure 5).

Soil-water monitoring at the rootzone depth was used to check the irrigation timing computed from the equation above. In Sector 1, the decrease in irrigation time was associated with a marked decrease in soil-water content during the growing season (Figure 6). Values for soil-water content for Sector 1 were above field capacity until the first week of November and they diminished steadily until late January (veraison). After that, the soil-moisture content was maintained around a threshold of 132 mm, which was estimated using a MAD of 0.55. For Sector 2, values for soil-water content were maintained above 147 mm, which was calculated using a MAD of 0.5. In general, values for soil-water content for Sector 1 were lower than those for Sector 2 (Figure 6). In both sectors, irrigation started when soil-water content reached the MAD.

Our experience indicates that the use of weather information in combination with soil-water monitoring could be an excellent tool for applying RDI in vineyards, especially in regions

FIGURE 5
Irrigation timing (IT) and water application for a Cabernet Sauvignon vineyard under a drip irrigation system, Molina Valley

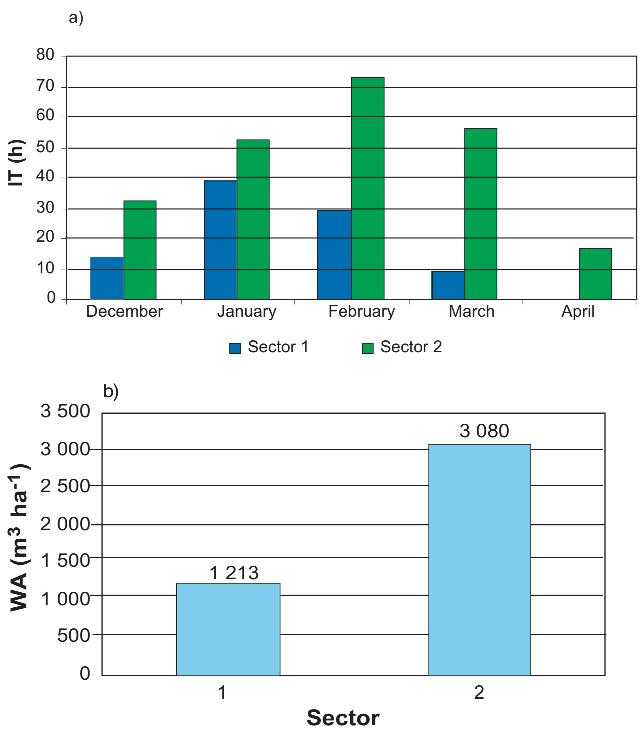
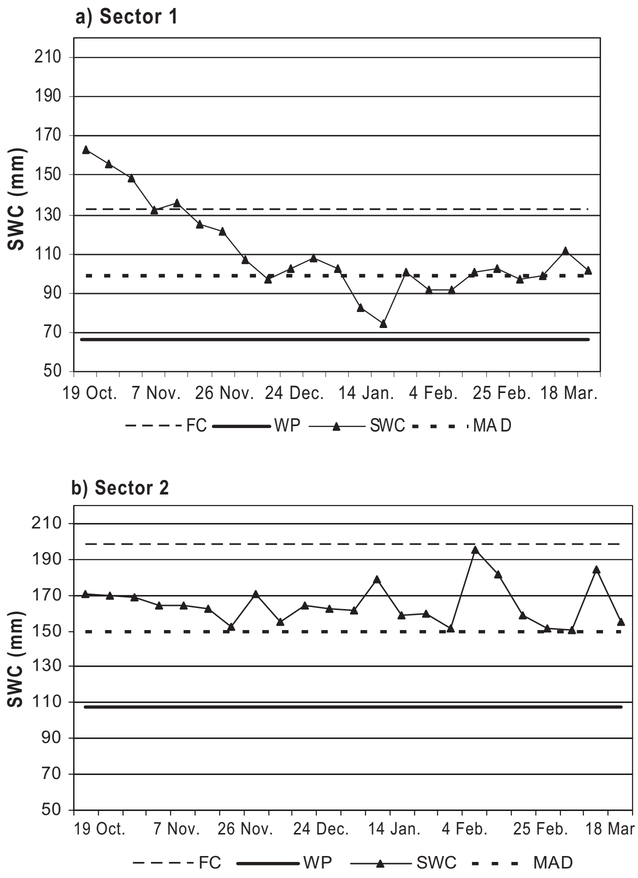


FIGURE 6
Evolution of soil-water content (SWC) for a Cabernet Sauvignon vineyard under a drip irrigation system (values for FC, WP and MAD included as reference)



presenting high variability in soil and climate conditions. Ortega-Farias *et al.* (2003) indicated that the development of maps with homogeneous sectors (according to spatial variability of the soil, water consumption, and vineyard vigour) reduced the water application of the vineyard and increased the must quality. In this case, a site-specific calibration of the irrigation coefficients (Kr = Kc × Ks) is required for each homogeneous sector within the vineyard.

CONCLUSIONS

Based on our experience, soil-water monitoring in combination with weather information could be used as a practical tool for a local calibration of the irrigation-management system according to spatial variability of soil, water consumption and vineyard vigour. Research is continuing to evaluate this spatial variability using precision farming approaches.

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Effects of soil management on soil physical properties and infiltration in olive orchards – implications for yield

INTRODUCTION

Olive production has a historic association with the Mediterranean region and even today 98 percent of the world olive area is located in the countries of the Mediterranean basin (Civantos, 1999). In the region, olives are by far the most important crop, and not just in terms of income and employment, but also in terms of environmental impact because it is cultivated as the sole crop in many areas. A good example is found in Andalusia, the southern region of Spain, where olive production covers 1.48 Mha (Consejería de Agricultura y Pesca, 2003) comprising 17 percent of the region. Despite an expansion of irrigation during the last decade, most olive production remains under rainfed conditions on sloping land, with only 15 percent on slopes less than 5 percent. Furthermore, most orchards are planted at low tree density so that only 9.5 percent exceed 200 trees/ha. In the Andalusia region, low tree density, sparse tree canopies maintained by pruning, and weed control by tillage are the main agronomic strategies that have been employed to ensure the survival of rainfed orchards.

In Spain, low levels of ground cover on sloping land in combination with a Mediterranean pattern of rainfall cause severe erosion (Pastor *et al*., 1999). These problems became especially acute with the advent of farm mechanization in the 1960s. Mechanization facilitated intensive, year-round tillage to maintain a weed-free environment, but at the same time exposed the soil surface to water erosion. Today, mechanical tillage (CT) is the most widespread soil-management system in Andalusia. However, new soil-management systems have been developed in recent decades as alternatives to mechanical tillage, partially encouraged by concerns of soil erosion. Among the most common are zero-tillage combined with herbicides to maintain a bare weed-free soil (NT) and cover crops, sown or established naturally from the soil (weed) seed bank in autumn, later mowed or killed with herbicides in early spring (CC). Numerous variations on these three basic soil-management systems are now common in the region. A complete description of soil-management practices can be found in Pastor *et al*. (1999).

This paper reviews the available published results concerning the relationships between soil management, infiltration, selected soil properties, and yield from experiments in olive orchards, mostly from southern Spain.

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FIGURE 1
Runoff coefficient for different soil management in olive orchards in runoff plot experiments

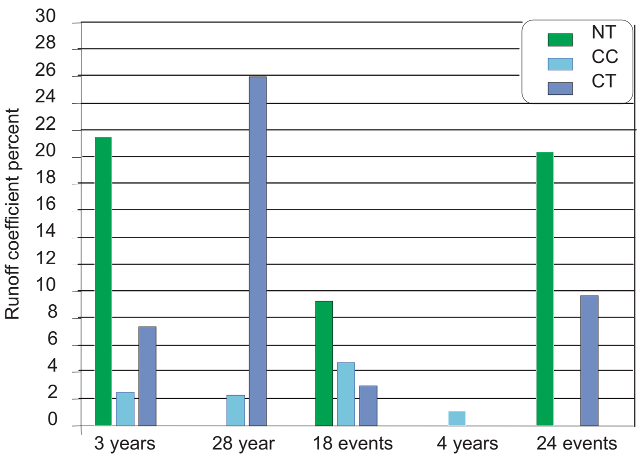
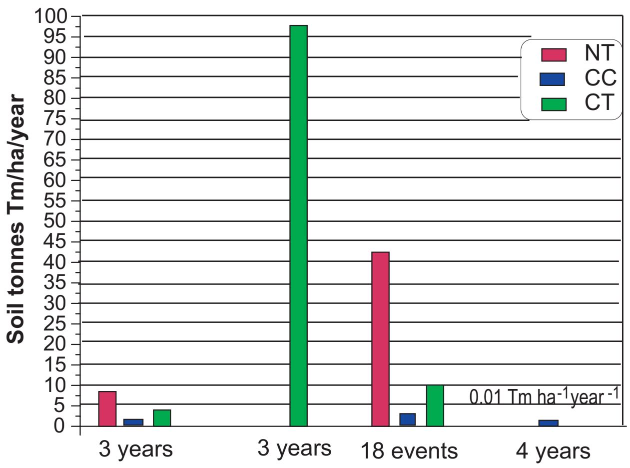


FIGURE 2
Soil losses for different soil management in olive orchards in runoff plot experiments



RESULTS

Runoff coefficients measured for various soil-management practices in olive production are presented in Figure 1. These data, from runoff plots in various Mediterranean countries ranging in area from 30–460 m², summarize, to our best knowledge, all relevant published work. The general trend is towards small runoff coefficients (< 6 percent) in CC management, and for greater runoff in NT. In contrast, CT shows moderate runoff except in the experiment of Raglione *et al.* (2000). In the experiments overall, where slopes ranged from 12 to 30 percent and lengths from 12 to 77 m, these differences in runoff translated to large differences in soil loss. This can be seen in Figure 2, where losses were small for CC, largest for NT (again with the exception of Raglione *et al.*, where soil loss was exceptionally high) and intermediate for CT.

Few associated measurements of infiltration rate were collected from the experiments included in Figures 1 and 2. However, there are other field studies that have measured infiltration, albeit without a standard technique, to compare the effect of varying soil management. One consistent conclusion from such studies is that infiltration rates are greater below the tree canopy than in the space outside, hereafter termed "lane". This is illustrated in Figure 3. Reasons advanced to explain these differences include greater compaction in the lanes as a consequence of traffic and degraded soil structure resulting from reduced organic matter (data not shown) in the top 3–5 cm. These differences have a significant effect on the spatial distribution of infiltration within the orchard, as shown in Figure 4 (Castro, 2004). In this example, greater infiltration beneath the canopy sometimes exceeded rainfall because of additions by runon from upslope lane areas.

When comparing infiltration rates between treatments, the overall picture is one of greater infiltration in CC and less infiltration in NT, both compared with CT. This can be seen in Figure 5 using saturated hydraulic conductivity, Ks, as an indicator of stabilized infiltration rate. Although CT showed pronounced temporal variations in infiltration rate due to surface sealing and compaction between consecutive tillage operations (Gómez *et al.*, 1999, data not shown) values tend to be greater than in NT because of less compaction (see Figure 6). There are few experiments comparing infiltration rates between CC and CT although there is evidence of slightly greater infiltration in CC (Figure 5). This response has also been demonstrated in previous experiments in orchards (Werenfels *et al*., 1963) and is attributed to greater macroporosity and improved soil structure, both compensating for greater bulk density compared with CT.

The yield responses of various experiments in rainfed olive orchards under different slope, plant density, and soil conditions in southern Spain are summarized in Figure 7. Olive-oil yield, not shown, provided a similar trend. Most of the differences are not statistically significant, although they do suggest a slightly greater yield for NT and CC compared with CT. Most of the CC experiments included in Figure 7 used a weed cover that emerged in winter and was then mechanically or chemically killed in early spring. It remains unclear why large reductions in surface runoff with NT have not translated into greater yield. Less damage to root systems, increased runon in the area beneath the canopy, and reduced deep percolation below the olive rootzone compared with CT are suggested as possible explanations, but all remain speculative. There are few data on the rooting system of olive trees (Connor and Fereres, 2004), and little is known about differences in water uptake by the tree from various areas and soil layers within any management system. Without greater knowledge of the temporal and spatial dynamics of soil water, explanations of the responses presented in Figure 7 must remain speculative.

However, the results presented in Figure 7 do indicate that competition for soil water between tree and cover crop can be prevented by early killing of the ground cover. In contrast, where the cover was kept alive until late spring, significant reductions in yield were evident (Figure 8). Such results emphasize that competition for soil water during spring does pose a significant risk to olive yield. Castro (2004) showed that differences in tree-water status, induced by competition for water during the cover crop period, persisted until the end of the summer

FIGURE 3
Saturated hydraulic conductivity, Ks, measured beneath the olive canopy and outside

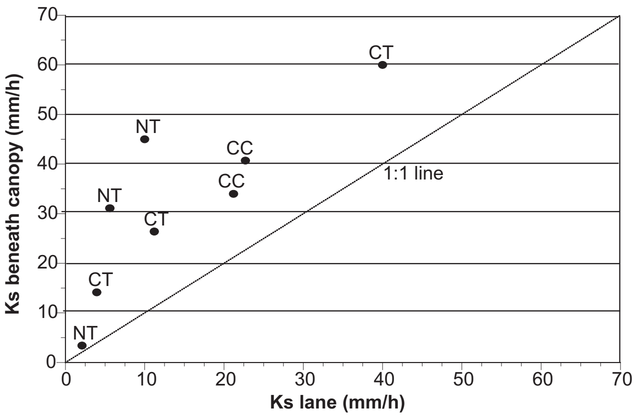


FIGURE 4
Saturated hydraulic conductivity, Ks, measured beneath the olive canopy and outside

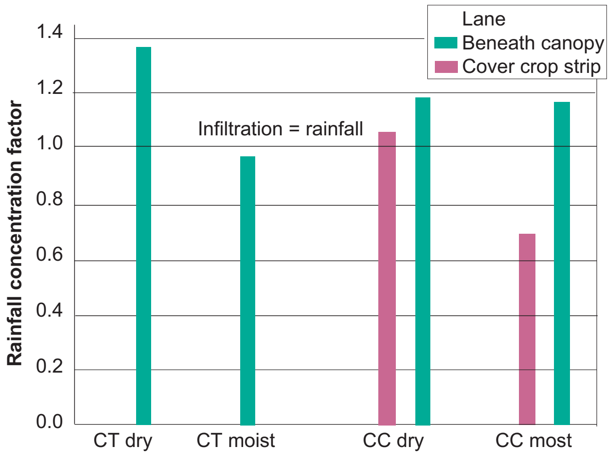


FIGURE 5
Comparison of saturated hydraulic conductivity, Ks, measured for different soil management.

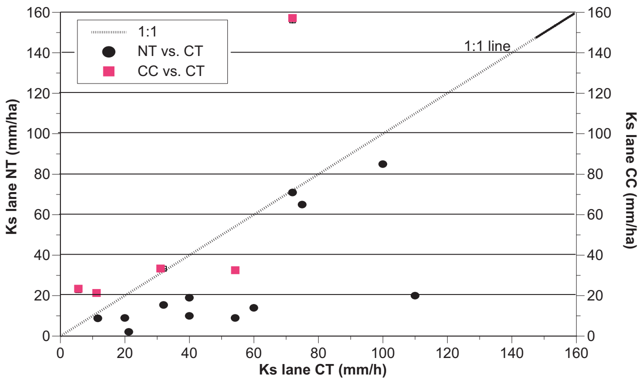


FIGURE 6
Comparison of bulk density, bd, conductivity, Ks, measured for different soil management

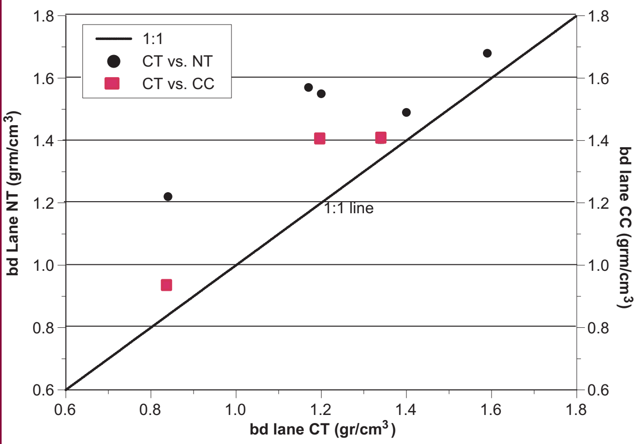


FIGURE 7
Olive fruit yield for different soil management

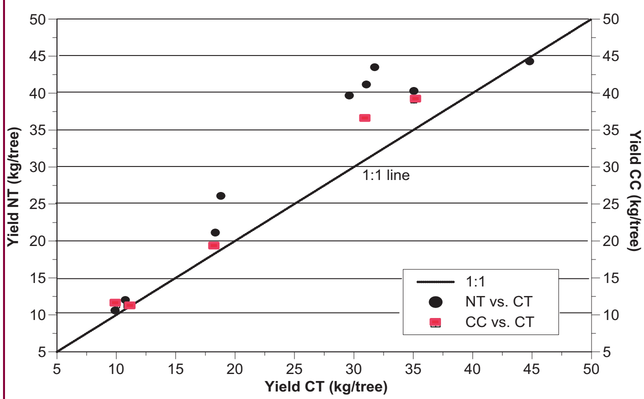
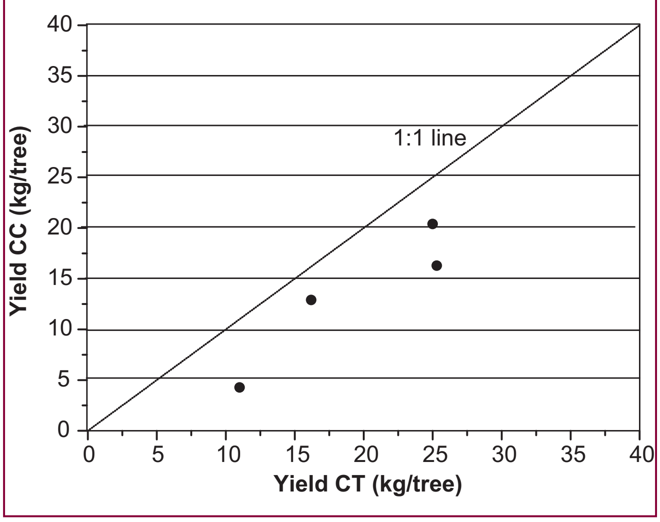


FIGURE 8
Yield, fruit, production for CT and CC killed in late spring



dry season. He also demonstrated that year-to-year variability of rainfall does not allow the identification of a fixed optimum killing date for CC. It is this perceived risk of yield loss, resulting from competition for water by ground cover, that appears to be the most important reason why farmers do not change management from CT to the alternative soil-protecting options.

While it is possible to maintain good percentage ground cover in experimental plots (Castro, 1993), the task has proved far more difficult in commercial practice. Farmers and weed scientists commonly observe large bare patches on CC-managed farms that they attribute mostly to soil compaction and/or soil erosion. However, there is little research at the farm level linking differences in ground cover to soil properties and erosion risk. One study measured the distribution of ground cover in July by remote sensing and made associated measurements of bulk density and infiltration rate. The cover data is presented in Figure 9 and the relationship between cover and the two soil properties in Figure 10. The measured average percentage ground cover of 25 percent is small relative to well-managed plot experiments in the region, reported at about 60 percent (Castro, 1993). These results reflect the difficulty of obtaining large percentages of ground cover on CC-managed farms, and support the casual observations (above) of the frequent existence of large areas of reduced ground cover. In the associated observations of soil properties, the correlations between ground cover, infiltration rate, and bulk density of the topsoil for the three areas marked in Figure 9 reveal that the areas of reduced ground cover are also more compacted.

CONCLUSIONS

Results, mostly from southern Spain, show that the main soil-management methods used in the region, CT, NT and CC, have large impacts on surface runoff and soil erosion as a consequence of modifications to soil infiltration rate associated with compaction and increased macroporosity induced by vegetation. They also indicate that olive orchards have two distinct areas: one beneath the canopy where bulk density is less and organic matter levels and infiltration rates are greater; and the other in the trafficked lanes between the tree rows. Changing management from CT to NT or CC killed in early spring did not reduce yield in these experimental data from rainfed orchards. There is no clear explanation why large observed differences in runoff did not lead to differences in yield but when CC was kept alive until late spring, olive yield was clearly reduced by competition for water. Changing from CT to NT increases erosion risk, mostly because of greater surface runoff. CC appears an alternative soil management to CT in traditional rainfed olive orchards and can reduce erosion without yield penalty, provided that the cover crop is killed in early spring. The determination of an optimum killing date for the many combinations of production and seasonal conditions remains uncertain. Finally, it is difficult to obtain increased density and ground cover in CC-managed farms owing, among other factors, to the compaction caused previously by intensive traffic. This problem must be recognized and addressed if the beneficial effects of CC are to be incorporated in soil-management systems to control erosion at the farm scale.

FIGURE 9
Map of ground at tree lanes during July 18th 2004 at a commercuial faro manager with CC killed in late May

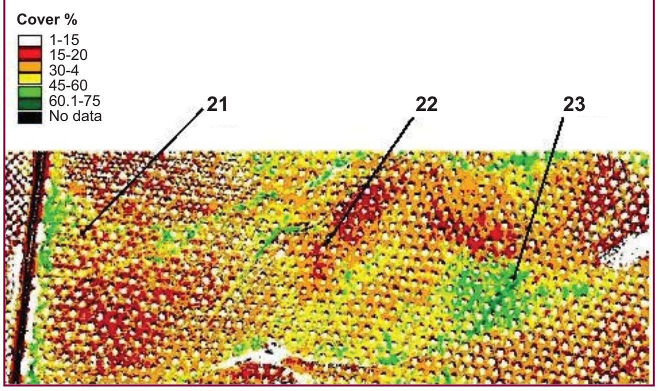
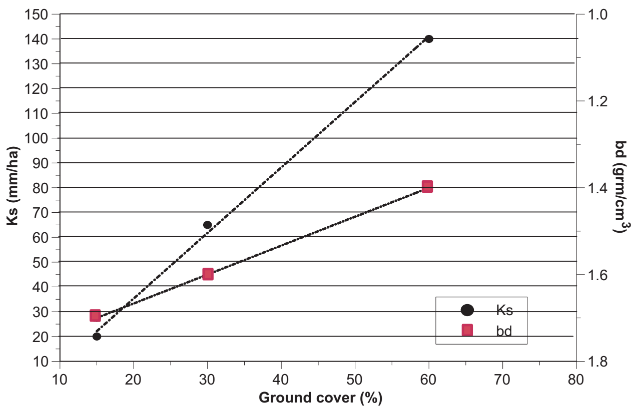


FIGURE 10
Ground cover, saturated hydraulic conductivity, Ks, and bulk density, bd, for the zones in Figure 9



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A systems approach for orchard management using simulation models

The goal of agricultural research is to improve agricultural productivity and sustainability by increasing yields and by using inputs (water, fertilizer, labour, and farm machinery) more efficiently and at less cost to the farmer and the environment. Recent literature has focused on many issues that jeopardize our ability to meet the future needs of food, fuel and fibre as a consequence of placing increasing demands on limited resources. Inappropriate agricultural-management practices, such as intensive tillage, can cause unacceptable degradation of the environment. Successful implementation of sustainable land-management and conservation practices will require quantitative evaluation of the factors that determine whether an agricultural system is sustainable or unsustainable. Only by identifying and measuring these factors will it become possible to evaluate the long-term performance of a given management practice. However, this is not an easy task. The issue of what constitutes sustainable land management is complex and transcends concerns of a physical–chemical–biological nature to include socio-economic, cultural, and political concerns. Because of this complexity, a land-management practice found to be sustainable at one site might not be equally sustainable at another site.

Decision-support systems (DSSs) and recent advances in the resolution and availability of remote-sensing imagery, coupled with a decrease in its cost, have facilitated the collection of timely information on soil and landscape spatial variability for improving capabilities to manage orchards. Simulation models and DSSs should use functional relationships to evaluate the water, energy, biomass and nutrient balances in orchard production. They require a minimum dataset of soil properties, weather data, genetic characteristics, and several management practices. DSSs and simulation models are able to optimize resource use through suggesting both tactical and strategic management strategies to improve orchard performance and profitability. Figure 1 shows an example of schematic databases, models and analysis tools for a sustainable DSS.

Critical to the development of a DSS for orchards is the assessment of the spatial variation in the soil-water balance for orchards. Adapting crop models for orchards has been done with varying degrees of detail. We suggest that the general estimation of leaf area index (LAI) through simulation or indirect remote-sensing measurements will be the most simple and generic model to evaluate the transpiration through orchard trees.

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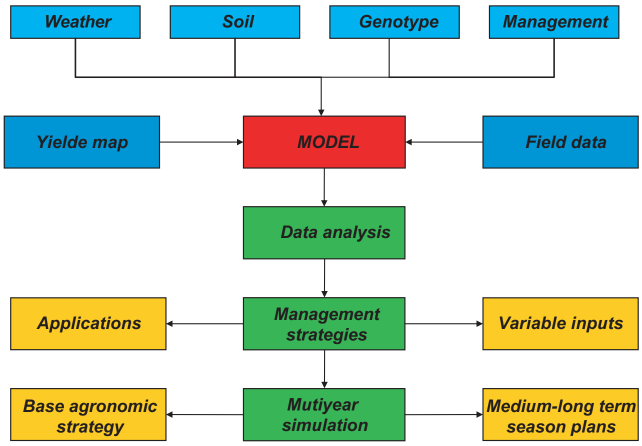
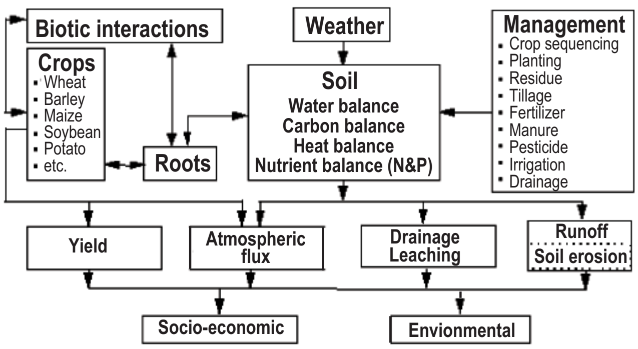
FIGURE 1
Decision-support systems for sustainable agriculture – schematic representation of database, models and analysis tools



Source: Adopted from Jones *et al*., 1993.

FIGURE 2
Diagram of the components of SALUS



The LAI depends on both the density of foliage on each tree and their spacing relative to one another. With this information, it is possible to reasonably simulate the evaporation from soil and plants separately when the trees are not short of a water supply in the rootzone because the source of water from these two processes is quite different. Specific relationships between LAI and transpiration and soil evaporation will need to be studied more thoroughly as they differ considerably from the usual agronomic row crops. Evaluating the spatial extent of the root system as the trees grow is the other challenge. This quantity is often spatially quite variable because of the varying depth of soil that is hospitable for rooting. The horizontal movement rate of tree roots in orchards is essential to evaluating the water available for uptake by roots.

An overview of the model System Approach to Land Use Sustainability (SALUS) is presented in Figure 2. SALUS can play a major role in identifying the best management decision for soil and water conservation in olive orchards and vineyards.

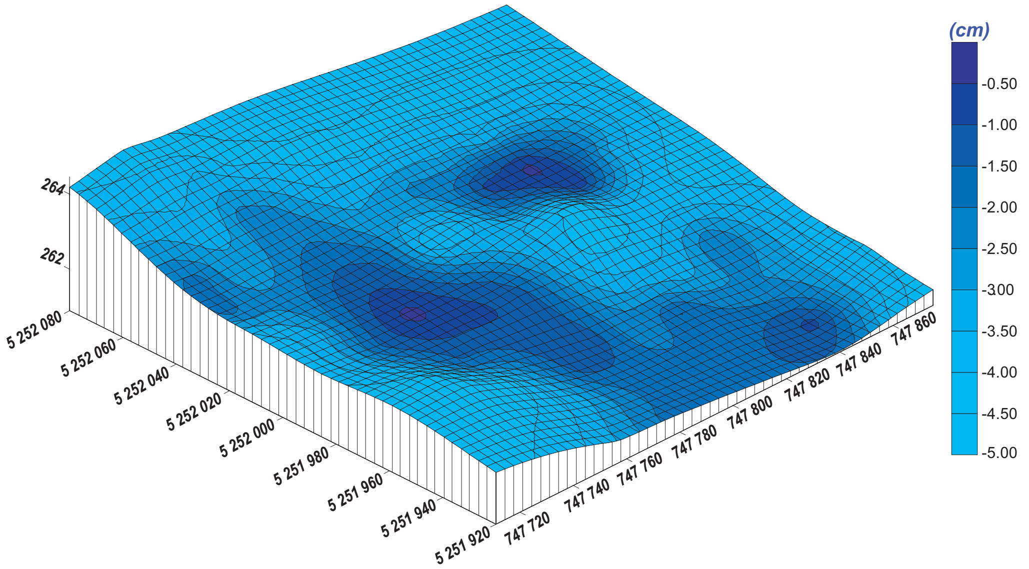
When landscape variation is included, the use of digital terrain modelling (DTM) can assist with spatial variation of outcomes, especially the soil-water balance. DTM provides an opportunity to model, analyse and display phenomena related to topography. Indeed, DTM includes the spatial distribution of terrain attributes. Thus, the spatial distribution of topographic attributes can be used as a direct or indirect measure of spatial variability of these processes. An example of an application of DTM is represented in Figure 3.

CONCLUSIONS

DSSs have the capability to make site-specific recommendation for pest management, fertilizer management, farm financial planning, and general crop management. They can provide analysis to assist with best management practices in order to accomplish the specific goals that growers may have. It is impractical to develop a single DSS for each decision of researchers, planners or policy-makers. However, it reasonable to expect that a few relatively powerful DSSs that currently exist can be adapted for use with orchards, somewhat similar to those for agronomic crop production.

Systems analysis will be important in evaluating management practices that bring about improvements in the production, profitability and sustainability of orchards. Future research and DSS development should focus on how to optimize the soil-water supply through management of the tree spacing within the landscape in order

FIGURE 3
Application of digital terrain modelling for simulating spatial soil-water balance



to accomplish the goals of producers and other decision-makers. Much more attention on the spatial variation of soils and the landscape will be the key to developing a useful DSS for orchards.