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DEFICIT IRRIGATION PRACTICES

FAO

Water Reports 22

ISSN 1020-1203

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Cover photo: Andreas Phocaides, Department of Agriculture, Ministry of Agriculture, Natural Resources and Environment. *Microirrigation in young fruit-trees, Nissou, Cyprus.*

ISSN 1020-1203

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DEFICIT IRRIGATION PRACTICES

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2002

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ISBN 92-5-104768-5

Foreword

Irrigated agriculture makes a major contribution to food security, producing nearly 40 percent of food and agricultural commodities on 17 percent of agricultural land. Irrigated areas have almost doubled in recent decades and contributed much to the growth in agricultural productivity over the last 50 years. Irrigated agriculture uses more than 70 percent of the water withdrawn from the earth's rivers; in developing countries the proportion exceeds 80 percent.

The scope for further irrigation development to meet food requirements in the coming years is, however, severely constrained by decreasing water resources and growing competition for clean water. While on a global scale water resources are still ample, serious water shortages are developing in the arid and semi-arid regions as existing water resources reach full exploitation. The situation is exacerbated by the declining quality of water and soil resources. The dependency on water has become a critical constraint on further progress and threatens to slow down development, endangering food supplies and aggravating rural poverty.

The great challenge for the coming decades will therefore be the task of increasing food production with less water, particularly in countries with limited water and land resources. Water productivity for food production was a major issue at the Second World Water Forum convened in March 2000 by the World Water Council in The Hague, the Netherlands, where a vision of progress towards water security was presented and an action framework for achieving this was developed. One of its main targets was defined as the need to increase water productivity for food production from rainfed and irrigated agriculture by 30 percent by 2015.

Water stress affects crop growth and productivity in many ways. Most of the responses have a negative effect on production but crops have different and often complex mechanisms to react to shortages of water. Several crops and genotypes have developed different degrees of drought tolerance, drought resistance or compensatory growth to deal with periods of stress. The highest crop productivity is achieved for high-yielding varieties with optimal water supply and high soil fertility levels, but under conditions of limited water supply crops will adapt to water stress and can produce well with less water.

In the context of improving water productivity, there is a growing interest in deficit irrigation, an irrigation practice whereby water supply is reduced below maximum levels and mild stress is allowed with minimal effects on yield. Under conditions of scarce water supply and drought, deficit irrigation can lead to greater economic gains than maximizing yields per unit of water for a given crop; farmers are more inclined to use water more efficiently, and more water-efficient cash crop selection helps optimize returns. However, this approach requires precise knowledge of crop response to water as drought tolerance varies considerably by species, cultivar and stage of growth.

Recognizing the potential of deficit irrigation practices in conserving scarce water resources, increasing farm profitability and enhancing environmental protection, the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture coordinated a research project between

1990 and 1995 entitled "The use of nuclear and related techniques in assessment of irrigation schedules of field crops to increase effective use of water in Irrigation projects". The results of this project were published in 1996 in IAEA-TECDOC-888 *Nuclear techniques to assess irrigation schedules for field crops* and externally in 1999 by Kluwer Academic Publishers *Crop yield response to deficit irrigation* (C. Kirda, P. Moutonnet, C. Hera and D.R. Nielsen, eds.).

The past five years have seen substantial progress in the practical application of deficit irrigation for both annual and perennial crops. Recognizing the need for wide dissemination of this new information, the Joint FAO/IAEA Division together with the FAO Land and Water Development Division invited specialists in this sector of research and development to contribute to a new publication to provide a state-of-the-art evaluation for a wide range of crops. Ms L.K. Heng and Mr P. Moutonnet (IAEA, Vienna) and Mr M. Smith (FAO, Rome) implemented this task.

The aim of this publication is to provide further information on the way crops react to stress, leading to practical guidelines to assist extensionists, farmers and decision-makers in minimizing water use for optimal crop production.

Contents

List of acronyms

CRP	coordinated research project
DR	diffusive resistance
DWU	daily water use
E_c	crop water use efficiency
E_{pan}	pan evaporation
ET	evapotranspiration
ET_a	actual evapotranspiration
ET_c	crop evapotranspiration
ET_m	maximum evapotranspiration
ET_o	reference crop evapotranspiration
ET_p	potential evapotranspiration
GDD	growing-degree-day
GMS	granular matrix sensor
HI	harvest index
HYV	high-yielding variety
IAEA	International Atomic Energy Agency
IW/CPE	irrigation water / cumulative pan evaporation
Kc	crop coefficient
kPa	kilopascal
k_y	crop yield response factor
LAI	leaf area index
N	nitrogen
NCP	North China Plain
P	phosphorous
PRD	partial rootzone drying
RBD	randomized block design
RDI	regulated deficit irrigation
RWC	relative water content
SDI	subsurface drip irrigation
SMNP	soil moisture neutron probe
SWP	soil water potential
TR	transpiration rate
UNR	ultra-narrow row
WBC	William Bon Chretien

Summary

This publication presents the results of a number of deficit irrigation studies carried out for various crops and under various ecological conditions, with a review of the impact of reduced water supplies on crop yield. The results of the studies are presented in ten contributions prepared by a team of scientists specialized in deficit irrigation. The articles were prepared at the request of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture in close collaboration with the FAO Land and Water Development Division.

The studies present the latest research concepts and involve various practices for deficit irrigation. Both annual and perennial crops were exposed to different levels of water stress, either during a particular growth phase, throughout the whole growing season or in a combination of growth stages. The overall finding, based on the synthesis of the different contributions, is that deficit or regulated-deficit irrigation can be beneficial where appropriately applied. Substantial savings of water can be achieved with little impact on the quality and quantity of the harvested yield. However, to be successful, an intimate knowledge of crop behaviour is required, as crop response to water stress varies considerably.

The use of models can be an important tool to simulate crop water behaviour under different conditions of water supply. The yield-response-to-water functions as developed by Doorenbos and Kassam (*FAO Irrigation and Drainage Paper No. 33*) were tested with the FAO CROPWAT model and applied successfully to evaluate and predict the impact of deficit irrigation on crop yield. The crop parameters used in the model include the crop response factor, which estimates relative yield reductions based on the measured reduction in crop transpiration. The factor is a useful indicator for the sensitivity and tolerance of crop and crop stage to water stress. Analyses showed that crops less sensitive to stress such as cotton, maize, groundnut, wheat, sunflower and sugar beet can adapt well to deficit irrigation practices provided good management practices can be secured. For more sensitive crops such as potatoes deficit irrigation proved less economic.

A study carried out on winter wheat in the North China Plain (NCP) between 1992 and 2000 showed possible water savings of 25 – 75 percent by applying deficit irrigation at various growth stages, without significant loss of yield and profits. A dynamic model was used to calculate the net profits of the irrigation treatments. Procedures were developed to schedule irrigation applications according to the number of irrigations required. For one irrigation, the application should take place between jointing and booting; for two irrigations the applications should take place between jointing and heading and from heading to early milk stage, while with three irrigations, the applications should take place at tillering stage before over wintering, between jointing and booting and from heading to milk stage.

In deficit studies carried out in India on irrigated groundnuts, it was possible to increase field water use efficiency (WUE) and dry matter by imposing transient soil moisture-deficit stress during the vegetative phase, i.e. 20 – 45 days after sowing. Water stress applied during vegetative growth may have had a favourable effect on root growth, contributing to more effective water use from deeper layers.

While most studies were able to demonstrate the benefits of deficit irrigation, potatoes grown under sprinkler irrigation in the semi-arid environment of eastern Oregon, United States of America, did not show an economic benefit when exposed to stress. Growing four varieties of potato under various deficit irrigation treatments resulted in gross revenues declining by more than the production costs, and hence reduced profits. The results of this case study suggest that deficit irrigation of potatoes would not be a viable management option for that region under current economic conditions.

Fruit crops such as peach and pear trees and grapevines reacted favourably to deficit irrigation practices, with important water savings and improved fruit quality. In southeastern Australia, regulated deficit irrigation (RDI) of peach and pear trees increased WUE by 60 percent, with no loss in yield or reduction in vegetative vigour. In Washington State, United States of America, RDI of grapevines prior to fruit set (veraison) was effective in controlling shoot growth and pruning weights, with no significant reduction in yield. RDI applied after veraison to vines with large canopies resulted in greater water deficit stress. Wine quality improved with pre-veraison RDI applied as compared to post-veraison RDI. RDI applied at anytime resulted in better early-season lignification of canes and cold hardening of buds.

In addition to RDI, partial root zone drying (PRD) is also a promising practice for inducing stress tolerance in fruit trees. PRD is a new irrigation technique that subjects one-half of the root system to a dry or drying phase while the other half is irrigated. The wetted and dried sides of the root system alternate on a 10-14-day cycle. Both RDI and PRD systems require high management skills. Close monitoring of soil water content is recommended. Both practices improve the WUE of wine grape production. Micro-irrigation facilitates the application of RDI and PRD. Practical guidelines for using RDI were developed.

Subsurface drip irrigation (SDI) also improved the WUE of crops and reduced farming costs. An approach was developed for deficit SDI on cotton grown in arid east Texas, United States of America, to enable farmers with a limited supply of water to decide on the optimal area to plant and the best row width/pattern to apply. By applying deficit SDI, it proved more economical to use the available water resources over the entire farm, rather than to try to maximize water and yield on part of the farm. Moreover, with SDI, it proved possible to apply a large part of the water required as pre-planting irrigation, thus effectively advancing the timing of water application to the beginning of the season when more water is available.

In conclusion, with increasing scarcity and growing competition for water, there will be more widespread adoption of deficit irrigation, especially in arid and semi-arid regions. The technique has already been applied to a wide variety of crops as presented in this publication. However, as different crops and trees respond differently to water stress, it is important that the technique undergo continuous refinement and improvement, as deficit irrigation requires more sophisticated water controls, accurate water management and soil water monitoring. Advances in new irrigation technologies with more refined measuring techniques and soil water sensors will help improve knowledge and management techniques. In this regard, recent years have witnessed major advances in developing and marketing user-friendly and affordable soil water sensors, which farmers are using increasingly in their farm management strategies. With these techniques, it is then possible to identify irrigation scheduling strategies that minimize water demand with minimal impacts on yields and crop quality, leading to improved food security.

Deficit irrigation scheduling based on plant growth stages showing water stress tolerance

SUMMARY

With increasing municipal and industrial demands for water, its allocation for agriculture is decreasing steadily. The major agricultural use of water is for irrigation, which, thus, is affected by decreased supply. Therefore, innovations are needed to increase the efficiency of use of the water that is available. There are several possible approaches. Irrigation technologies and irrigation scheduling may be adapted for more-effective and rational uses of limited supplies of water. Drip and sprinkler irrigation methods are preferable to less efficient traditional surface methods. It is necessary to develop new irrigation scheduling approaches, not necessarily based on full crop water requirement, but ones designed to ensure the optimal use of allocated water. Deficit (or regulated deficit) irrigation is one way of maximizing water use efficiency (WUE) for higher yields per unit of irrigation water applied: the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing season. The expectation is that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. The grower must have prior knowledge of crop yield responses to deficit irrigation. This paper reviews yield responses of major field crops to deficit irrigation, including cotton, maize, potato, sugar cane, soybean and wheat. Crop yields obtained under various levels of reduced evapotranspiration were fitted to the linear crop yield response functions of Stewart *et al.* (1977). Results show that cotton, maize, wheat, sunflower, sugar beet and potato are well suited to deficit irrigation practices, with reduced evapotranspiration imposed throughout the growing season. This list may also include common bean, groundnut, soybean and sugar cane where reduced evapotranspiration is limited to (a) certain growth stage(s). With a 25 percent deficit, WUE was 1.2 times that achieved under normal irrigation practices. Irrigation scheduling based on deficit irrigation requires careful evaluation to ensure enhanced efficiency of use of increasingly scarce supplies of irrigation water.

GENERAL CONCEPTS AND RATIONALE

In the past, crop irrigation requirements did not consider limitations of the available water supplies. The design of irrigation schemes does not address situations in which moisture availability is the major constraint on crop yields. However, in arid and semi-arid regions, increasing municipal and industrial demands for water are necessitating major changes in irrigation management and scheduling in order to increase the efficiency of use of water that is allocated to agriculture.

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Agronomic measures such as varying tillage practices, mulching and anti-transpirants can reduce the demand for irrigation water. Another option is deficit irrigation, with plants exposed to certain levels of water stress during either a particular growth period or throughout the whole growth season, without significant reduction in yields.

Much published research has evaluated the feasibility of deficit irrigation and whether significant savings in irrigation water are possible without significant yield penalties. Stegman (1982) reported that the yield of maize, sprinkler irrigated to induce a 30 – 40 percent depletion of available water between irrigations, was not statistically different from the yield obtained with trickle irrigation maintaining near zero water potential in the rootzone. Ziska and Hall (1983) reported that cowpea had the ability to maintain seed yields when subjected to drought during the vegetative stage provided subsequent irrigation intervals did not exceed eight days. The work of Korte *et al*. (1983), Eck *et al*. (1987), Speck *et al*. (1989), and of many others, has shown that soybean is amenable to limited irrigation. Stegman *et al*. (1990) indicated that although short-term water stress in soybean during early flowering may result in flower and pod drop in the lower canopy, increased pod set in the upper nodes compensates for this where there is a resumption of normal irrigation.

Cotton shows complex responses to deficit irrigation because of its deep root system, its ability to maintain low leaf water potential and to osmotically regulate leaf-turgor pressure, i.e. so-called conditioning. Thomas *et al*. (1976) found that plants that suffered a gentle water stress during the vegetative period showed higher tolerance of water deficit imposed later as a result of adaptation to existing soil water status. Grimes and Dickens (1977) reported that both early and late irrigations lowered cotton yields. However, water stress during vegetative growth, causing leaf water potential less than a critical midday value of -1.6 MPa , adversely affected the final yield (Grimes and Yamada, 1982).

Similar work on sugar beet (Okman, 1973; Oylukan, 1973; and Winter, 1980), sunflower (Jana *et al*., 1982; Rawson and Turner, 1983; and Karaata, 1991), wheat (Day and Intalap, 1970; and Musick and Dusck, 1980), potato (Bartoszuk, 1987; Trebejo and Midmore, 1990; and Minhas and Bansal, 1991) and on many other crops has demonstrated the possibility of achieving optimum crop yields under deficit irrigation practices by allowing a certain level of yield loss from a given crop with higher returns gained from the diversion of water for irrigation of other crops. Where water scarcity exists at the regional level, irrigation managers should adopt the same approach to sustain regional crop production, and thereby maximize income (Stegman *et al*., 1980). This new concept of irrigation scheduling has different names, such as regulated deficit irrigation, pre-planned deficit evapotranspiration, and deficit irrigation (English *et al*., 1990).

Furthermore, yield reductions from disease and pests, losses during harvest and storage, and arising from insufficient applications of fertilizer are much greater than reductions in yields expected from deficit irrigation. On the other hand, deficit irrigation, where properly practised, may increase crop quality. For example, the protein content and baking quality of wheat, the length and strength of cotton fibres, and the sucrose concentration of sugar beet and grape all increase under deficit irrigation.

DEFICIT IRRIGATION MANAGEMENT

Deficit irrigation practices differ from traditional water supplying practices. The manager needs to know the level of transpiration deficiency allowable without significant reduction in crop yields. The main objective of deficit irrigation is to increase the WUE of a crop by eliminating irrigations that have little impact on yield. The resulting yield reduction may be small compared with the benefits gained through diverting the saved water to irrigate other crops for which water would normally be insufficient under traditional irrigation practices.

Before implementing a deficit irrigation programme, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season (Kirda and Kanber, 1999). High-yielding varieties (HYVs) are more sensitive to water stress than low-yielding varieties; for example, deficit irrigation had a more adverse efect on the yields of new maize varieties than on those of traditional varieties (FAO, 1979). Crops or crop varieties that are most suitable for deficit irrigation are those with a short growing season and are tolerant of drought (Stewart and Musick, 1982).

In order to ensure successful deficit irrigation, it is necessary to consider the water retention capacity of the soil. In sandy soils plants may undergo water stress quickly under deficit irrigation, whereas plants in deep soils of fine texture may have ample time to adjust to low soil water matric pressure, and may remain unaffected by low soil water content. Therefore, success with deficit irrigation is more probable in finely textured soils.

Under deficit irrigation practices, agronomic practices may require modification , e.g. decrease plant population, apply less fertilizer, adopt flexible planting dates, and select shorter-season varieties.

Deficit irrigation scheduling

Discussions in this section are based on data from a coordinated research programme (CRP) on crop yield responses to deficit irrigation Kirda *et al.*, 1999b, conducted under the auspices of the Soil and Water Management and Crop Nutrition Section of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Vienna. A wide range of field crops (including cotton, wheat, sugar beet, soybean, sugar cane, potato, and maize) were the subject of four years of field experiments. Crop yield response data from deficit irrigation were fitted to the following linear equation used earlier by Stewart *et al.* (1977):

$$\frac{Y}{Y_m} = 1 - k_y \left[1 - \frac{ET_a}{ET_m} \right] \qquad (1)$$

where Y and Y_m are expected and maximum crop yields, corresponding to ET_a and ET_m, actual and maximum evapotranspiration, respectively; k_y is a crop yield response factor that varies depending on species, variety, irrigation method and management, and growth stage when deficit evapotraspiration is imposed. The crop yield response factor gives an indication of whether the crop is tolerant of water stress. A response factor greater than unity indicates that the expected relative yield decrease for a given evapotraspiration deficit is proportionately greater than the relative decrease in evapotranspiration (Kirda *et al.*, 1999a). For example, soybean yield decreases proportionately more where evapotranspiration deficiency takes place during flowering and pod development rather than during vegetative growth (Figure 1).

Table 1 summarizes crop response factors that are less than unity for situations where deficit irrigation practices may seem to be acceptable and an infeasible option either for the season or for a particular growth stage. Under the defined conditions, the relative yield decrease was

TABLE 1
Crop response factors where yield reduction is proportionally less than relative evapotranspiration deficit

Crop	Specific growth stage	k_y	Irrigation method	Reference
Common bean	Vegetative; Yield formation	0.57 0.87	Furrow	Calvache and Reichardt (1999)
	Whole season	0.99	Sprinkler	
Cotton	Flowering and yield formation	0.99	Sprinkler	Bastug (1987)
	Whole season	0.86	Drip	Yavuz (1993)
	Bud formation; Flowering	0.75 0.48	Check Furrow	Prieto and Angueira (1999)
	Boll formation; Flowering; Vegetation	0.46 0.67 0.88	Furrow	Anac *et al*. (1999)
Groundnut	Flowering	0.74	Furrow	Ahmad (1999)
Maize	Whole season	0.74	Sprinkler	Craciun and Craciun (1999)
Soybean	Vegetative	0.58	Furrow	Kirda *et al*. (1999a)
Sunflower	Whole season Vegetative and yielding	0.91 0.83	Furrow Furrow	Karaata (1991)
Sugar beet	Whole season; Yield formation and ripening; Vegetative and yield formation	0.86 0.74 0.64	Furrow Furrow	Bazza and Tayaa(1999)
Sugar cane	Tillering	0.40	Furrow	Pene and Edi (1999)
Potato	Vegetative; Flowering; Tuber formation	0.40 0.33 0.46	Furrow	Iqbal *et al*. (1999)
	Whole season	0.83	Drip	Kovacs *et al*. (1999)
Wheat	Whole season; Whole season	0.76 0.93	Sprinkler Basin	Madanoglu (1977)
	Flowering and grain filling	0.39	Basin	Waheed *et al*. (1999)

proportionately less than the decreased application of irrigation water. Therefore, one should expect crop WUE (E_c) to increase even if crop yields fell. The equation for crop WUE is:

$$E_c = \frac{Y}{ET_a} \quad (2)$$

where:
Y = crop yield (kg/ha)
ET_a = actual evapotranspiration (mm)

Alternatively, the equation for crop WUE can be derived from Equation (1):

$$E_c = \frac{Y}{ET_a} = \left[k_y - \frac{k_y - 1}{ET_a / ET_m}\right] \times \frac{Y_m}{ET_m} \quad (3)$$

FIGURE 1
Relative seed yield response of soybean to relative ET deficit

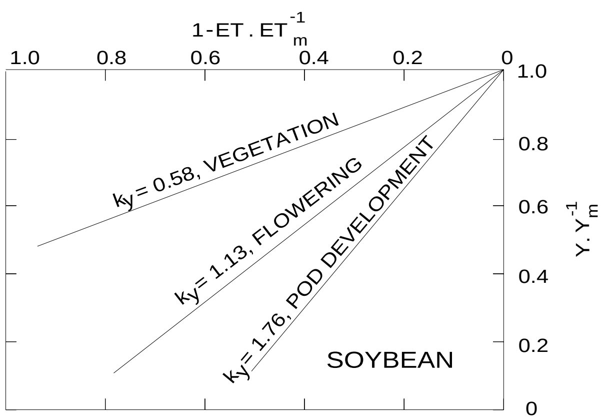
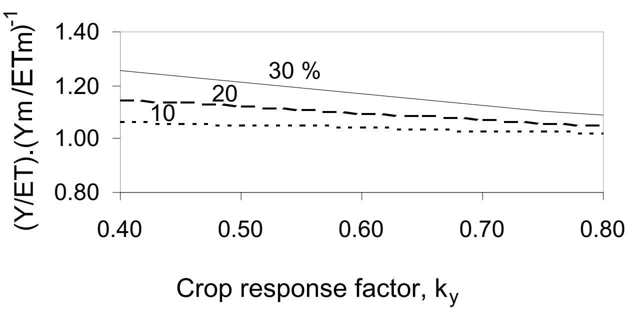


TABLE 2
Expected relative yield and relative water use efficiency, for a planned evapotraspiration deficit of 25 percent

Crop	Stage when ET deficit occurred	k_y	Irrigation method	Expected relative yield	Relative water use efficiency
Common bean	Vegetative;	0.57	Furrow	0.86	1.14
	Yield formation	0.87		0.78	1.04
Cotton	Whole season;	0.86	Drip	0.79	1.05
	Boll formation and flowering	0.48	Furrow	0.88	1.17
Groundnut	Flowering	0.74	Furrow	0.82	1.09
Maize	Whole season	0.74	Sprinkler	0.82	1.09
Potato	Whole season;	0.83	Drip	0.79	1.06
	Vegetative	0.40	Furrow	0.90	1.20
Soybean	Vegetative	0.58	Furrow	0.86	1.14
Sugar beet	Whole season;	0.86	Furrow	0.79	1.05
	Mid-season	0.64		0.84	1.12
Sugar cane	Tillering	0.40	Furrow	0.90	1.20
Sunflower	Whole season;	0.91	Furrow	0.77	1.03
	Vegetative yielding	0.83		0.79	1.06
Wheat	Whole season;	0.76	Sprinkler	0.81	1.08
	Flowering and grain filling	0.39	Basin	0.90	1.20

FIGURE 2
Dependence of crop field water use efficiency on the crop yield response factor and planned ET deficit, percentage values



where E_c varies depending on crop response factor. Diverting the saved water to increase the area irrigated may compensate for decreases in crop yields. Table 2 shows probable increases in irrigation WUE, corresponding to a 25 percent relative evapo-transpiration deficit for the main field crops. Estimates of relative crop yields were made where yield decreases were less than relative evapo-transpiration deficits. For example, an expected yield was 82 percent for maize for the 25 percent relative ET deficit, when it prevailed for the whole growing season (Table 2). The field crop WUE was 1.09 times higher than when no ET deficit occurred. This suggests that increasing the areas irrigated with the water saved would compensate for any yield loss. If the planned ET deficit is imposed throughout the season, it is possible to calculate the total irrigation water saved if one knows total crop water requirement. However, if the stress is imposed during a specific growth stage, one needs to know the total water requirement (i.e. crop water consumption) during that stage to quantify the water saved. As crop yield response factor (k_y) increases, field WUE decreases, which in turn implies that benefit from deficit irrigation is unlikely. Figure 2 shows interrelations between field WUE, crop yield response factor, and planned ET deficit. Only those crops and growth stages with a lower crop yield response factor (k_y<1.0) can generate significant savings in irrigation water through deficit irrigation.

Conclusions

The proper application of deficit irrigation practices can generate significant savings in irrigation water allocation. Among field crops, groundnut, soybean, common bean and sugar cane show proportionately less yield reduction than the relative evapotraspiration deficit imposed at certain growth stages.

Crops such as cotton, maize, wheat, sunflower, sugar beet and potato are well suited for deficit irrigation applied either throughout the growing season or at pre-determined growth stages. For example, deficit irrigation imposed during flowering and boll formation stages in cotton, during vegetative growth of soybean, flowering and grain filling stages of wheat, vegetative and yielding stages of sunflower and sugar beet will provide acceptable and feasible irrigation options for minimal yield reductions with limited supplies of irrigation water. This work may provide guidelines for practising deficit irrigation for identifying likely growth stages for imposing reduced ET, and for assessing the economic feasibility and acceptability of deficit irrigation through the estimation of expected relative yield decreases.

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Yield response factors of field crops to deficit irrigation

SUMMARY

Water is essential for crop production, and any shortage has an impact on final yields. Therefore, farmers have a tendency to over-irrigate, an approach that runs counter to the conservation of scarce resources. At present, owing to the global expansion of irrigated areas and the limited availablility of irrigation water, there is a need to optimize WUE in order to maximize crop yields under frequently occurring situations of deficit irrigation. When water deficit occurs during a specific crop development period, the yield response can vary depending on crop sensitivity at that growth stage. Therefore, timing the water deficit appropriately is a tool for scheduling irrigation where a limited supply of water is available. A standard formulation relates four parameters (Y_a, Y_m, ET_a and ET_m) to a fifth: k_y, the yield response factor, which relates relative yield decrease to relative evapotranspiration deficit. Two series of k_y values obtained from FAO data sets and from an International Atomic Energy Agency (IAEA) coordinated research project (CRP) showed a wide range of variation for this parameter $0.20 < k_y < 1.15$ (FAO), and $0.08 < k_y < 1.75$ (IAEA). The two data sets, whilst showing the same trends, gave neither identical average values for k_y nor similar ranges of variation.

Water is a finite resource for which there is increasing competition among agricultural, industrial and domestic sectors. According to Kemp (1996), in Mediterranean countries, “The World Bank argues that the allocation of water to agriculture, which accounts for about 90 percent of regional water use, no longer makes economic sense… In Morocco, for example, it is estimated that the value added by a cubic meter of water in irrigated agriculture is a mere 15 cents; used in industry it is a striking $25. In Jordan, which uses highly efficient drip irrigation for over half of its irrigated agriculture, the equivalent figures are 30 cents for agriculture and $15 for industry.” Therefore, there is an urgent need to maximize crop yields under conditions of limited water supply. Kang *et al*. (2000) have shown that regulated deficit irrigation at certain periods during maize growth saved water while maintaining yield.

The upper limit for yield is set by soil fertility, climatic conditions and management practices. Where all of these are optimal throughout the growing season, yield reaches the maximum value as does evapotranspiration. Any significant decrease in soil water storage has an impact on water availability for a crop and, subsequently, on actual yield and actual evapotranspiration. A standard formulation (Vaux and Pruitt, 1983) relates these four parameters to a fifth: the yield

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response factor, which links relative yield decrease to relative evapotranspiration deficit, as follows:

$$1 - \frac{Y_a}{Y_m} = k_y \times (1 - \frac{ET_a}{ET_m}) \quad (1)$$

where: Y_a = actual yield (kg/ha)
Y_m = maximum yield (kg/ha)
ET_a = actual evotranspiration (mm)
Et_m = maximum evapotranspiration (mm)
k_y = yield response factor

Calculations of Y_m, ET_m and ET_a are well documented (FAO, 1977; and FAO, 1998) and the literature has provided values for k_y (FAO, 1979). From these four parameters, it is possible to calculate Y_a where the available water supply does not meet the full moisture requirements of the crop. Where water deficit occurs during a specific growth stage, the yield response will depend on crop sensitivity during that period. Therefore, the timing of the deficit is a tool for scheduling the use of a limited water supply and in setting priorities among several irrigated crops. As an example, the World Meteorological Organization recommended the utilization of Computer-Aided Learning (CAL) software in meteorology (Bell, 1994), especially the French educational computer program BILHY (Bilan Hydrique). BILHY is useful for training extension workers and meteorologists in the subject of soil moisture; the user has to decide, according to pedological, agricultural and meteorological parameters, whether or not to irrigate.

FAO has facilitated the calculation of crop water requirements and irrigation planning through a series of technical papers (FAO, 1992; and FAO, 1993). Nevertheless, the process is still difficult and requires several data sets. Another approach is based on field experiments on crops exposed to deficit irrigation, with soil moisture status monitored using the soil moisture neutron probe (SMNP) and sets of tensiometers (Vachaud *et al*., 1978). The SMNP is useful for assessing the soil hydraulic conductivity versus the soil water content throughout the internal drainage process, as described by Hillel *et al*. (1972) and Libardi *et al*. (1980). The monitoring of soil water content profiles (with the SMNP) and gradients of hydraulic heads below the rootzone (with tensiometers) allows the periodical calculation of water balance and water flows, and hence access to ET_a and subsequently to the yield response factors k_y.

Mannocchi and Mecarelli (1994) showed that, using Equation (1), it was possible to model relationships between crop yield and water applied. These relationships acted as a constraint in a mathematical programming framework, with the aim of optimizing (in economic terms) the application of available irrigation water, taking into account the possibility of varying the cropping pattern. An optimal solution was possible only on an annual basis; there was an attempt to define a method for determining a single, constant and optimal solution.

The objective of this study was to compare two series of yield response factors k_y obtained separately by FAO, through the literature or calculations, and by an IAEA coordinated research project (CRP) under monitored field conditions.

Materials and methods

Implementation of the CRP "Nuclear techniques to assess irrigation schedules for field crops" involved a network of eleven developing countries from 1990 to 1995; results were published in a technical document (IAEA, 1996), with a later synthesis of this research in book form (Kirda *et al.*, 1999). The measurements of crop yield responses to deficit irrigation related to two sets of conditions:

- A reduced amount of irrigation water and a deficit imposed throughout the season. The code for this treatment was $Tr._{0000}$. An SMNP took weekly measurements of the soil water content profile; the irrigation scheduleing was such as to maintain the soil water storage at 50 – 70 percent of its capacity.
- Water stress was imposed during specific growth stages of the crop under consideration. In general, four physiological growth stages for each crop are sufficient to describe their sensitivity to water stress: (a) initial (planting to 10 percent ground cover); (b) crop development (10 percent ground cover to effective full cover and initiation of flowering); (c) mid-season (effective soil cover to onset of maturity); (d) late season (onset of maturity to harvest). The deficit irrigation was applied only during one specific growth stage to be assessed for water sensitivity. The codes for these treatments were $Tr._{0111}$, $Tr._{1011}$, $Tr._{1101}$ and $Tr._{1110}$ (i.e. $_0$ and $_1$ correspond to the stages during which irrigation water was or was not restricted, respectively). During the period of restricted irrigation, the threshold of 50 – 70 percent, was enforced.

Periodical SMNP profiles and tensiometer readings were used both for monitoring soil water storage and for calculating ET_a throughout the successive crop growth periods.

Results

Table 1 collates values of k_y from FAO publications for 11 crops or crop yields. Table 2 collates values of k_y obtained by research-contract holders for the IAEA CRP for ten crops in nine countries. Some crops were grown in more than one country; e.g. cotton was cultivated in three countries, and some values were not calculated/obtained for certain crop growth periods.

FAO vs. CRP comparisons were possible for 21 pairs of k_y values (Table 3). Some crops (cotton, wheat and bean) may be over-represented as they were grown in more than in one country. The t-Test gave a significant difference between the k_y pairs at the 1-percent level of probability (and at the 2-percent level with the two-tail distribution).

The average k_y value was higher (+38 percent) for the CRP series than for the FAO series. Therefore, in-field experiments indicated a higher impact of deficit irrigation practices on crop yield than previously expected.

Figure 1 shows the same data; the correlation was weak (Pearson correlation =

Table 1
FAO yield response factors

Crop	$Tr._{0000}$*	$Tr._{0111}$	$Tr._{1011}$	$Tr._{1101}$	$Tr._{1110}$
Cotton	0.85	0.20	0.50		0.25
Bean	1.15	0.20	1.10	0.75	0.20
Groundnut	0.70	0.20	0.80	0.60	0.20
Maize	1.25				
Potato	1.10	0.60		0.70	0.20
Soybean	0.85	0.20	0.80	1.00	
Sugar cane	1.20	0.75	0.50	0.50	0.10
Sugar beet	0.80				
Sugar beet	0.90				
Sunflower	0.95	0.40	1.00	0.80	
Winter wheat	1.00	0.20	0.60	0.50	

*Corresponds to continuous deficit irrigation, whereas $Tr._{0111}$ to $Tr._{1110}$ correspond to restricted water supplies imposed at specific growth stages.

Figure 1
Comparative assessment of response factors, FAO vs. CRP

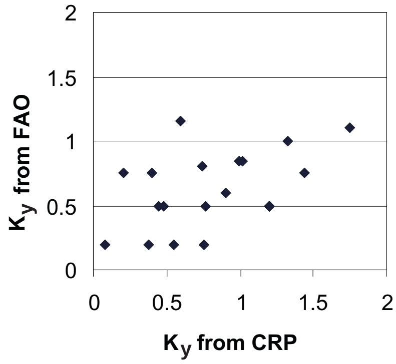

TABLE 2
CPR yield response factors

Crop, country	$Tr._{0000}$*	$Tr._{0111}$	$Tr._{1011}$	$Tr._{1101}$	$Tr._{1110}$
Bean, Brazil	0.59	0.38	1.75	1.44	0.08
Bean, Ecuador	1.43	0.56	1.35	0.87	0.17
Cotton, Argentina	1.02	0.75	0.48		
Cotton, Pakistan	0.71	0.80	0.60	0.05	
Cotton, Turkey	0.99		0.76		
Groundnut, Malaysia			0.74		
Maize, Romania	1.33				
Potato, Pakistan		0.40	0.33	0.46	
Soybean, Turkey		0.58	1.13	1.76	
Sugar cane, Senegal		0.20	1.20	1.20	
Sugar cane, Senegal		0.40	1.20	1.20	
Sugar beet, Morocco	0.95				
Sugar beet, Morocco	1.07				
Sunflower, Turkey	0.91	1.19	0.94	1.14	
Wheat, Chile	1.32	0.55	0.90	0.44	0.25
Wheat, Pakistan	0.87	2.54	0.81	0.48	0.62

*Corresponds to continuous deficit irrigation, whereas $Tr._{0111}$ to $Tr._{1110}$ correspond to restricted water supplies imposed at specific growth stages.

0.43) and the range of variation of k_y was wider for the CRP data than for the FAO data (slope = 0.65). Therefore, although there was a significant relationship between the two sets of data, the in-field values obtained by the CRP research group were greater than published FAO data, particularly for small reductions in yield through deficit irrigation (intercept = 0.44). At the highest levels of yield reduction, in-field CRP data were also higher than FAO data. It would be worthwhile completing these data sets by further calculations and with well managed field experiments on different soils and in different geographical areas.

TABLE 3
Twenty-one pairs of response factors values obtained from the CRP and FAO publications

C CRP	FAO			
Var. 1	*Var. 2*			
0.59	1.15			
0.38	0.2			
1.75	1.1		*Variable 1*	*Variable 2*
1.44	0.75	Mean	0.837	0.614
0.08	0.20	Variance	0.192	0.082
0.99	0.85	Observations	21	21
0.76	0.50	Pearson correlation	0.428	
1.02	0.85	Hypothesized mean difference	0	
0.75	0.20	df	20	
0.48	0.50	t stat	2.505	
1.32	1.00	P(T<=t) one-tail	0.010	
0.55	0.20	t critical one-tail	1.724	
0.90	0.60	P(T<=t) two-tail	0.020	
0.44	0.50	t critical two-tail	2.085	
0.20	0.75			
1.20	0.50			
1.20	0.50			
0.40	0.75			
1.20	0.50			
1.20	0.50			
0.74	0.80			

CONCLUSIONS

Crop production depends mainly on soil water status throughout the growing season. A high level of soil water availability usually ensures an optimal yield with maximum ET_a with potential losses of water and N fertilizer through leaching. Any restriction in the supply of irrigation water is likely to induce a decrease in crop yield. However, the impact of deficit irrigation on crop yield can be insignificant where the water stress is applied to the crop during specific growth stages that are less sensitive to moisture deficiency. The two series of yield response factors, k_y, showed wide ranges of variation of this parameter: $0.20 < k_y < 1.15$ (FAO), and $0.08 < k_y < 1.75$ (CRP). The two data sets, whilst showing the same trends, gave neither identical average values for k_y nor similar ranges of variation.

Therefore, it will be necessary to extend these data sets to other crops and cultivars, and to other soils and weather conditions, to achieve mathematical optimization of deficit irrigation systems.

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Use of the FAO CROPWAT model in deficit irrigation studies

Summary

Dwindling water resources and increasing food requirements require greater efficiency in water use, both in rainfed and in irrigated agriculture. Regulated deficit irrigation provides a means of reducing water consumption while minimizing adverse effects on yield. Models can play a useful role in developing practical recommendations for optimizing crop production under conditions of scarce water supply. To assess the applicability of the FAO CROPWAT model for deficit irrigation scheduling, a study utilized data provided in studies from a joint FAO/IAEA coordinated research project (CRP) on "The use of nuclear and related techniques in assessment of irrigation schedules of field crops to increase effective use of water in irrigation projects," carried out in Turkey, Morocco and Pakistan on cotton, sugar beet, and potato, respectively. The study revealed that the CROPWAT model can adequately predict the effects of water stress, but requires calibration of the main crop parameters. Procedures were developed to calibrate the various crop parameters based on research findings from the treatments. The study demonstrated that the model could be useful in improving the design of experimental methods in research studies and in identifying inconsistencies in procedures and results. Furthermore, the model permitted a more systematic analysis of results, a more uniform presentation of data, and a greater compatibility of results. Moreover, this paper concludes that models are a powerful tool for extending findings and conclusions to conditions not tested in the field, and that useful predictions on deficit irrigation scheduling are possible under various conditions of water supply, soil, and of crop management.

Scarce water resources and growing competition for water will reduce its availability for irrigation. At the same time, the need to meet the growing demand for food will require increased crop production from less water. Achieving greater efficiency of water use will be a primary challenge for the near future and will include the employment of techniques and practices that deliver a more accurate supply of water to crops. In this context, deficit irrigation can play an important role in increasing water use efficiency (WUE).

The objective of regulated deficit irrigation is to save water by subjecting crops to periods of moisture stress with minimal effects on yields. The water stress results in less evapotranspiration by closure of the stomata, reduced assimilation of carbon, and decreased biomass production. The reduced biomass production has little effect on ultimate yields where the crop is able to compensate in terms of reproductive capacity.

In some cases, periods of reduced growth may trigger physiological processes that actually increase yield and/or income. Such processes include flower-induction in the case of cotton, increased root development exploring deeper soil layers, early ripening of grains, and improved

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quality and flavour of fruits. However, stress applied during reproductive growth can affect fruit or grain set, resulting in decreased yields. The effects of stress on yields are complex and may differ with species, cultivar, and growth stage; they have been the subject of many studies. Extensive field research is required to better understand the physical and biological processes that control crop responses to moisture stress.

For that purpose, the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture coordinated a research project that involved 14 member states in the period 1990 – 1995. The objective of the research was to improve WUE through deficit irrigation scheduling. With a common research protocol, scientists from the 14 cooperating research institutes defined field procedures to assess the effects of fertility and water stress, applied at various growth stages, on growth characteristics, yield and yield-quality. Based on the findings and knowledge of crop sensitivity to water stress, it was possible to develop recommendations for irrigation scheduling to meet moisture requirements during stress-sensitive growth stages and to impose deficits during less stress-sensitive stages.

Models that simulate crop growth and water flow in the rootzone can be a powerful tool for extrapolating findings and conclusions from field studies to conditions not tested, allowing predictions for deficit irrigation scheduling under various conditions of water supply and of soil and crop management. Furthermore, the use of models may be important to standardize research procedures in such coordinated research programmes and thus facilitate more-meaningful comparisons between studies carried out in different locations and countries.

The CROPWAT model developed by the FAO Land and Water Development Division (FAO, 1992) includes a simple water balance model that allows the simulation of crop water stress conditions and estimations of yield reductions based on well established methodologies for determination of crop evapotranspiration (FAO, 1998) and yield responses to water (FAO, 1979).

To assess the applicability of the CROPWAT programme for recommendations on deficit irrigation scheduling, a study utilized data reported in studies from the International Atomic Energy Agency (IAEA).

Methodology

Data from three field studies within an FAO/IAEA coordinated research project (CRP), reported by Kirda *et al*. (1999), were used to evaluate the utility of the CROPWAT model in simulating deficit irrigation scheduling. The field studies applied various irrigation treatments for various crops, inducing water stress at various growth stages, with soil water status determined over the growing season using soil moisture neutron probe (SMNP). The reported information on climate, soil and crops constituted the input data while the study used reported yield and crop consumptive water use to validate the various crop parameters of CROPWAT model.

The CROPWAT model

CROPWAT is a computer program for irrigation planning and management, developed by the Land and Water Development Division of FAO (FAO, 1992). Its basic functions include the calculation of reference evapotranspiration, crop water requirements, and crop and scheme irrigation. Through a daily water balance, the user can simulate various water supply conditions and estimate yield reductions and irrigation and rainfall efficiencies. Typical applications of the water balance include the development of irrigation schedules for various crops and various irrigation methods, the evaluation of irrigation practices, as well as rainfed production and drought effects. Calculations and outputs are based on the CROPWAT version 7.2, available at the FAO Web site (http://www.fao.org/ agl/aglw/cropwat.htm).

Calculation procedure

The calculation of reference evapotranspiration (ET_o) is based on the FAO Penman-Monteith method (FAO, 1998). Input data include monthly and ten-daily for temperature (maximum and minimum), humidity, sunshine, and wind-speed. Crop water requirements (ETcrop) over the growing season are determined from ET_o and estimates of crop evaporation rates, expressed as crop coefficients (K_c), based on well-established procedures (FAO, 1977), according to the following equation:

$$ETcrop = Kc \times ET_o \quad (1)$$

FAO (1998) has presented updated values for crop coefficients. Through estimates of effective rainfall, crop irrigation requirements are calculated assuming optimal water supply. Inputs on the cropping pattern will allow estimates of scheme irrigation requirements.

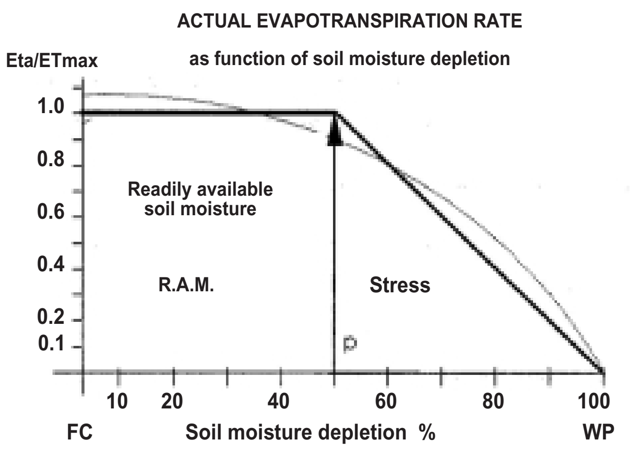
With inputs on soil water retention and infiltration characteristics and estimates of rooting depth, a daily soil water balance is calculated, predicting water content in the rooted soil by means of a water conservation equation, which takes into account the incoming and outgoing flow of water.

Stress conditions in the root zone are defined by the critical soil water content, expressed as the fraction of total available soil water between field capacity and wilting point that is readily available for crop transpiration, and characterizes a soil moisture condition in which crop transpiration is not limited by any flow restrictions in the rootzone.

The critical soil water content varies for different crops and different crop stages and is determined by the rooting density characteristics of the crop, evaporation rate and, to some extent, by the soil type. FAO (1998) has updated the estimates of critical soil moisture, representing onset of stress, previously reported in FAO (1977) and FAO (1979).

Figure 1 presents the rate of reduced crop evapotranspiration, ET_a/ETcrop, as estimated according to soil moisture depletion (FAO, 1992).

FIGURE 1
Crop evaporation rate under soil moisture stress



The effect of water stress on yield is quantified by relating the relative yield decrease to the relative evapotranspiration deficit through an empirically derived yield response factor (K_y) (FAO 1979):

$$1 - \frac{Ya}{Ymax} = K_y \, (1 - \frac{ET_a}{ET_m}) \qquad (2)$$

where:

1–Ya/Ymax = the fractional yield reduction as a result of the decrease in evaporation rate ($1 - ET_a/ET_m$)

An analysis of an extensive set of research information yielded values for (K_y) for 26 crops at various growth stages. This enables the degree of sensitivity to water to be taken into account estimates of yield reductions for various crops and growth stages based on soil moisture status.

CROPWAT input data

Calculations of water and irrigation requirements utilize inputs of climatic, crop and soil data, as well as irrigation and rain data. The climatic input data required are reference evapotranspiration (monthly/decade) and rainfall (monthly/decade/daily). Reference evapotranspiration can be calculated from actual temperature, humidity, sunshine/radiation and wind-speed data, according to the FAO Penman-Monteith method (FAO, 1998). The CLIMWAT-database provides monthly climatic data for CROPWAT on 144 countries (FAO, 1993).

The crop parameters used for the estimation of the crop evapotranspiration, water-balance calculations, and yield reductions due to stress include: Kc, length of the growing season, critical depletion level p, and yield response factor K_y. The program includes standard data for main crops and it is possible to adjust them to meet actual conditions. Table 1 provides an example of the input data of crop parameters.

TABLE 1
Parameters for cotton in Turkey

	Growth stage (planted 18 May)				
	Init	**Devel**	**Mid**	**Late**	**Total**
Crop coefficient (Kc)					
CROPWAT calibration	0.40	–>[a]	1.20	0.80	
CROPWAT standard (FAO, 1998)	0.35	–>	1.20	0.70	
Crop height (m)			1.00		
Rooting depth (m)	0.30	–>	0.90	0.90	
Depletion level (fraction)	0.60	–>	0.60	0.60	
Yield response factor (K_y)					
CROPWAT calibration	0.50	0.50	0.60	0.30	1.50
FAO (1979)	0.20	0.20	0.50	0.25	0.85
Anaç *et al.* (1999)	0.64	0.64	0.66	0.63	1.49

[a]Intermediate value

The soil data include information on total available soil water content and the maximum infiltration rate for runoff estimates. In addition, the initial soil water content at the start of the season is needed.

The impact on yield of various levels of water supply is simulated by setting the dates and the application depths of the water from rain or irrigation. Through the soil moisture content and evapotranspiration rates, the soil water balance is determined on a daily basis. Output tables enable the assessment of the effects on yield reduction, for the various growth stages and efficiencies in water supply.

Case studies

Data availability and adequacy determined the selection of the case studies from Turkey, Morocco, and Pakistan as being appropriate for analysing the suitability of the CROPWAT model in deficit irrigation scheduling.

Cotton – Turkey

Anaç *et al*. (1999) of the Irrigation and Drainage Department at Ege University, Bornova-Izmir, Turkey, carried out a three-year (1992-94) a study on optimum irrigation scheduling for cotton under deficit irrigation. They applied five furrow-irrigation treatments: optimal irrigation with full watering and no stress (111); stress applied at one of three growth stages, vegetative (011), flowering (101), or boll formation (110); and stress applied at all three stages (000).

The irrigation water was applied to furrows through perforated pipes. The number of irrigation applications varied with treatment, but ranged from eight for the full treatment to four for the full-deficit treatment. The total irrigation water applied over the season for each treatment to achieve field capacity was recorded. The individual irrigation application depths were determined on the basis of soil water storage depletion. Under no-stress conditions, irrigation was applied when the available soil moisture in the rootzone was depleted to 60 percent of the total available soil moisture (40 percent depletion). In stress conditions, irrigation was applied whenever soil moisture content was depleted to 20 – 25 percent of the total available soil moisture in the root zone (75 – 80 percent depletion) at the respective growth stages.

Actual crop evapotranspiration for each of the treatments was measured using an SMNP over the soil profile. Irrigation water applications were recorded. The number and total irrigation depths for each season were available. However, there were no detailed data on individual irrigation applications or actual climate data.

The application of CROPWAT utilized climatic and ET_o data from the CLIMWAT data for Borova, which showed good correlation with the measured water use over the growing season. The standard crop values provided by CROPWAT did not correspond adequately with the reported treatments, and an iterative procedure was applied to calibrate the crop parameters to the reported values in the various treatments.

Sugar beet – Morocco

The objective was to improve irrigation management practices using water deficit techniques. Bazza (1999) of the Institut Agronomique et Veterinaire Hassan II carried out the study on sugar beet in the Doukkala region in western Morocco in1992 – 1993. The study compared ten irrigation treatments, putting the crop under stress during one of four growth stages: crop establishment (0111), vegetative development (1011), yield formation (1101), and root growth and ripening (1110). It included three controls: one provided optimal watering (1111), one provided stress at all growth stages (0000) and one mimicked traditional practices. This last control consisted of five surface irrigations of 35, 40, 80, 65 and 60 mm respectively on the following dates: 9 December 1992; and 6 January, 2 April, 25 April and 9 May 1993. In addition, in three treatments two periods of stress were applied: 0011, 1001, 1100.

Irrigation timing and the application depth for each irrigation were reported for all ten treatments. In addition, consumptive water use and yield in root and sugar weight were determined for each treatment. As no detailed climate data were available, the study used average monthly climatic data from the nearby station of Casablanca, available in the CLIMWAT data set used. It also used actual rain data.

Data from the optimal irrigation treatment were used to calibrate Kc, while K_y was calibrated with a step-wise procedure based on the yield reductions in the different treatments.

Potato – Pakistan

Mohsin Iqbal *et al.* (1999) of the Nuclear Institute for Food and Agriculture, Peshawar, Pakistan, carried out a field study on the response of potato to water stress at various growth stages during the period 1990 – 1995.

They applied seven irrigation treatments, imposing stress at four growth stages. The first treatment entailed optimal watering without any stress. In four treatments, stress was applied during establishment (0111), flowering (1011), tuber formation (1101), or during ripening (1110). In one treatment, stress was applied at all four stages, while one control treatment represented the traditional practice, i.e. irrigation applied at intervals of 10 – 15 days depending on the time of the year.

The timing of, and application depth for, all irrigations were recorded. The study utilized climate data from the CLIMWAT database for Peshawar, as no other such data were available.

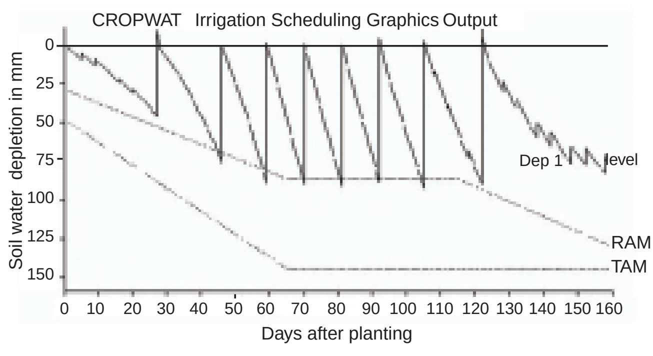
Analysis

The analyses examined the climate, crop and soil data, and the conditions as given for each case study. The standard crop data given in the CROPWAT model were calibrated using a step-wise procedure. The first step was to adjust the Kc values and the critical depletion factor so that they met conditions and data for the optimal irrigation treatment, with which no stress was applied. The next steps were to analyse the treatments and adjust the K_y to achieve the measured yield responses to water stress imposed during the various crop growth stages.

Optimal irrigation, i.e. no stress, was applied by allowing depletion to 60 percent of total available soil moisture. Figure 2 represents the soil water balance for optimal irrigation of cotton in Turkey (eight irrigation applications).

The cotton crop was subjected to deficit irrigation by imposing water stress in one or more growth stages. This was achieved by adapting the full irrigation treatment to achieve water stress in the specific stages of growth. Figure 3 shows an example where water stress was imposed on the cotton crop during flowering.

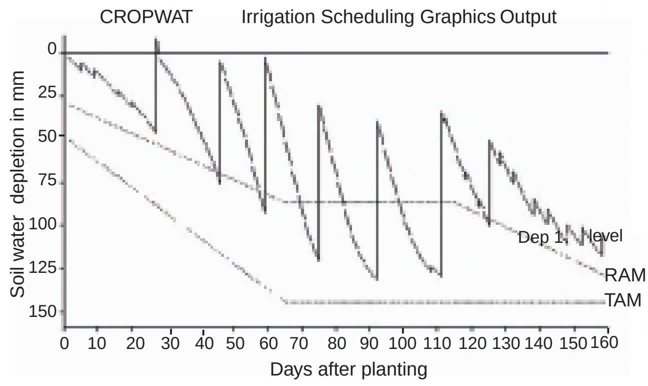
FIGURE 2
Soil water balance for optimal irrigation treatment of cotton



(Note: Upward lines are rainfall or irrigation; TAM= total available moisture; RAM= readily available moisture)

In the various treatments, irrigation was withheld until the water content was depleted to 20 percent of total available soil moisture. Stress applied in the flowering stage resulted in irrigation on days 75, 92, and 111 after sowing (Figure 3).

FIGURE 3
Soil water balance with stress during flowering stage of cotton in Turkey



RESULTS

Cotton – Turkey

Table 1 presents calibrations of the crop parameters. Values for Kc were comparable with standard values for cotton in CROPWAT, with crop factors representing the generally more arid conditions. Yield response factors were also comparable, but the cotton proved to be more sensitive to stress than previously reported (FAO, 1979).

Table 2 presents comparisons of the measured yield reduction with the treatments with the yield reductions calculated with the CROPWAT model. The yield reductions are expressed as a percentage of the yield obtained under optimal irrigation (111).

TABLE 2
Comparison of measured and CROPWAT simulated yield reductions for cotton

Irrigation treatment	Measured		CROPWAT	
	Yield (t/ha)	Yield Red'n (%)	Yield reduction (%)	
			Cumulative	Seasonal
Normal watering (111)	3.31	0	0	0
Stress during veg. growth (011)	3.05	8	13	12
Stress at flowering (101)	3.01	9	14	16
Stress at boll formation (110)	3.13	5	6	6
Stress at all three stages (000)	2.29	31	28	31

The seasonal and cumulative yield reductions calculated by CROPWAT were comparable with measured yield reductions (Table 2). Furthermore, the simulated results reflected the impact that stress in the different growth stages has on yield reduction, i.e. stress at flowering leads to a larger yield reduction than stress at boll formation.

Sugar beet – Morocco

Table 3 presents the results of the calibration of the CROPWAT crop parameters for sugar beet adjusted to the optimum irrigation schedule reported in the study. Kc values were below expected standards for cotton as previously reported (FAO, 1998). This may be due to a difference in climatic conditions between the CLIM-WAT values for Casablanca and the climate conditions in the study area. Inadequate records on soil moisture conditions and derived crop water consumption are also possible causes. Rooting depth and depletion level indicated a strong sensitivity to stress. Yield response factors were comparable with previously reported values (FAO, 1979). However, these were for the growing season as a whole.

[a]Intermediate value

TABLE 3
Crop parameters for sugar beet in Morocco

	Growth stage				
	Initial	Devel.	Mid	Late	Total
Crop coefficient (Kc)					
CROPWAT calibration	0.40	–>[a]	1.20	0.80	
CROPWAT standard (FAO, 1998)	0.35	–>	1.20	0.70	
Crop height (m)			1.00		
Rooting depth (m)	0.30	–>	0.90	0.90	
Depletion level (fraction)	0.60	–>	0.60	0.60	
Yield response factor (K_y)					
CROPWAT calibration	0.50	0.50	0.60	0.30	1.50
FAO (1979)	0.20	0.20	0.50	0.25	0.85
Anaç *et al.* (1999)	0.64	0.64	0.66	0.63	1.49

Figure 4 shows the water balance over the growing season for the optimal treatment. It demonstrates the effects of winter rain during the development stage, and of the fortnightly irrigations at the establishment stage in autumn and the maturing stage in spring.

Table 4 measured yield reductions resulting from the treatments and the yield reductions calculated with the CROPWAT model, expressed as a percentage of the beet yield obtained with full irrigation.

FIGURE 4
Soil water balance for optimal irrigation of sugar beet in Morocco

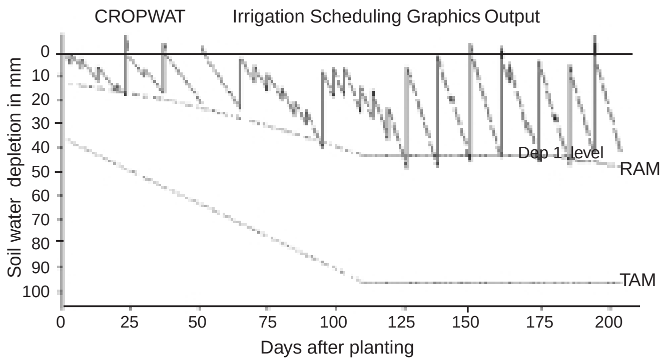


TABLE 4
Comparison of measured and CROPWAT simulated yield reductions for sugar beet in Morocco

Irrigation treatment	Measured		CROPWAT	
	Yield (t/ha)	Yield red'n (%)	Yield reduction (%)	
			Cumulative	Seasonal
Normal watering in all four stages	81.4	0	0	0
Stress in all four stages	30.0	63	61	62
Traditional practice	64.1	21	32	23
Stress in Stage 1 (initial)	79.4	2	5	4
Stress in Stage 2 (veg. developm't)	75.1	8	9	10
Stress in Stage 3 (yield formation)	61.9	24	31	31
Stress in Stage 4 (ripening)	71.8	12	16	7
Stress in Stages 1 and 2	69.4	15	16	16
Stress in Stages 2 and 3	45.4	44	40	44
Stress in Stages 3 and 4	37.7	54	52	43

For almost all the treatments, the yield reductions calculated by CROPWAT were close to the measured reductions. For most of the ten treatments, the simulated results were slightly higher than the measured yield reductions. The simulation results correctly reflected the trends in sensitivity of sugar beet to water stress during the various growth stages.

Potato – Pakistan

Table 5 presents the calibrations of CROPWAT crop parameters for potato adjusted for the optimum irrigation schedule. The Kc values were well below the expected standard values for potato reported previously (FAO, 1998). Reported irrigation frequencies would not seem to correspond well with average climate data for Peshawar from CLIM-WAT. However, rooting depth and depletion level corresponded to standard values expected for potato. Yield response factors corresponded well with those reported previously (FAO, 1979).

Table 6 presents the measured yield reductions for each treatment and yield reductions calculated with the CROPWAT model, expressed as a percentage of the yield obtained with full irrigation.

The measured yield reductions and the simulation results revealed particular sensitivity to moisture stress during establishment and at flowering. The comparison of measured yield reductions with simulation results reveals the sensitivity during establishment and flowering. Reported yield reductions appear less consistent, with larger deviations from CROPWAT's

TABLE 5
Crop parameters for potato in Pakistan

	Growth stage				
	Initial	Devel	Mid	Late	Total
Length (days)	20	30	35	25	110
Crop coefficient (Kc)					
CROPWAT calibration	0.35	–>[a]	0.80	0.50	
CROPWAT standard (FAO, 1998)	0.35	–>	1.10	0.75	
Crop height (m)			0.40		
Rooting depth (m)	0.25	–>	0.60	0.50	
Depletion level (fraction)	0.30	–>	0.50	0.50	
Yield response factor (K_y)					
CROPWAT calibration	0.45	0.80	0.80	0.30	1.10
FAO (1979)	0.45	0.80	0.70	0.20	1.10

[a]Intermediate value

TABLE 6
Comparison of measured and CROPWAT simulated yield reductions for potato

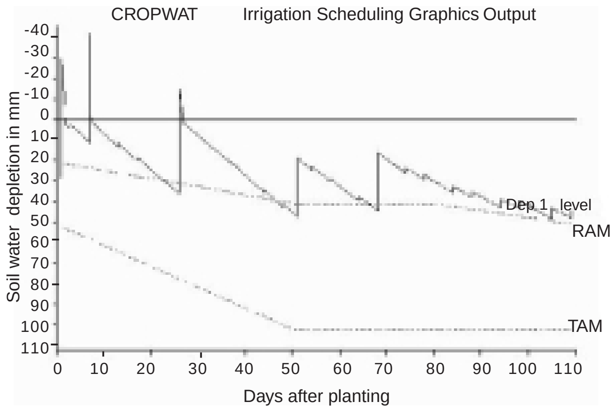
Irrigation treatment	Measured		CROPWAT	
	Yield (t/ha)	Yield red'n (%)	Yield reduction (%)	
			Cumulative	Seasonal
T1 Full irrigation	14.4	0	2	1
T2 Full deficit irrigation	8.71	40	56	22
T3 Farmer practice	13.8	4	2	1
T4 Stress (establishment stage)	10.4	28	21	8
T5 Stress (flowering stage)	12.4	14	17	6
T6 Stress (tuber formation stage)	11.2	22	11	3

calculated values. Moreover, there was a larger disparity between the seasonal and cumulative yield reductions in the CROPWAT calculations; the total season may require an upward adjustment of k_y.

Discussion

The use of the CROPWAT model can provide useful insights into the design of irrigation studies and parameters selected for irrigation treatments. Apparent inconsistencies in these case studies raise questions that require further scrutiny of the original field data. For example in the Pakistan experiment, the irrigation application depths at the beginning of the growing season do not seem justified, as demonstrated by the soil moisture content (Figure 5).

Figure 5
Soil water balance of potato for optimal irrigation treatment



The soil water balance shows that the irrigation applications on days 1 and 6 after planting seem in excess of requirements. In contrast, the final two irrigation applications appear to have been insufficient to properly rewet the soil profile.

Estimated crop water use, based on soil moisture measurements, appears to have been below normally expected evapotranspiration values, in both Morocco and Pakistan, and the derived crop factors in the optimal irrigation treatment were below standard values. This may have been due to differences in estimates for ET_o (taken from the CLIMWAT database rather than from actual recorded climate data), but also may reflect inadequacies in the recorded soil moisture values and derived crop consumptive use data.

A general problem in reported studies on deficit irrigation is lack of essential data, or incomplete records that preclude meaningful comparisons with simulation models such as CROPWAT.

Conclusions

Based on this comparative analysis, the conclusion is that the CROPWAT model can adequately simulate yield reduction as a result of imposed water stress. It accounted well for the relative sensitivity of different growth stages and was able to reproduce the negative impact of water stress on yield.

It is necessary to adjust standard values provided in CROPWAT in order to predict stress and yield reduction satisfactorily. A step-wise procedure, developed to calibrate and adjust the crop parameters, yielded satisfactory results in the modelling process.

The model proved useful in identifying inconsistencies in the design and possible shortcomings or errors in the data records. Therefore, the model may be a powerful tool for helping researchers analyse results and draw conclusions. Use of models will help achieve a more-uniform recording of data and allow meaningful comparisons of findings in different studies and countries.

An important attribute of the CROPWAT model is that it allows extension of the findings and conclusions from studies to conditions not tested in the field. Thus, it can provide practical recommendations to farmers and extension staff on deficit irrigation scheduling under various conditions of water supply, soil, and crop management conditions.

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Deficit subsurface drip irrigation of cotton

Summary

An experiment in arid west Texas, United States of America, grew cotton with subsurface drip irrigation providing four basic levels of water resource and three row widths (1.02 m, 0.76 m, and approximately 0.38 m). The former two row-width treatments contained three planting configurations (a full pattern and two skip patterns). In all, there were seven row-width-pattern configurations, each of which had four water levels, for a total of 28 treatments. Where farmers do not have enough water with which to irrigate their crops, they may choose: (1) to reduce their planted area and apply more water (up to the full water requirement) on this portion of their land; or (2) plant the entire area, whereby they apply a quantity of irrigation water that only partially meets consumptive use requirements. The purpose of this study was to develop mathematical characterizations for yield as a function of water resource for various popular row width/patterns, and then to use these equations in crop budget models to determine economically optimum scenarios for local cotton growers. The full cotton production budgets were based on a 405-ha farm. The assumed water resource varied from scarcely any to enough, with proper management, to supply the majority of crop water needs. In almost all scenarios, it was economically sound to stretch the water resource over the entire farm, rather than to try to maximize yield on portions of the farm. A break-even economic water resource between covering the entire farm irrigating only portions of it was about 2.0 mm/day. Ultra-narrow-row treatments significantly exceeded the treatments with traditional row widths at all four water levels. The highest yield of lint was 1 833 kg/ha. Applying large portions of the moisture requirement as pre-planting irrigation enabled yields of 600 – 900 kg/ha of lint for the full pattern width treatments on the smallest water treatment, which applied 36 mm of in-season irrigation. The skip-row patterns did not yield as much as the full-row patterns.

Materials and methods

Experimental design

The trial lasted three years starting in 1997 in St. Lawrence, Texas, United States of America, which grows 33 000 ha of cotton annually, 30 percent of which irrigated with subsurface drip irrigation (SDI). The region is semi-arid and receives less than 400 mm/year of rainfall. This

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lack of precipitation makes dryland cotton production risky. Farmers usually adapt a skip-row configuration that allows the cotton plants to mine water from the unplanted rows.

The small groundwater resources in the region, although rechargeable, supply 250-500 mm of irrigation water during the 6½-month pumping season; nearly half of this amount is pre-plant irrigation that is stored in the soil. The soil in the experiment was a Reakor silty clay loam, which possesses good moisture storage ability. The experiment included two basic row widths (1.02 m and 0.76 m), each of which had three separate row patterns: (1) no row skips; (2) every other row skipped; and (3) every third row skipped. Local cotton growers term these "Every Row" "1-and-1" and "2-and-1", respectively. These six configurations were accompanied by a seventh, ultra-narrow row (UNR), treatment. The UNR width was 0.25 m in 1997 and 0.38 m during the other two years. All full-planting patterns (i.e., the 1.02-m Every Row, the 0.76-m Every Row, and the UNR) were irrigated using one of four water resource amounts, equivalent to 0.6, 1.2, 2.4, and 4.7 mm/d. The experiment used water resource amounts instead of percentages of evapotranspiration (ET) because employing percent of ET to initiate a treatment leads to a curtailing of early-season pumping as ET levels are low. In reality, farmers with smaller water resources are likely to pump water continuously during this period, building a reservoir. The skip-row patterns also had four water levels, but were proportionately less than the full-row patterns based on the amount of skips in the pattern. All water levels used in the test were well below the peak water use level for cotton in this region (9 mm/d).

The management of the experiment was based on operating the irrigation system in a "common sense" method. For example, as an SDI system enables local farmers to begin pre-irrigation in December, the systems in the experiment were operated in a similar manner, and the soil profiles were filled where possible. Thus, for the full-row patterns, the soil profile was fully recharged prior to planting in all cases, except for the smallest water treatment, with which the profile was generally half full prior to planting. The patterns with skip row would have received smaller amounts of pre-irrigation.

The drip lines were installed at a depth of approximately 0.35 m. A delivery manifold connected lateral lines with a flushing manifold on the distill end. The lines were placed directly beneath the planted rows, except in the case of UNR where the spacing was 0.76 m. The same delivery manifold tied in all three row patterns for the 1.02-m row width. As there was one drip lateral per planted row of cotton, the resultant relative deliveries of water to the various pattern treatments on an aerial basis were 1.00, 0.67, and 0.50 for the Every Row, 2-and-1, and 1-and-1 patterns, respectively. The ranges of water amounts received by the different patterns were: Every Row from 0.6 to 4.8 mm/d, 2-and-1 from 0.4 to 3.2 mm/d, and 1-and-1 from 0.3 to 2.4 mm/d. As local growers with large-capacity wells tended to plant Every Row, and farmers with smaller water resources tended to use row skips, the range of water amounts tested for each pattern tended to be appropriate.

The ultimate goal of the research was to develop mathematical equations of yield as a function of available groundwater resources for the various patterns that could be used in economic analyses. The three row patterns of the 0.76-m group had a similar set-up, but ran for approximately 33 percent less time to compensate for the closer lateral spacings. This made all water application amounts between the two row-width groups similar. The UNR plots were tied into the 0.76-m lateral.

The drip lateral had emitters spaced 0.6-m apart with a nominal discharge of 4 litres/h. The emitters were impregnated with Treflan® to inhibit root intrusion. The plot length was 17.1 m. Treatments were replicated three times. Blocks were irrigated twice per week using an electric timer with appropriate run times to give the desired application depths. Water meters were tied into each delivery manifold to ensure accuracy. A cotton variety genetically modified with Bt traits (Deltapine NuCOTN 33B) was used to limit insect predation and its possible influence on the results. Planting dates were 23, 12 and 19 May for the years 1997, 1998 and 1999, respectively. Urea (32-0-0) was injected into the drip system from around first bloom, at an amount proportional to the water resource, in three chemigation events approximately two weeks apart. The average amounts of nitrogen applied for the three years were 43, 65, 93 and 145 kg/ha for the full-pattern treatments. The skip patterns received proportionately less.

The location for the experiment was on the farm of a local cotton grower, who performed most of the operations. The 1.02-m treatments were planted in beds, with all other treatments planted flat. The UNR treatment was planted with a grain drill (width = 0.25 m) the first year; during the final two years a planter with a row-width setting of 0.38 m was used. Harvest data were gathered by hand-picking two row lengths of 3.0 m, except in the case of the UNR, where an area of 0.8 m^2 was picked.

Third-order polynomial equations of yield as a function of water resource amount were developed for the seven various patterns. Equations were also developed for a separate pattern, 4-and-1, by averaging the yield results of Every Row and 2-and-1 for equivalent amounts of water. The equations were in the form of:

$$Y = a + bW + cW^{1/2} + dW^2 \quad (1)$$

where: Y = yield (kg/ha)
W = water resource available (mm/d)
a, b, c, and d are constants

Economic analyses

Economic analyses determined the net total returns for each pattern/spacing under a wide range of water resources. These analyses also investigated the benefits of installing SDI over the entire farm (405 ha) versus installing it only on various fractions, which would increase allocations of water (and thus SDI yield) to those portions, but would dictate that the omitted area produced dryland yield levels.

Yields for the different row patterns/spacings were determined under conditions of varying water resource amounts using Equation (1). All yields were reduced 5 percent to account for possible differences between machine-stripping and the hand-picking. A fixed cost of about US$100/ha was assumed for the machinery of the farm, irrespective of the percentage of land in SDI. The quantity of water and the amount of SDI installed were used to directly calculate yields, as well as several variable costs (fertilizer, pumping and ginning) and fixed costs (land and SDI annual costs). Thus, 100 percent of all returns and about 75 percent of all costs in the cotton budget were self-generated. Costs of pesticides, fuel, etc. that made up the other portion of the cotton budget were based on the authors' estimates. Dryland net returns were assumed at about US$80/ha based on extension service information that did not include the fixed costs captured under the SDI portion of the overall farm budgets.

RESULTS

Table 1 shows irrigation amounts applied both pre-plant and in-season for the Every Row treatments (2-and-1 and 1-and-1 received 67 and 50 percent of the irrigation amounts, respectively). The pre-season applications contributed 45-81 percent to total irrigation amounts. On average, the lowest full pattern treatment received a total of only 325 mm (irrigation plus rainfall), whereas the highest treatment received 650 mm. Unruh *et al.* (1999) showed that yields were higher in years with more in-season rainfall.

TABLE 1
Average amount of irrigation and in-season rainfall for the Every Row treatments, 1997-99

	Irrigation supplied at treatment capacity of:			
	0.6 mm/d	1.2 mm/d	2.5 mm/d	4.8 mm/d
	(mm)			
Pre-season irrigation	154	223	223	229
In-season irrigation	36	75	149	286
Total irrigation	190	298	375	516
In-season rainfall	135	135	135	135
Total water	325	432	510	650
	(%)			
Fraction of irrigation applied pre-season	81	75	60	45

Yield results

Yields were similar from year to year. UNR provided the highest lint yields for all water levels, followed by the 0.76-m treatment (Table 2). Due to hydraulics of the system, the 0.76-m patterns, which included the UNR treatment, received approximately 4 percent more water than the 1.02-m treatments. The yield response curves show that the UNR treatment responded most strongly, followed by the 0.76-m treatments (Figures 1 and 2). The 1.02-m treatments (the row spacing generally used by local farmers) had the lowest yields. Normal yields for the area are 560 and 224 kg/ha for furrow-irrigated and dryland conditions, respectively.

Table 2
Average yields, 1997-99

Treatment	Yield with treatment capacity of			
	0.6 mm/d	1.2 mm/d	2.5 mm/d	4.8 mm/d
	(kg/ha)			
Every (1.02 m)	596	837	1 083	1 308
4-and-1 (1.02 m)	549	751	966	1 149
2-and-1 (1.02 m)	500	671	843	998
1-and-1 (1.02 m)	427	556	695	785
Every (0.76 m)	658	993	1 302	1 570
4-and-1 (0.76 m)	633	890	1 149	1 348
2-and-1 (0.76 m)	605	798	984	1 139
1-and-1 (0.76 m)	429	582	723	842
Ultra-narrow row	880	1 224	1 553	1 833

Table 3 shows the values for the constants in Equation (1).

TABLE 3
Values for constants in Equation (1)

Treatment	Constant			
	a	*b*	*c*	*d*
Every (1.02 m)	-263	-378	1 401	14.0
4-and-1 (1.02 m)	-154	-336	1 230	11.9
2-and-1 (1.02 m)	-60.9	-311	1 086	10.8
1-and-1 (1.02 m)	-76.4	-462	1 168	28.4
Every (0.76 m)	-597	-619	2 067	26.7
4-and-1 (0.76 m)	-253	-426	1 530	15.3
2-and-1 (0.76 m)	-69.6	-434	1 322	22.8
1-and-1 (0.76 m)	-77.5	-405	1 132	23.6
Ultra-narrow row	-376	-587	2 044	24.2

Economic analyses

Figures 3 and 4 show the net profits for a 405-ha farm with limited water resources (0.3 mm/day) (UNR data included for comparison). The UNR had the highest net returns (about US$15 000). This optimum return for UNR occurred when the irrigation

FIGURE 1
Average yield data for the 1.02-m patterns and UNR, 1997-99

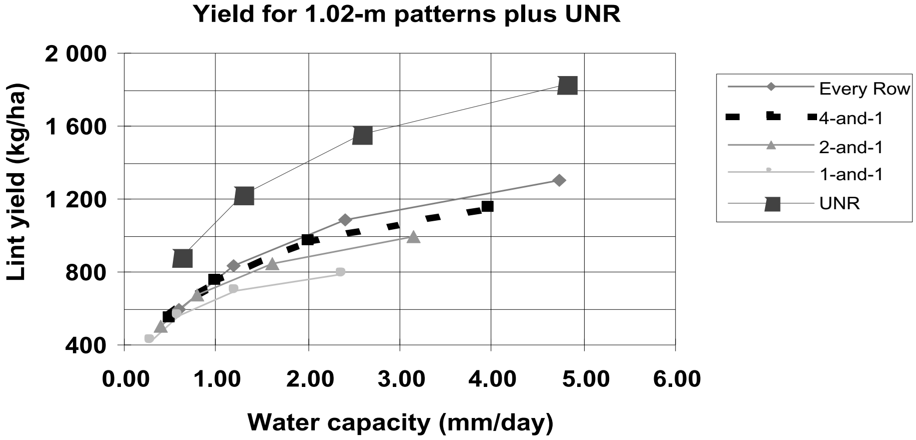
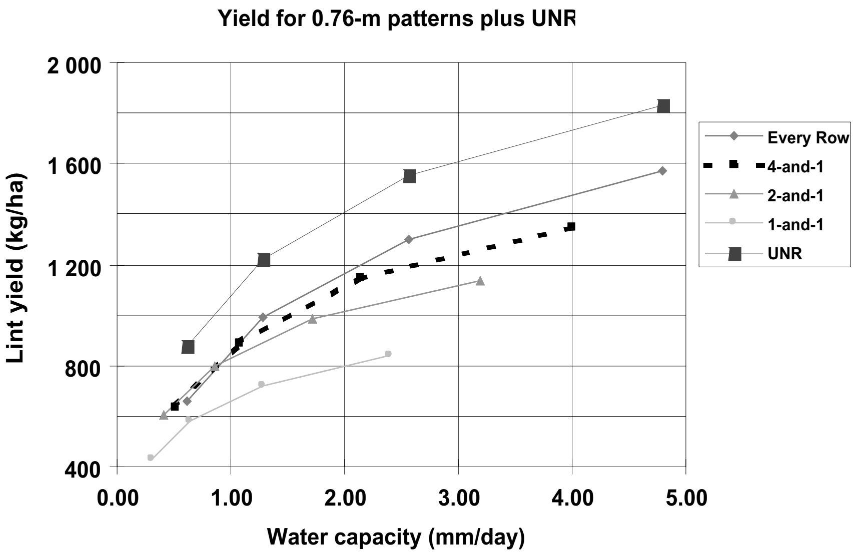


FIGURE 2
Average yield data for the 0.76-m patterns and UNR, 1997-99



system was configured for 1.0 mm/day. For a 405-ha farm with an available water resource of 0.3 mm/day, this would mean 121 ha of SDI [(0.3/1.0) x 405] and 284 ha of dryland. All the other treatments in Figures 3 and 4 showed net losses at all points.

When the water resource was less than 1.0 mm/d, it was slightly more economic to use the 4-and-1 and the 2-and-1 rather than the Every Row pattern on the 0.76-m patterns, (data not shown). In all other instances, Every Row was more economic than the skip patterns.

Once a farm's water resource reached 2.0 mm/d or greater, the analysis showed that it was best to install SDI over the entire 405 ha. Figures 5 and 6 show net returns for a farm with a water resource of 1.5 mm/d. At this point, optimum economic levels were reached when about 90 percent of the farm was in SDI. Returns for the UNR, 0.76-m Every Row, and the 1.02-m Every Row were approximately US$175 000, 100 000 and 50 000, respectively, for the

FIGURE 3
Net profit for farm with a 0.3-mm/d water resource using various row patterns with 1.02-m row width

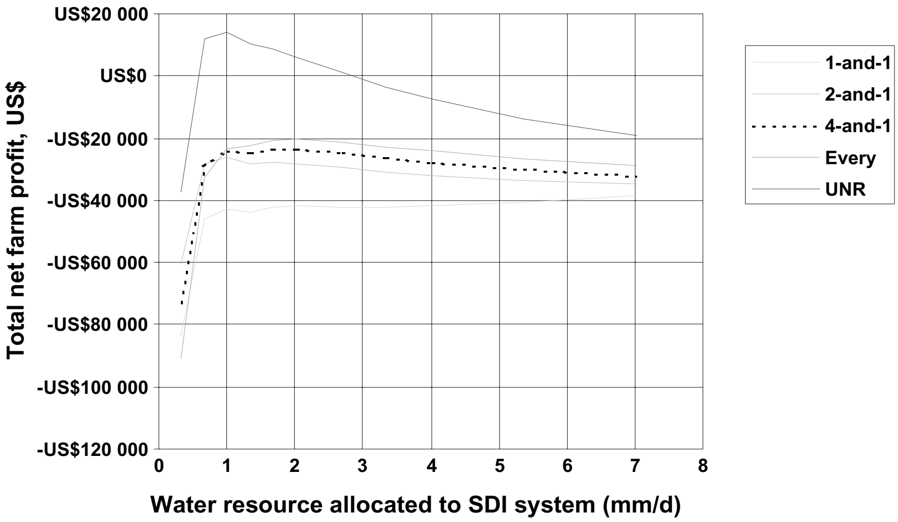
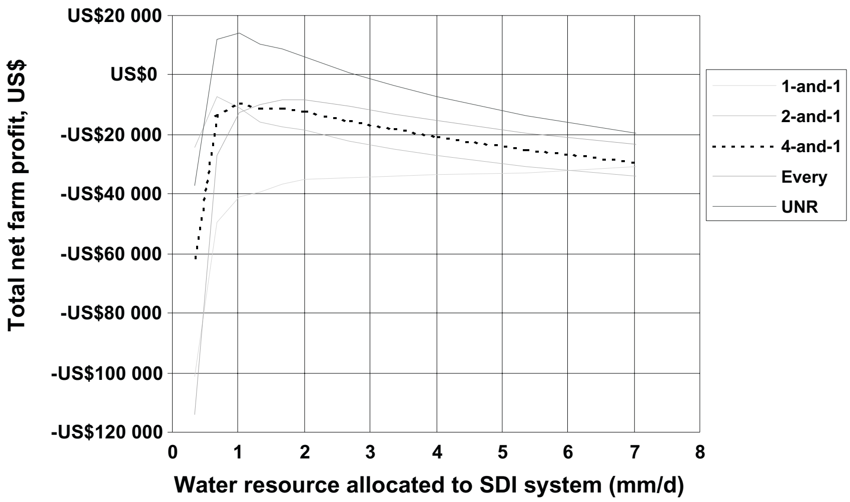


FIGURE 4
Net profit for farm with a 0.3-mm/d water resource using various row patterns with 0.76-m row width



1.5-mm/d water resource level. When the farm had a water resource of 3.0 mm/day, the net profits were about US$286 000, 191 000, and 86 000 for the UNR, 0.76 Every Row, and the 1.02-m Every Row treatments, respectively.

Figure 7 shows net farm returns as a function of both farm water resources and fraction of farm in SDI, with data for UNR, 0.76-m Every Row, and the 1.02-m Every Row. The X axis shows the farm's water resource.The Y axis represents the portion of SDI installed on the farm (hectares of SDI/405). As an example, if this farm uses UNR and it has a water capacity of 2.0 mm/d and 300 ha of SDI are installed, then the SDI ratio is 0.74 and net profits should be a little

FIGURE 5
Net profit for farm with a 1.5-mm/d water resource using various row patterns with 1.02-m row width

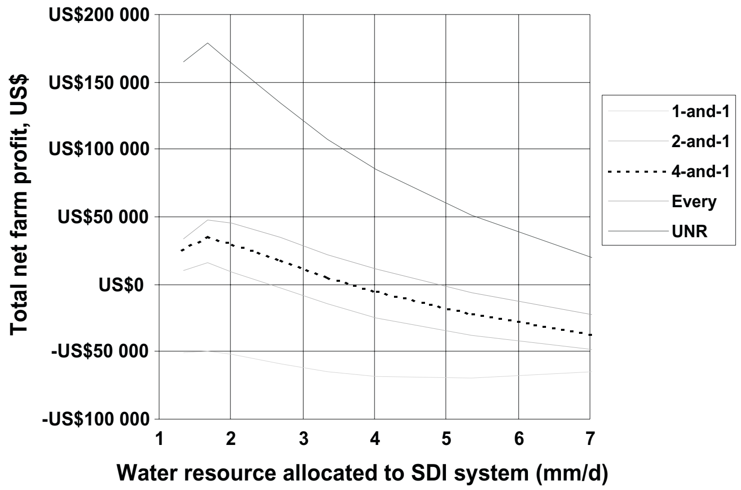
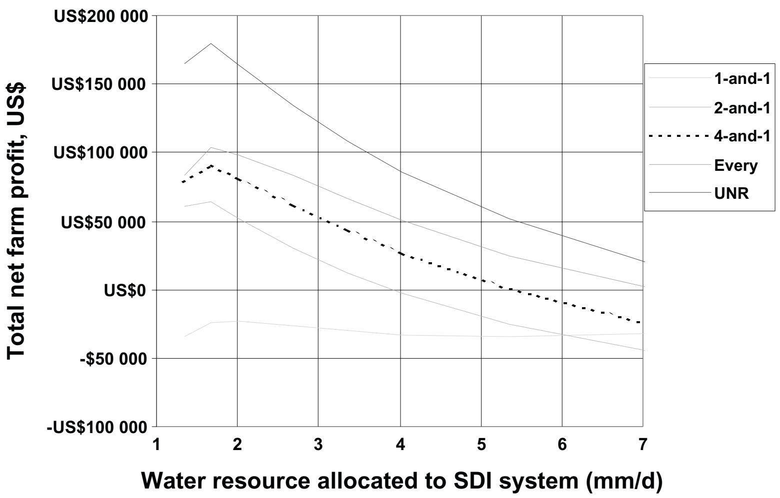


FIGURE 6
Net profit for farm with a 1.5-mm/d water resource using various row patterns with 0.76-m row width

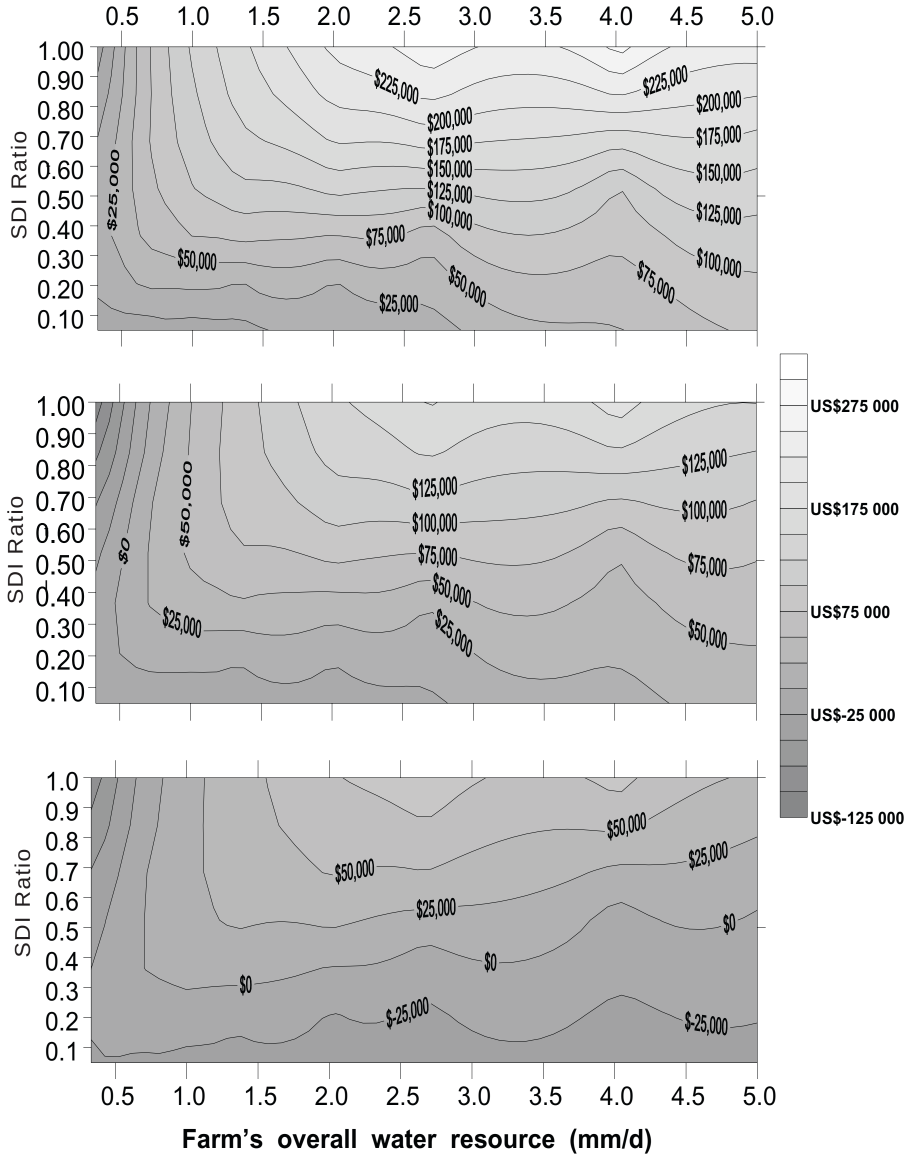


over US$175 000. With all acreage converted to SDI (ratio = 1.0), net profits would be over US$225 000.

CONCLUSIONS

The experiment provided estimates of yields and incomes for a certain region of Texas. Therefore, the data do not necessarily apply to other soil types and weather patterns.UNR had the highest yields and largest farm net returns. However, UNR production practices, specifically in planting and harvesting, are difficult to manage successfully, and local growers not adopted them widely.

Figure 7
Net farm returns for the entire 405-ha farm for UNR (top), 0.76-m Every Row (middle) and 1.02-m Every Row (bottom)



The 0.76-m treatments had significantly higher yields and net farm returns than did their 1.02-m counterparts. With a water resource greater than 1.0 mm/d, Every Row was more economic than skip patterns. When the water resource was less than 1.0 mm/d, then 4-and-1 and the 2-and-1 were more economic.

The high proportion of pre-plant irrigation that was beneficially used was important in making the SDI enterprises viable, especially with less water available. Questions remain regarding the skip-row patterns and pre-plant irrigation. As blank rows existed, these treatments, depending on lateral water movement, may store more useable pre-plant irrigation water than do the Every Row patterns. However, as tested, all treatments received the same amount of pre-plant irrigation.

One of the most significant findings was that, in almost all cases, the economic analyses showed that it was better to stretch the water resource over the entire farm, rather than to concentrate it to maximize yields on parts of the farm. The exception to this was where the farm had very little available water (less than 2.0 mm/d), when it was better to decrease installed SDI acreage to ensure that 1.0-1.5 mm/d was available to any SDI that was installed.

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Response of groundnut to deficit irrigation during vegetative growth

SUMMARY

Studies were conducted to investigate patterns of field water use efficiency (WUE) by groundnut under moisture stress. Experiment 1 examined four cultivars of Spanish groundnut (*Arachis hypogaea* L. ssp. *fastigiata* var. *vulgaris*), Ak 12-24, J 11, GAUG 1 and GG 2, during the summer seasons of 1989 and 1990. The crops were subjected to soil moisture deficit stress by withholding irrigation for 30 d, starting at 20 d after sowing (treatment T 101), and for 25 d starting at 20 d (T 102). In treatment T 101, the stress period was followed by two relief irrigations with an interval of 5 d. In Experiment 2, stress was imposed on cv. GG 2 from 10 to 30 d after sowing, based on an irrigation water/cumulative pan evaporation (IW/CPE) ratio of 0.6. In one case, this period of stress was followed with irrigation to maintain IW/CPE at 1.0 until harvest (T 200, control); in the second case, the initial stress period was followed by maintenance of IW/CPE at 0.8 until harvest (treatment T 201); in the third case, IW/CPE of 0.6 was continued until harvest (treatment T 202). The results of Experiment 1 showed that leaf area indices of plants stressed during the vegetative phase were higher during the reproductive phase, i.e. from 80 d after sowing until harvest, than those of control (T 100) plants. In general, percent dry matter distribution to leaves remained higher in control plants; percent dry matter distribution to the leaves of stressed plants was lower both during and after stress. Dry matter distributions to pods, and thus the harvest indices, were higher in the stressed plants. Among the treatments, total biomass and economic yields were higher in T 102, followed by T 101. The results of Experiment 2 were consistent with those of Experiment 1. Where groundnut is cultivated with irrigation, it is possible to increase field WUE and dry matter production, including economic yield, by imposing a transient deficit in soil moisture during the vegetative phase.

Groundnut is an important source of oil (51 percent), protein (28 percent) and minerals (2.5 percent). India and China account for about 50 percent of global production, and developing countries in the semi-arid tropics contribute 60 percent. The average in-shell yield is 900 kg/ha (FAO, 1999). Groundnut is an important component of intercropping systems in the dry tropics, and the haulm provides fodder for cattle. High and stable groundnut productivity is an essential element in the improvement of efficiency of farming systems in the semi-arid tropics.

In India, farmers grow groundnuts on ustic alfisols, oxisols, and usterts (the dry vertic soils). The major groundnut-producing areas are in western and southern India. The crop is primarily rainfed, and moisture is a primary constraint on yield. As a result, the tendency is bring groundnut under irrigation for cultivation during the summer season (January/June). Water use by groundnut

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in different cropping seasons in different parts of the world varies between 250 mm under rainfed conditions (Angus *et al*. 1983) to 831 mm under irrigated conditions (irrigation at intervals of seven to ten days during winter months) (Nageswara Rao *et al*., 1985). The total water use of a groundnut crop may be affected by scheduling irrigations based on requirements at the various growth stages.

The average yields (1 400 kg/ha) of the summer season crop are almost double those obtained in the rainy season. Therefore, the contribution of summer season crops to total production is about 45 percent. The key factor affecting growth and yield is the availability of moisture during the cropping season. There is a need for strategies that maximize the efficiency of use of the limited amounts of water that are available. Therefore, a study attempted to examine the effects on water use efficiency (WUE) of scheduling irrigation to take advantage of the lower water requirements of groundnut during the early growth phase. Two experiments were conducted with two moisture-deficit regimes, the first for two years and the second for one year, to determine the effects of early-stage irrigation.

Materials and methods

The experimental site

The study site was the research farm of the National Research Centre for Groundnut at Junagadh (21°31'N, 70°36'E). The soil was a vertic ustochrept with low organic matter content and available nitrogen (N) and phosphorus (P) (Table 1). Soil temperatures were recorded in all plots daily at 0900, 1300 and 1500 hours, at depths of 15 and 30 cm. Soil moisture contents at two depths, i.e. 0-15 cm and 15-30 cm, were estimated gravimetrically at the end of each stress period.

Table 1
Minerological, physical and chemical properties of the soil of the experimental site at Junagadh

Soil characteristics	Soil depth	
	0–15 cm	15–30 cm
Mineralogical		
Sand (%)	22.4	20.0
Silt (%)	14.0	15.8
Clay (%)	63.6	64.2
Ca + Mg carbonate (%)	33.7	35.2
Physical		
Field capacity (%)	30.3	30.2
Permanent wilting point (%)	14.4	13.9
Bulk density (g/cm)	1.44	1.46
Chemical		
pH	7.80	7.70
EC (dS/m)	0.280	0.270
Available P_2O_5 (kg/ha)	23.9	20.1
Available K_2O (kg/ha)	211	205
Available nitrogen (kg/ha)	235	223
Organic carbon (%)	0.830	0.760

Experiment 1

Experiment 1 studied four short-duration (120-125 days) groundnut (*Arachis hypogaea* L. ssp. *fastigiata* var. *vulgaris*) cultivars, *viz.* Ak 12-24, J 11, GAUG 1 and GG 2, during the summer seasons of 1989 and 1990. Fertilizers were applied as urea (25 kg N/ha) and single superphosphate (40 kg/ha P_2O_5). The experiment had three replications in a randomized block design (RBD) with 5x3-m plots. The spacing was 30 cm between rows, and 10 cm between plants within rows. After sowing, the crop was irrigated twice at an interval of seven days to ensure good emergence. Recommended agronomic practices and plant protection measures, except irrigation, were followed to maintain crop health. The irrigations provided 50 mm of water, with treatments as follows:

- T 100: control crop; irrigations at intervals of 10 d from emergence until harvest.
- T 101: stress imposed during vegetative phase; irrigation withheld for 30 d starting at 20 d after sowing.

- T 102: stress imposed during vegetative phase; irrigation withheld for 25 d starting at 20 d after sowiing, followed by two irrigations at intervals of 5 d.

After the treatment periods, treatment and control plots received the same irrigation.

Data collection

Data on leaf area development, dry mass accumulation and its partitioning among various plant parts other than the roots were recorded every 10 d starting at 20 d after sowing. Dry matter distribution to various plant parts was calculated on a percentage basis. At each sampling date, 0.28 m^2 of each plot was sampled. Leaf area was measured with a LI-COR 3000 area meter, and the plant parts were then dried at 80°C to a constant weight. At the final harvest (125 d after sowing) pod yields were recorded. The harvest index (HI) and shelling outturn were calculated with the following formulae.

$$HI = \frac{Total\ dry\ pod\ mass\ at\ final\ harvest}{Total\ dry\ biomass\ at\ final\ harvest}$$

$$Shelling\ outturn\ (\%) = \frac{Mass\ of\ \text{kernels}}{Mass\ of\ pods} \times 100$$

During the 1990 season, leaf transpiration rate (TR), diffusive resistance (DR), and relative water content (RWC) were measured on the second and the third leaves from the apex of the main axis at the end of each stress period at around 1400 hours. Transpiration and leaf diffusive resistance were measured on abaxial and adaxial sides of the leaves with a steady-state porometer (LI-COR 1600), and leaf RWC values were determined using the formula of Barrs and Weatherly (1962):

$$RWC\ (\%) = \frac{Leaf\ fresh\ wt - Leaf\ dry\ wt}{Leaf\ turgid\ wt - Leaf\ dry\ wt} \times 100$$

Data were analysed statistically in a factorial set-up.

Experiment 2

During the summer of 1999, an experiment was conducted in an RBD with three replications in plots of 10x5 m with cv. GG 2.

The treatments were:

- T 200: control crop; deficit irrigation at an IW/CPE ratio of 0.6 imposed during vegetative phases from 10 d until 30 d after emergence; thereafter irrigations to maintain an IW/CPE ratio of 1.0 until final harvest (total application of 550 mm of water).
- Treatment T 201: deficit irrigation at an IW/CPE ratio of 0.6 imposed from 10 d until 30 d after emergence, after which an IW/CPE of 0.8 maintained until harvest (450 mm).
- Treatment T 202: deficit irrigation at IW/CPE ratio of 0.6 imposed from 10 d after emergence until harvest at 125 d (400 mm).

To ensure uniform emergence, each plot received two irrigations immediately after sowing and 5 d later. The irrigations provided 50 mm of water. Soil moisture at 15-cm intervals was recorded before each irrigation with the help of a neutron probe. Total pod yields and dry matter production were recorded at final harvest.

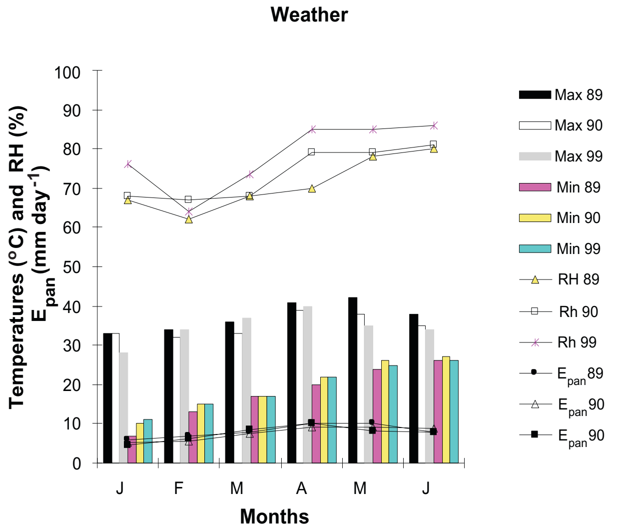
Results and discussion

Experiment 1

Characteristics of the growing season

The monthly mean maximum temperatures ranged between 32°C (February) and 42°C (April), while minimum temperatures ranged between 7°C (January) and 27°C (June). There was no rainfall during the growing period (last week of January to first week of June) in either year. Pan evaporation ranged between 5 and 10 mm/d, the highest being during April and May in both years. This is why summer crops in Junagadh are fully irrigated. During vegetative growth (January and February), evaporative demands (ET_m), and hence crop water requirements, are low. The requirements increase in the later stages of crop growth, especially during pegging and pod development, when evaporative demands also are high (April and May) (Figure 1). The soil needs to be moist for peg penetration and pod development.

Figure 1
Monthly mean temperature, relative humidity, and pan evaporation during two summer cropping seasons, 1989–90, and 1999



Soil temperature and water content

In comparison with control plots, soil temperatures (means of the observations recorded at 0900, 1300 and 1500 hours during 1989 and 1990) at 15 cm were 3.2°C higher in treatment T101 and 1.2°C higher in treatment T 102 (Table 2). Soil water contents at both depths were always less in the irrigation-withheld plots than in the control plots. In control plots the water content generally remained around 18-20 percent at a depth of 0-15 cm, and 19-23 percent at 15-30 cm.

Table 2
Soil water content and temperature under various moisture stress treatments

Depth	Soil water content (%)				Soil temperature (°C)			
	T 101		T 102		T 101		T 102	
	1989	1990	1989	1990	1989	1990	1989	1990
0–15 cm								
Treated	9.5	10.0	14.0	13.1	30.5	31.0	28.5	29.7
Control	19.4	20.0	18.0	18.9	27.0	28.0	27.0	28.5
s.e	0.20	0.32	0.05	0.08	0.39	0.22	0.15	0.25
15–30 cm								
Treated	14.0	15.0	17.1	18.0	25.0	26.1	28.0	29.4
Control	23.0	21.0	21.5	20.1	28.0	29.7	26.6	28.0
s.e.	0.13	0.18	0.45	0.36	0.63	0.15	0.15	0.36

At the peak stress periods, i.e. 30 d without irrigation with T 101 and 25 d without irrigation with T 102, water contents in the surface layer (0-15 cm) were depleted to 9.5 percent in 1989 and to 10 percent in 1990 with T 101, and to 4.0 percent in 1989 and to 6.0 percent in 1990 with T 102 (Table 2). At 15-30 cm, the soil water content was depleted, but less so.

Transpiration and leaf water content

In general, TR and RWC were significantly lower, and leaf DR was higher, in stressed plants than in their respective controls (Table 3). Although the cultivars differed significantly in terms of TR, DR and RWC, the trends of changes in these parameters due to stress were similar. The difference in the values of TR, DR and RWC compared to their respective controls were small. Leaf RWC under stress was also low. During the stress period, leaf temperatures of stressed plants were consistently higher than ambient (data not presented).

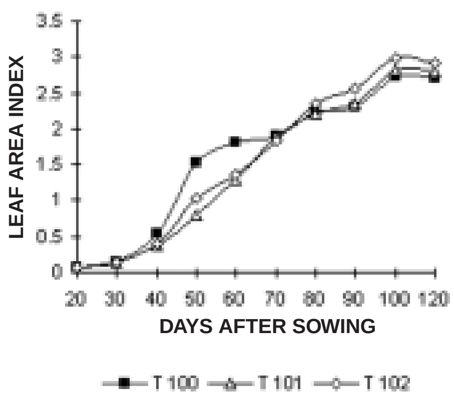
TABLE 3
Leaf diffusive resistance, transpiration and relative water content of groundnut at peak stress, 1990

Treatment	DR (cm^2/s)	TR ($\mu g/cm^2/s$)	RWC (%)
T 100	2.5	12.9	87
T 101 (50 d)	5.1	8.8	71
s.e.	0.48	0.20	0.69
T 100	2.5	13.8	86
T 102 (45 d)	4.1	9.6	73
s.e.	0.53	0.21	0.70

Leaf area index

As groundnut is an indeterminate crop, the leaf area index (LAI) values tended to increase rapidly from 40 d after sowing and continued to increase until 100 d. Genotype effects on LAI were significant. However, Figure 2 only trends in LAI that present stress influences. LAI values of control plants (T 100) were significantly higher during the 50-60-d period. However, the LAIs of plants stressed in the vegetative phase were higher during the reproductive phase, i.e. from 80 d until harvest, than the control plants. During the reproductive phase, the highest LAI was with treatment T102. Therefore, transient soil moisture stress during the vegetative phase increased LAI during the reproductive phase.

FIGURE 2
Leaf area index of groundnut with various treatments, mean values over two years

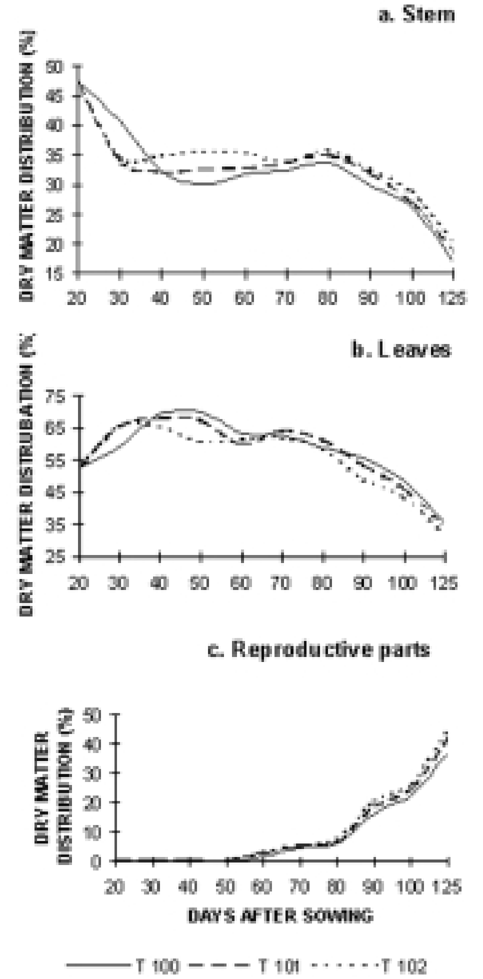


Dry matter distribution

In general, transient soil moisture deficit stress during vegetative growth resulted in higher biomass at harvest (Table 4). During early growth (20 d after sowing) about 45-50 percent of dry matter was distributed to stems (Figure 3). Plants under stress distributed relatively more dry matter to the stems, not only during stress but also after it, than did control plants, although the differences were not statistically significant at final harvest. In contrast, percent dry matter distribution to leaves was significantly higher in the control plants between 40 and 50 d after sowing, when maximum percent dry matter was obtained. Stressed plants had significantly lower dry matter distribution to the leaves both during the stress period and after relief of stress (Figure 3).

Accumulation of dry matter in the reproductive parts (pegs and pods) began at 50 d after sowing (Figure 3), and percent dry matter accumulation increased slowly from 50 to 80 d, and then rapidly until final harvest. Dry matter distribution throughout pod development period until maturity was higher in stressed plants, particularly treatment T 102, which resulted in higher pod yields in both years. In general, there were improvements also in shelling outturn due to imposition of stress during vegetative growth, except in the case of cultivar GG 2. In 1989, the shelling outturn in cv. GAUG 1, due to stress (T 102) was higher (75 percent) as compared to control plants (70 percent) (Table 4).

FIGURE 3
Percent dry matter distribution to stem, leaves, and reproductive parts of groundnut 1989 and 1990, mean values



Harvest index

In general, HIs increased due to the imposition of soil moisture deficit stress during the vegetative phase (Table 4). Cultivar GG 2 gave the highest HI values, irrespective of treatment, in both years. The 100-seed weight was highest (44.4 g) in GG 2 in treatment T101 in both years.

Yield and water use efficiency

Genotypic variation in pod yield was significant. Cultivar GG 2, known for its moisture stress tolerance gave the highest pod yields under control and treatments in both years (Table 4). Consequently, the percent increase in pod yield due to stress was lowest in cv. GG 2 (8.4 percent); it was highest in cv. Ak 12-24 (25 percent). Total biomass and pod yield values at the final harvest were highest with treatment T 102 in both years. The higher reproductive efficiency of these plants was due to improved synchrony in flowering, higher conversion rates of flowers to pegs, and of pegs to pods, e.g. the high peg-to-pod conversion rate observed with T 102 (Nautiyal *et al.* 1999). Water stress in the vegetative stage stimulated the growth of reproductive and vegetative parts.

Field WUE among treatments and cultivars varied widely (Table 5). Watering regime and variety had significant effects on field WUE. Although the highest field WUE (6.2) was for cv. Ak12-24 in 1989, GG2 provided the highest overall values, particularly in 1989. Overall, T 101 values were higher than T 102 values, which were higher than the control values. Thus, withholding irrigation during vegetative growth improved WUE.

Experiment 2

This experiment built on findings that mild stress during vegetative growth was beneficial to biomass accumulation and yield production. Control plants gave the highest biomass accumulation

TABLE 4
Biomass, pod yield, harvest index and shelling outturn of groundnut cultivars under stress treatments 1989 and 1990

Component/ Treatment	1989				1990			
	Ak	J 11	GAUG	GG2	Ak	J 11	GAUG	GG2
Biomass (g/m^2)								
T 100	837	766	779	868	670	689	683	678
T 101	999	956	849	843	824	781	688	657
T 102	1 161	1 039	1 016	915	936	770	781	734
s.e.	5.91				9.56			
Pod yield (g/m^2)								
T 100	226	231	238	328	233	236	233	284
T 101	295	306	272	303	311	270	236	282
T 102	303	322	304	344	311	293	284	324
s.e.	60.0				67.7			
Harvest index (%)								
T 100	26	29	30	37	31	31	30	38
T 101	35	32	31	38	29	31	31	38
T 102	29	31	32	40	30	34	33	39
s.e.	0.70				0.85			
Shelling outturn (%)								
T 100	74	72	70	75	74	70	71	75
T 101	73	72	72	75	72	73	70	74
T 102	74	73	75	76	75	74	73	76
s.e.	0.64				0.30			

TABLE 5
Field water use efficiency for groundnut pod production in 1989 and 1990

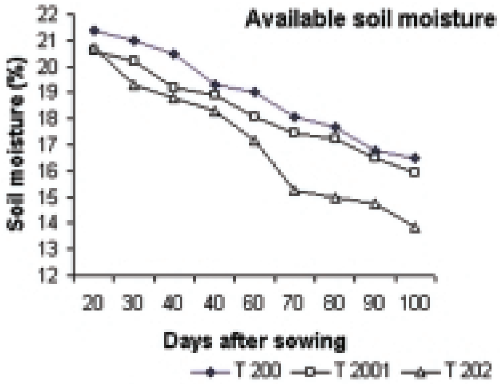
Irrigation treatments	Water used (mm)	Ak 12-24	J 11	GAUG 1	GG 2	Mean
		(kg/ha/mm)				
1989						
T 100	600	3.5	3.5	3.7	5.0	3.9
T 101	500	5.9	6.1	5.4	6.0	5.9
T 102	550	5.0	5.4	5.1	5.7	5.3
Mean	—	4.8	5.0	4.7	5.5	—
1990						
T 100	600	3.6	3.6	3.6	4.4	3.8
T 101	500	6.2	5.4	4.7	5.6	5.5
T 102	550	5.2	4.9	4.7	5.4	5.0
Mean	—	5.0	4.6	4.3	5.1	—

TABLE 6
Effect of soil moisture deficit stress on groundnut cultivar GG 2, summer 1999

Irrigation treatment	Total water applied (mm)	Pod yield (kg/ha)	Haulm yield (kg/ha)	Harvest index (%)	Total biomass (kg/ha)	100-seed wt (g)	100-pod wt (g)	Shelling outturn (%)
T 200	550	2 056	4 511	31.3	6 567	31.7	75.9	63.6
T 201	450	1 836	4 557	28.7	6 393	30.5	73.9	62.1
T 202	400	1 716	3 963	30.2	5 679	27.8	69.7	61.1
s.e.	—	75	125	1.50	122	0.71	1.27	0.49

and pod yield (Table 6). Reductions in biomass and pod yield were greater with T 202 than with T 201. The significant reduction in HI with T 201 suggests that the reduction in economic yield due to prolonged moisture deficit stress was more than the reduction in biological yield. Stress during the vegetative phase was beneficial in terms of economic yield. The available soil moisture at 0-15 cm soil depth was consistently higher in T 200 than T 201 (Figure 4). These results tend to support those obtained in Experiment 1, indicating that mild stress during vegetative growth may be beneficial to groundnut biomass accumulation and pod yield; the trend might have been clearer in Experiment 2 if the control plants had not been exposed to stress. Prolonged stress (T 202), even when mild, was detrimental to crop development and final yield production. Thus, the water requirement of a groundnut crop during the vegetative phase is relatively low, and higher during the flowering, pegging and initial pod development periods.

FIGURE 4
Available soil moisture at 0-15 cm depth, Experiment 2, in 1999



CONCLUSION

Climate, agronomic and variatal facators determine total water use by a crop. The data presented here show that by water deficit stress during the vegetative phase of development, can increase WUE significantly. Soil moisture deficit stress during vegetative growth increased total biomass accumulation and pod yield. These increases were due mainly to increases in leaf area during reproduction, and partitioning of more dry matter to the reproductive parts. In addition, the yield advantage due to water stress in the vegetative phase was due to improved synchrony in flowering and the increased peg-to-pod conversion. Moreover, stress during vegetative growth may have promoted root growth, an area which requires further study.

The results presented here show it is possible to increase field WUE and dry matter production, including the economic yield of groundnut crops cultivated under irrigated conditions by the imposition of transient soil moisture deficit stress during the vegetative phase. However, exact scheduling may differ in different environments.

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Deficit irrigation of potato

Summary

Potato (*Solanum tuberosum* L.) can respond to water stress with yield reductions and loss of tuber grade. The economic opportunities to practise deficit irrigation are more limited for potato than for some other crops. Four potato varieties were grown under four, season-long, sprinkler irrigation treatments during three successive years (1992-1994) on a silt loam soil in eastern Oregon, United States of America. The check treatment was irrigated when soil water potential (SWP) at the 0.2-m depth reached -60 kPa. This treatment received at most the accumulated evapotranspiration (ET_c) to avoid exceeding the water holding capacity of the top 0.3 m of soil. The three deficit irrigation treatments were irrigated when SWP at the 0.2-m depth reached -80 kPa and had the following percent of the accumulated ET_c applied at each irrigation: (i) 100 percent, (ii) 70 percent, and (iii) 50 percent, with 70 percent during tuber bulking. Based on regression of applied water over three years, potatoes lost both total yield and grade when irrigations were reduced. Based on regression of applied water reductions in irrigation, gross revenues declined more than production costs, resulting in reduced profits. The results of this case study suggest that deficit irrigation of potatoes in the semi-arid environment of eastern Oregon would not be a viable management tool because the small financial benefits would not offset the high risks of reduced yields and profits from the reduced water applications. Results from eastern Oregon are compared with those obtained elsewhere.

Political constraints, rising costs, and groundwater scarcities are resulting in less water being available for agriculture. In some areas, groundwater supplies are being exhausted. Competition for water supplies is a worldwide phenomenon. In the Pacific northwest of the United States, political pressures are growing to reallocate water from irrigation to provide instream flows for preserving native fish populations, to provide for water and power needs of growing urban areas, and to reduce non-point source pollution of groundwater and surface water. Deficit irrigation may be one approach to address these issues.

Deficit irrigation is a strategy which allows a crop to sustain some degree of water deficit in order to reduce irrigation costs and potentially increase revenues. English and Raja (1996) described three deficit irrigation case studies in which the reductions in irrigation costs were greater than the reductions in revenue due to reduced yields. Deficit irrigation can lead, in principle, to increased profits where water costs are high or where water supplies are limited. In these case studies, crop value was associated closely with yield, and crop grade and marketability were not germane. Under these circumstances, deficit irrigation can be a practical choice for growers.

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Deficit irrigation has proved successful with a number of crops in various parts of the world. These crops are relatively resistant to water stress, or they can avoid stress by deep rooting, allowing access to soil moisture lower in the soil profile. However, deficit irrigation of potatoes may be difficult to manage because reductions in tuber yield and quality can result from even brief periods of water stress following tuber set (Eldredge *et al.,* 1992; Lynch *et al.,* 1995; Shock *et al.,* 1993; Wright and Stark, 1990). For cv. Russet Burbank, which is predominant in the Pacific northwest of the United States of America, short-duration shortages in water supply during early tuber bulking induced losses in tuber grade (Robins and Domingo, 1956; Salter and Goode, 1967; Thompson and Kelly, 1957) and internal quality directly related to market value (Eldredge *et al.,* 1996). However, in some circumstances, potatoes can tolerate limited deficit irrigation before tuber set without significant reductions in external and internal tuber quality (Shock *et al.,* 1992). Potato varieties differ in tolerance to water stress (Jefferies and MacKerron, 1993a, b; Lynch and Tai, 1989; Martin and Miller, 1983; Miller and Martin, 1987a, b). The adoption of new potato cultivars by growers and processors makes it desirable to re-examine deficit irrigation.

The advent of more efficient irrigation methods allied with the use of soil moisture monitoring devices can make deficit irrigation of potatoes more manageable. Sprinkler irrigation and subsurface drip irrigation (SDI) permit more precise control of the amount of water applied than does furrow irrigation, allowing accurate management of crop rootzone soil moisture. Irrigation scheduling with estimated crop evapotranspiration (ET_c) and a target soil water potential (SWP) level can provide the feedback for managing irrigations. Careful irrigation scheduling has resulted in optimum potato yield and quality. For silt loam, the soil water potential in the top 0.3 m should remain wetter than -60 kPa (Eldredge *et al.,*1996).

The objectives of this research were: (i) to determine potato response to mild, season-long precision deficit irrigation by partial ET_c replacement at a SWP of -80 kPa; (ii) to compare the responses of several major commercial varieties to deficit irrigation; and (iii) to evaluate the potential for deficit irrigation to improve the economic efficiency of potato production.

MATERIALS AND METHODS

Deficit irrigation trials at Oregon State University's Malheur Experiment Station, Ontario, Oregon, United States of America, were conducted in three successive years on an owyhee silt loam (coarse-silty, mixed, mesic, xerollic camborthid). As the cultural practices are described elsewhere (Shock *et al*., 1998), this section includes only the details related to the irrigation treatments, irrigation scheduling, and the evaluation of the potato crops.

In the experimental design, irrigation treatments were the main plots, replicated five times. The varieties were split plots within the main plots. The varieties were: Russet Burbank, Shepody, Frontier Russet, and Ranger Russet. Irrigation treatments were arranged in randomzied complete blocks and consisted of an adequately irrigated check and three progressively drier deficit irrigation treatments (Table 1). The control treatment was irrigated when the soil water potential at 0.2-m depth reached -60 kPa and received no more water than the accumulated ET_c since the previous irrigation. The deficit irrigation treatments were irrigated when the SWP at 0.2 m reached -80 kPa and had a percentage of the accumulated ET_c since the last irrigation applied at each irrigation: i) 100 percent; ii) 70 percent; and iii) 50 percent until tuber set, then 70 percent for six weeks, and 50 percent thereafter.

TABLE 1
Irrigation treatments for potato

Treatment		1992			1993			1994		
Irrigation criterion (kPa)	Irrigation amount (% ET_c)	Total water applied (mm)	Average SWP[a] (kPa)	Time, w/ SWP <–60 kPa (d)	Total water applied (mm)	Ave. SWP (kPa)	Time w/ SWP <–60 kPa (d)	Total water applied (mm)	Ave. SWP (kPa)	Time w/ SWP <–60 kPa (d)
-60	100	589	–50	11	466	–30	3	544	–37	4
-80	100	566	–64	25	255	–41	12	380	–54	26
-80	70	411	–58	35	259	–51	21	356	–59	26
-80	50,70,50[b]	368	–72	44	259	–63	36	327	–60	31
$LSD_{0.05}$		46	22	18	39	14	12	70	17	14

[a] Average daily, 0800 hours measurements at 0.2-m depth, from five plots, recorded a few days before tuber set through to 7 September each year

[b] 50% of accumulated ET_C replaced until tuber set, then 70% of ET_C replaced for six weeks, then 50% of ET_C replaced until last irrigation

ET_c estimates: 1992 - 66 mm; 1993 - 491 mm; 1994 - 622 mm.

To reduce the risk of water losses through leaching, each irrigation was limited to avoid exceeding the water holding capacity of the soil to a depth of 0.3 m. For the control treatment, individual water applications did not exceed 30 mm, and for the plots irrigated at -80 kPa with 100 percent ET_c replaced, individual water applications did not exceed 35 mm. The level of -80 kPa was chosen as it was the SWP at which a single episode of water stress, during tuber bulking, had been previously reduced Russet Burbank tuber grade and quality at the experimental site (Eldredge *et al.,* 1996).

Plots were 13 rows wide (12 m) and 12 m long. Each plot was irrigated using sprinkler heads adjusted to cover a 90° angle at each corner of the plot. The water application rate was 10 mm/h and the coefficient of uniformity for the sprinkler system, calculated according to Christiansen (1942), was 86 percent. All plots with the same treatment were irrigated when the average SWP of the sensors for those plots reached the treatment threshold value. Each year, the irrigations were initiated no earlier than one week before tuber set.

Soil water potential was measured in each plot by two granular matrix sensors (GMSs; Watermark Soil Moisture Sensors, Model 200SS, Irrometer Co., Riverside, California, United States of America) centred at the 0.2-m depth and two GMSs centred at the 0.5-m depth. The four GMSs in each plot were offset 0.15 m from the hill centre (Stieber and Shock, 1995). Sensor readings had been calibrated against tensiometer measurements of SWP (Eldredge *et al.,* 1993). The GMSs were read at 0800 hours daily starting a few days before tuber set each year. Potato ET_c was estimated daily and recorded from crop emergence until the final irrigation, using an AgriMet (United States Bureau of Reclamation, Boise, Idaho, United States of America) weather station at the Malheur Experiment Station and a modified Penman equation (Wright, 1982). Treatments could be irrigated daily, as needed, because sensor readings and Et_c calculations were available daily.

Tubers were harvested and graded by market class (U.S. No. 1 and U.S. No. 2) and size (113-170 g, 170-283 g, and >283 g). They were graded as U.S. No. 2 where any of the following conditions existed: growth cracks, bottleneck shape, abnormally curved shape, or two or more knobs.

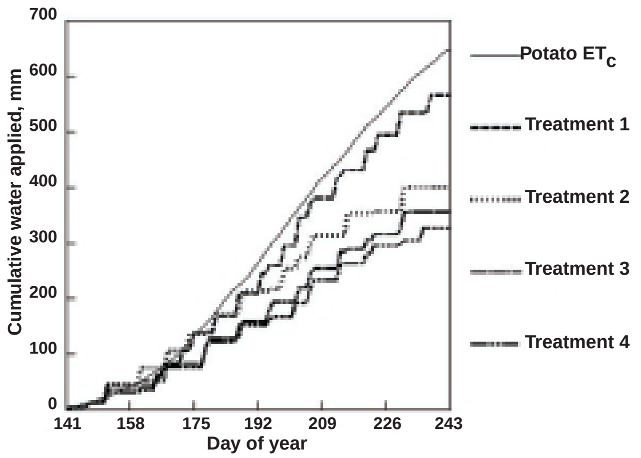
Tuber specific gravity and stem-end fry colour were determined (Shock *et al.*, 1994). Monetary values for the crops were calculated according to a 1996 potato growing and sales contract for processing potatoes (ORE-IDA Foods, Inc., Boise, Idaho, United States of America). Potato production costs were calculated from data prepared by Malheur County Extension

(Oregon State University, Ontario, Oregon, United States of America) and were considered the same for all treatments except for harvest costs, which were calculated per unit of total yield. Irrigation costs were calculated from data prepared by Patterson *et al.* (1996) and were considered the same for all treatments except for pump power costs, calculated per millimetre of water applied. Total yields and U.S. No. 1 yields and net profits averaged across varieties were regressed against applied water plus rainfall for the three years.

Results

Water applications over time for all treatments were close to, and less than, the target ET_c values each year (Table 1 and Figure 1). Precipitation during the tuber bulking period was 46, 57 and 7 mm for 1992, 1993 and 1994, respectively. The number of days with SWP at 0.2-m depth below -60 kPa increased with the change in the irrigation criterion from -60 to -80 kPa and with the decreases in applied water (Table 1). The accumulated growing degree days (10-30°C) during the tuber bulking period were 931, 695 and 946 for 1992, 1993 and 1994, respectively.

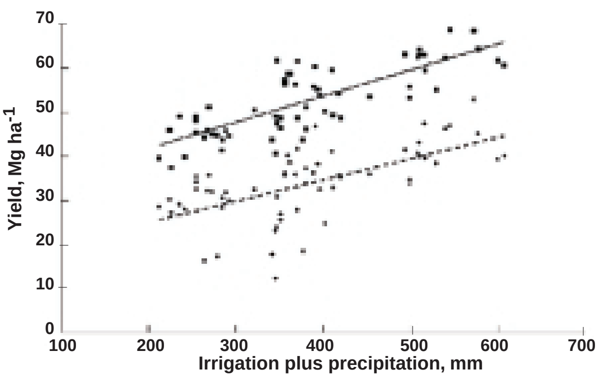
Figure 1
Cumulative ET_c and water applied plus rainfall for potatoes submitted to four irrigation treatments, 1994



Treatment 1 was irrigated at -60 kPa and had a target of 100% of ET_c applied. Treatments 2, 3 and 4 were irrigated at -80 kPa and had targets of 100%, 70%, and <70% of ET_c applied, respectively; data for 1992 and 1993 were similar.

Tuber yields in the well-irrigated treatments of this trial averaged 57 Mg/ha, while Malheur County growers had an average yield of 46 Mg/ha over the same years with the cultivars Shepody and Russet Burbank. Reductions in total yield due to the progressive deficit irrigation treatments averaged 6.7, 10 and 14 percent with corresponding water savings of 25, 36 and 40 percent. Total yield and U.S. No. 1 yield both increased with increases in water supply in each of the three years (Figure 2).

Figure 2
Effect of irrigation plus precipitation on potato tuber yield for three years averaged over four varieties



Regression equations are:
Total yield: Y = 29.84 + .0595xX (R^2 = 0.63, P = 0.001)
U.S. No. 1 yield: Y = 15.28 + .0484xX (R^2 = 0.39, P = 0.001)

The irrigation x cultivar interaction was significant only in 1992 for total and U.S. No. 2 yields. In 1992, U.S. No. 2 yield of Russet Burbank increased with deficit irrigation whereas total yield was insensitive. In contrast, U.S. No. 2 yields for Frontier Russet, Ranger Russet, and Shepody were insensitive to deficit irrigation, whereas total yields declined.

Deficit irrigation had small effects on tuber stem-end fry colour in 1992 and 1993, and was associated with reduced tuber specific gravity only in 1994. The market value of the crop includes considerations of marketable yield, tuber size and grade, fry colour, and specific gravity. Based on the prevailing market contract, estimated profit to the grower decreased on average by 32, 41 and 68 percent with corresponding average water savings of 25, 36 and 40 percent.

Discussion

Potato water requirements

Potato ET_c averaged 593 mm over the three years of the study. Potato ET_c requirements are well established and are based on weather data, the timing of the stages of plant development, canopy coverage, and crop coefficients during development (Wright and Stark, 1990). They range broadly from less than 300 to 700 mm, depending on the environment, the year, and rate of crop growth.

Yield responses to irrigation deficits

Yield and grade responded linearly to applied water. In arid regions, studies have shown that potato yield responds linearly to applied water where irrigation plus rainfall is less than or equal to ET_c (Hane and Pumphrey, 1984; Hegney and Hoffman, 1997; Martin *et al.*, 1992; Shalhevet *et al.,* 1983). Losses in potato yield and grade in response to deficit irrigation were in agreement with previous observations, e.g. Eldredge *et al.* (1992) and Stark and McCann (1992).

Tuber grade responses to irrigation deficits

External tuber defects that cause loss of grade are consistent with water stress during early formation and bulking of the tubers (Robins and Domingo, 1956; Salter and Goode, 1967; Thompson and Kelly, 1957).

Tuber internal quality responses to water stress

Short-term deficit irrigation intensities (driest SWP experienced) in this study were within the ranges of SWP for a silt loam that resulted in dark stem-end fry colour and loss in tuber specific gravity in previous work (Eldredge *et al.,* 1996). The lack of consistent stem-end fry colour response or loss in tuber specific gravity to the season-long deficit irrigation in this study indicates that the potato plants may have become drought hardened in the manner hypothesized by van Loon (1981). The use of sensors for SWP feedback allowed the regulation of stress, such that it reoccurred at the same level throughout the growing season.

In contrast, well-watered potato plants, subjected to irrigation deficits after tuber initiation during the middle of the growing season, produced tubers with reduced specific gravity (Hang and Miller, 1986; Miller and Martin, 1987b). Miller and Martin (1987a) found that the specific gravity of Russet Burbank fell following deficit irrigation at 80 percent of ET_c on a sandy soil.

Stark and McCann (1992) reported reduced specific gravity and darker stem-end fry colour for Russet Burbank subjected to deficit irrigation at 80 percent of ET_c on a silt loam soil. In the present study, irrigation management maintained rootzone SWP higher than -80 kPa, thus attenuating the intensity of water stress resulting from the deficit irrigation treatments. The aforementioned studies, despite using daily irrigations, did not use SWP feedback for irrigation scheduling.

Differential response of varieties to deficit irrigation

The variety x irrigation-treatment interactions were not consistently strong in the present study. Other authors have found strong potato-genotype x water-stress interactions (Jefferies and MacKerron, 1993b).

Economic outcome

Deficit irrigation reduced gross revenues more than production costs (Shock *et al.,* 1998). Reductions in water applied resulted in small decreases in irrigation costs, because only electrical power for the pumping was saved. Water costs independent of pumping did not diminish with decreased irrigation because the district charged a fixed fee per hectare of water. Cost reductions with deficit irrigation would be greater than in the present study if the pumping lift were high or the water more costly. Over the three years, profits rose with increases in applied water. These results are complementary to those of Stark and McCann (1992), who observed declines in yield, grade, specific gravity, and fry colour for processing potatoes grown at Kimberly, Idaho, United States of America, with deficit irrigation.

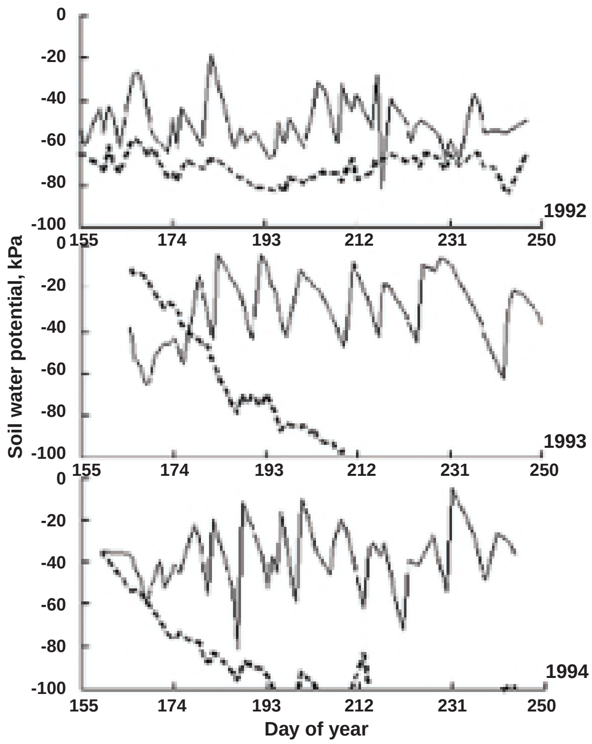
In this study, the environmental benefits of the well watered control treatment were significant, with 10 percent less water applied than full estimated ET_c and with a low leaching potential. Because the reductions in production costs due to reduced water applications were small and because the check treatment resulted in significant environmental benefits, there would be no benefit from deficit irrigation drier than the check treatment. In eastern Oregon, deficit irrigation after tuber set could lead to greater risk to potato growers and could reduce the processing industry's competitiveness due to deficiencies in tuber yield and quality.

Opportunities to conserve water through irrigation scheduling

In the present study, the leaching potential, as determined by the SWP treatments, was low, even for the wettest treatment. In each year, SWP at 0.5-m depth remained lower (drier) than at 0.2 m for all treatments, and total water applied (irrigation plus precipitation) was less or slightly less than the estimated ET_c, suggesting that loss of water by leaching was minimal (Figure 3). Irrigation scheduling, using both a target SWP and controlled water application that did not exceed the water holding capacity of the top 0.3 m of soil, resulted in total seasonal water applied being slightly less than estimated ET_c, even wirh irrigation at -60 kPa. Stored moisture at lower depths in the soil profile can in part supply this small water deficit, as suggested by the increasing dryness of the soil at 0.5 m for the check treatment in 1993 and 1994 (Figure 3). Alternatively, small water savings may accrue by limiting irrigations before tuber set (Shock *et al.,* 1992). Where feasible, SDI can improve water use efficiency for potato compared to sprinkler irrigation, by reducing evaporative losses of water (DeTar *et al.,* 1995; Sammis, 1980; Shea *et al*., 1999).

The ideal SWP for irrigation scheduling varies from -20 to -60 kPa, depending on soil type, irrigation system, production area, and variety (Holder and Cary, 1984; van Loon, 1981). For silt loam in eastern Oregon, the soil water potential in the top 0.3 m should remain wetter than -60 kPa. Irrigation of Russet Burbank on sandy soils in Australia required -20 kPa during early tuber bulking and -20 to -40 kPa after-wards (Hegney and Hoffman, 1997). Careful irrigation scheduling with an appropriate local SWP irrigation criterion and ET_c replacement can achieve efficient water use, while maintaining profitability in a crop sensitive to deficit irrigation.

FIGURE 3
Soil water potential for potatoes irrigated at: -60 kPa replacing ET_C



Solid line: 0.2 m depth, broken line: 0.5 m depth

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Management of supplemental irrigation of winter wheat for maximum profit

Summary

Irrigation scheduling to manage supplemental water for maximum net profit of winter wheat (*Triticum aestivum* L.) in the North China Plain was investigated under variable water applications at two sites from 1992 to 2000. The effects of number and timing of irrigation applications on yields were examined. Based on determinations of sensitivity indices to water stress at various growth stages, a dynamic model was used to calculate the net profits of the irrigation treatments. The results indicate that one, two and three irrigations of 60 mm in wet, normal and dry years, respectively, achieve relatively high yields and maximum net profits. Therefore, the four irrigations generally applied to winter wheat may be reduced to three, two or one, with concomitant water savings.

The North China Plain (NCP) is one of the most important grain producing areas in the People's Republic of China, especially for winter wheat. Its output accounts for more than 19 percent of national wheat production. Due to serious water shortages in the NCP, available irrigation is decreasing rapidly. Where groundwater is used, the amounts pumped in recent years have caused serious depletion. At the sites of the experiment the water table is declining at a rate of 1-1.5 m/year. For winter wheat, average rainfall during the growing season from October to May ranges from approximately 60-200 mm. Supplemental irrigation is required because the water consumption is about 450-500 mm. Farmers generally irrigate winter wheat three to five times, with 180-300 mm of the total water application for each season, from wells, rivers or reservoirs.

Despite these serious shortages, wastage of irrigation water is common in the NCP because of inefficient methods and poor scheduling, resulting in decreased water use efficiency (WUE) and profits. The purpose of this research was to determine rational irrigation scheduling for winter wheat with limited availability of water to obtain optimum yields and maximize profits.

The relationships between crop yields and water use are complicated. Yield may depend on when water is applied or on the amount. Information on optimal scheduling of limited amounts of water to maximize yields of high quality crops is essential if irrigation water is to be used most efficiently (Al-Kaisi *et al*., 1997). The various crop development stages possess different sensitivities to moisture stress (FAO, 1979; English and Nakamura, 1989; Ghahraman and Sepaskhah, 1997). Timing, duration and the degree of water stress all affect yield.

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This paper describes field experiments in which winter wheat yields and profits were examined under various irrigation scheduling regimes. Crop yield/water relations were determined. Water sensitivity indices were analysed at various growth stages. Based on the results, optimum irrigation schedules for maximum net profit for winter wheat were established using a dynamic mathematical model.

MATERIALS AND METHODS

Sites and experiments

Irrigation scheduling experiments were carried out with winter wheat at Luancheng Eco-Agro-System Experimental Station (in a high-production region) and at Hengshui Dryland Farming Institute (relatively low-production region) from 1991 to 1993, 1994 to 1995, and 1997 to 2000, i.e. six growing seasons. The stations are located in the central part of the NCP. At Luancheng, there is loamy soil of high organic content; field capacity of 35.5 percent and wilting point of 11.3 percent by volume, for the surface to 100-cm soil layer. At Hengshui, the sandy loamy soil is of relatively low fertility; field capacity is at 30.4 percent and wilting point at 11.0 percent by volume for the same soil layer. Table 1 lists rainfall at the two sites during the experiments. Seasonal rainfall is far less than the water requirement (WR) of winter wheat calculated by the Penman-Monteith equation.

TABLE 1
Rainfall and water requirements during winter wheat growth at the two experimental sites

Site	Component	1991–92	1992–93	1994–95	Ave. 1960–1995
		(mm)			
Hengshui	Rainfall	229	47.7	125	126
	WR	—	—	—	452
		1997–98	1998–99	1999–2000	Ave. 1975–2000
Luancheng	Rainfall	127	60.4	54.1	117
	WR	—	—	—	468

The experiments had a randomized design with various combinations of number and timing of irrigations (Table 2), with four replications of each treatment. Surface irrigation was used with plastic tubes, and irrigation water was recorded. Meteorological stations at the experimental sites recorded temperature, rainfall, wind velocity, evaporatio, and solar radiation. Plots were 5x8 m, 2 m apart.

TABLE 2
Number and scheduling of irrigations applied to winter wheat

No. of irrigations	Irrigation scheduling: Before over-wintering	Recovering	Jointing	Booting to heading	Milky filling
0					
1			x		
2		x		x	
3	x		x		x
4	x		x	x	x
5	x	x	x	x	x

Crops and management

The experiments used common varieties. Planting is generally in early October with a row spacing of 16 cm and a seeding density of 300/m^2. Harvest is in early June. The straw is returned to the soil. Chemical N, P, and K were applied as base fertilizer, and N was re-applied at the jointing stage. Plots were hand-harvested individually, with a thresher used to separate the grain.

Soil water measurements

Soil water contents were monitored using a neutron probe (IH-II, the United Kingdom) at intervals of 7 days for each 20-cm layer; aluminium access tubes were installed to a depth of 200 cm for each plot. Evapotranspiration (ET) was calculated by the following equation:

$$ET = DS + P + I - D - R \quad (1)$$

where:
- DS = the change in soil water storage (mm)
- P = rainfall (mm)
- I = irrigation (mm)
- D = drainage from the bottom of root zone (mm)
- R = runoff (mm).

As rainfall intensity is low during winter wheat growth, no runoff occurs and the drainage from the rootzone is negligible, in which case ET is the sum of rainfall, irrigation and the change in soil water storage.

Crop sensitivity to water stress

Yield decrease is related to the sensitivity of the crop to water stress at various stages of growth. Jensen (1968) proposed a mathematical relationship between relative yield and the relative amount of evapotranspiration as follows:

$$\frac{Y}{Y_m} = \prod_{i=1}^{n} \left(\frac{ET_i}{ET_{im}}\right)^{l_i} \quad (2)$$

where:
- Y = the actual yield under partial irrigation (kg/ha)
- Y_m = the yield under non-limiting water use from full irrigation (kg/ha)
- n = the number of growth stages
- ET_i = the actual amount of water used by the crop at growth-stage i (mm)
- ET_{im} = the non-limiting crop water use or potential water requirement at growth-stage i (mm)
- λ_i = the relative sensitivity (sensitivity index) to water stress during growth-stage i.

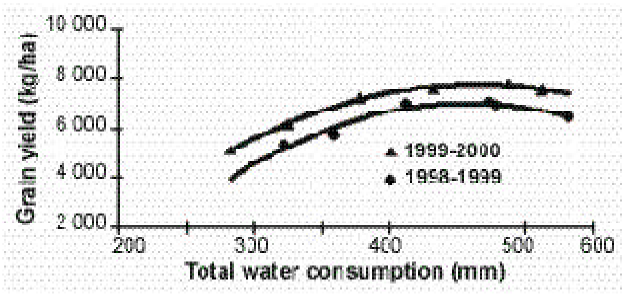
The value of λ_i for a given crop changes with growth stage. A more sensitive growth stage has a higher value of λ_i.

Results and discussion

Relation of crop yield to water consumption

Tables 3 and 4 show the six years of results at the two sites. Different combinations of irrigation number and timing achieved various yields. The largest number of irrigations did not generate the highest yield. A single irrigation produced the highest yield during the 1997–98 season (relatively more rainfall), and four irrigations in the 1999-2000 season (least rainfall) produced the highest yield at Luancheng. Other studies have reported that the relationship between yield and water consumption, including irrigation, is not linear (Yuan *et al.*, 1992). The results of the present study showed that crop yields initially improved with increased water consumption, but that beyond a certain water use level yields decreased (Figure1) over irrigation reduced winter-wheat production.

FIGURE 1
Relation of winter wheat yield with water consumption during two seasons at Luancheng



Irrigation water use efficiency

The relation of irrigation to crop yield is called the irrigation-production function. Many researchers (Zhang *et al.*, 1993) have reported that this function can be described with a quadratic relationship:

$$Y = b_0 + b_1 W + b_2 W^2 \quad (3)$$

where:

Y = crop yield (kg/ha)

W = total irrigation during the whole crop-growth period (mm)

b_0, b_1 and b_2 are coefficients (kg/ha, kg/ha/mm, kg/ha/mm^2, respec-tively).

It is possible to divide yield increases with irrigation into three phases. In the first phase, the value of the increased yield exceeds the increase in cost; in the second phase, the value of the increased yield is equal to the increase in cost; and in the third phase, the increase in yield is of less value that the increase in cost. The following equations express these situations:

First phase ? YxPy > ? WxPw
Second phase ? YxPy = ? WxPw
Third phase ? YxPy < ? WxPw

TABLE 3
Effects of timing and number of irrigations on winter wheat yields at Luancheng

Season	Number of irrigations	Total irrigation (mm)	Total water consumption (mm)	Grain yield (kg/ha)
1997–98	0	0	299	5 414
	1	84.7	334	6 088
	2	95.0	338	5 955
	3	176	376	5 651
1998–99	0	0	323	5 326
	1	60	359	5 751
	2	120	412	6 999
	3	180	474	7 064
	4	240	478	6 937
	5	300	532	6 449
1999–2000	0	0	283	5 104
	1	60	325	6 181
	2	120	377	7 249
	3	180	433	7 593
	4	240	489	7 770
	5	300	512	7 590

TABLE 4
Effects of timing and number of irrigations on winter wheat yields at Hengshui

Season	Number of irrigations	Total irrigation (mm)	Total water consumption (mm)	Grain yield (kg/ha)
1991–92	0	0	279	5 235
	1	60	347	5 869
	2	120	394	5 955
	3	180	424	5 720
	4	240	477	5 478
1992–93	0	0	145	1 959
	1	60	205	2 825
	2	120	264	3 495
	3	180	324	4 545
	4	240	370	4 170
1994–95	0	0	179	3 128
	1	60	282	4 204
	2	120	352	5 775
	3	180	408	5 940
	4	240	463	5 730

where: ΔY = yield increase from irrigation (kg/ha)
Py = unit price of the crop (price/kg)
Pw = unit price of the water (price/ha/mm)
ΔW = increase in irrigation (mm).

In the first phase, net output value increases with irrigation. In the second phase, the net profit from irrigation is maximum. In the third phrase, the net profit from irrigation decreases. Therefore, the irrigation quantity for maximum profit is that for the second phase. By derivation of Equation (3) and combination of it with $\Delta Y \mathrm{x} Py = \Delta W \mathrm{x} Pw$, the following equation yields the irrigation amount to maximize profit:.

$$W = (Pw/Py - b_1)/2b_2 \quad (4)$$

Table 5 provides correlations of yield with irrigation at the two sites for the various seasons. The total irrigation amount for maximum profit was lower than the irrigation amount for maximum yield. Therefore, it it possible to change the general practice of irrigation for maximum yield in the NCP for increased profit savings in large volumes of water. With the worsening water-shortage problem, irrigation costs may increase in the future, and then further reductions in water use may actually increase profits.

TABLE 5
Irrigation production function and economic irrigation quota for winter wheat

Site	Season	Irrigation production function	Irrigation for max. yield (mm)	Irrigation for max. profit (mm)	
				Low fee	High fee
Luan.	1997–98	$Y = -0.0632W^2 + 12.4W + 5\,418$*	98.3	90.4	58.7
	1998–99	$Y = -0.0499W^2 + 19.4W + 5\,162$	194	184	144
	1999-2000	$Y = -0.0489W^2 + 23.0W + 5\,075$	235	225	184
Heng.	1991–92	$Y = -0.0411W^2 + 9.43W + 5\,288$	115	103	53.9
	1992–93	$Y = -0.0417W^2 + 19.2W + 1\,870$	231	219	171
	1994–95	$Y = -0.0789W^2 + 29.5W + 2\,999$	187	181	155

*Y = yield (kg/ha) W = total irrigation (mm)
Note: when calculating irrigation for maximum profit, the price of winter wheat was US$0.11/kg; low water fee= US$0.118/m^3; and high water fee= US$0.0588/m^3.

Optimizing irrigation scheduling for maximum profit

The effect of water stress on the yield of winter wheat depends on the growth stage during which the stress is imposed. Table 6 shows sensitivity indices to water stress from the Jensen model based on water deficit field experiments at Luancheng (Zhang *et al*., 1999). In the NCP, rainfall varies greatly during the winter growing season. Taking account of the sensitivity index and rainfall, a dynamic model can be used to programme the irrigation schedule for maximum profit.

TABLE 6
Sensitivity indices of winter wheat to water stress at ivarious growth stages

λ_i at growth stage					
Before over-wintering	Recovering	Jointing	Booting	Heading to milky filling	Maturing
0.0781	-0.1098	0.2984	0.2366	0.1102	-0.0541

Target function

The target function is that which maximizes net profit per unit area, according to the following equation:

$$max\ I = I^* = max(B\text{-}C) \tag{5}$$

where:
- I = net income per unit area (value/ha)
- B = total output value per unit area (value/ha)
- C = total input value per unit area (value/ha).

The following equations yield the values for B and C:

$$B = (P_{Y1}+P_{Y2}xL)Y \tag{6}$$

$$C = (P_{W1}+P_{W2})W+K(\frac{W}{50}+\frac{4\times Y}{250})+F_c \tag{7}$$

where:
- Y = grain yield of winter wheat (kg/ha)
- L = ratio of straw yield to grain yield
- W = total irrigation water (m^3/ha)
- K = daily labour cost (cost/person)
- P_{Y1}, P_{Y2} = grain and straw price (value/kg)
- P_{W1}, P_{W2} = water fee and irrigation energy cost (cost/m^3 and cost/unit energy)
- W/50 = days needed for irrigation (50 m^3 irrigation per day)
- $4xY/250$ = harvesting cost (250 kg grain per four days)
- F_c = seed, sowing, fertilizer and other costs (cost/ha)

The Jensen model calculates the effect of water deficit on crop yields:

$$Y = Y_m x \prod_{i=1}^{n}(\frac{ET_i}{ET_{im}})^{\lambda_i} (i=1, 2, 3,\ldots, n) \tag{8}$$

where:
- ET_i = water consumption at growth stage i (m^3/ha)
- λ_i = sensitivity index to water stress at growth stage i
- ET_{im} = water consumption at growth stage i without water stress (m^3/ha)
- Y_m = grain yield without water stress (kg/ha).

Combining Equations (6), (7) and (8) into (5) yields:

$$I^* = max(B\text{-}C)$$

$$= max\{(P_{Y1}+P_{Y2}xL)Y\text{-}[(P_{W1}+P_{W2})W+K(\frac{W}{50}+\frac{4\times Y}{250})+F_c]\}$$

$$= max\{(P_{Y1}+P_{Y2}xL \qquad)Y_m x \prod_{i=1}^{n}(\frac{ET_i}{ET_{im}})^{\lambda_i}\text{-}(P_{W1}+P_{W2}+\frac{K}{50})W\text{-}F_c\}$$

And letting:

$$(P_{Y1}+P_{Y2}xL - \frac{4\times K}{250}) = M$$

$$(P_{W1}+P_{W2}+\frac{K}{50}) = N$$

$$W = \sum_{i=1}^{n} W_i\, i = 1, 2,\ldots, n$$

Then, the following equation yields the target function.

$$I^* \quad = \quad max\{MxY_m x \prod_{i=1}^{n}(\frac{ET_i}{ET_{im}})^{\lambda_i} - Nx \sum_{i=1}^{n} W_i - F_C\} \qquad (9)$$

where: M, N = target coefficients (price/ha)
W_i = irrigation at stage i (m^3/ha)
λ_i = the value in Table 6.

The calculation of growth stage water consumption without water stress uses the Penman-Menteith equation recommended by FAO, based on average meteorological parameters for 1960 to 1990. The crop coefficient is from field experiments (Liu *et al.*, 1998). The irrigation scheduling for maximum profit in different rainfall years, dry, normal and wet years are programmed. The type of seasonal rainfall is classified by the meteorological statistical method based on the seasonal rainfall data from 1951 to 1999 in the central part of the NCP, with P = 75, 50 and 25 percent, respectively. The quantity of water for each irrigation is assumed to be 60 mm, which is common in the well-pumping irrigation region of the NCP.

Determining the variables

The equation for calculating water allocation for different growth stages is:

$$q_{i+1} = q_i - W_i \qquad 10)$$

where: q_i = water allocated at the beginning of growth stage i
q_{i+1} = water allocated at the beginning of growth stage $i+1$

The equation for calculating the soil water that can be used at the beginning of a stage:

$$S_{i+1} \quad = \quad S_i+P_{oi}+W_i+K_i+ET_i+E_i \qquad (11)$$

where: S_i = soil water that can be used by the crop at the beginning of growth stage i (m^3/ha)
S_{i+1} = soil water that can be used at the beginning of growth stage $i+1$ (m^3/ha)
W_i = irrigation at growth-stage i (m^3/ha)
P_{0i} = effective rainfall at growth stage i (m^3/ha)
ET_i = evapotranspiration at growth stage i (m^3/ha)
K_i = groundwater replenishment to soil water at growth stage i (m^3/ha)
E_i = percolation from rootzone at growth stage i (m^3/ha).

The programming uses the following binding conditions:

$$0 = W_i = q_i \qquad i = 1, 2,\ldots, n \qquad (12)$$

$$\sum_{i=1}^{n} W_i = W \qquad (13)$$

$$ß_w = ß = ß_f \qquad (14)$$

where: W = available irrigation water during the whole growth period (m^3/ha).
$ß_f$ = field capacity (v/v)
$ß_w$ = low limit of soil water content
$ß$ = soil water content.

TABLE 7
Simulated irrigation scheduling for maximum profit of winter wheat

Seasonal rainfall pattern		Growth stages of winter wheat					Total (mm)	Simulated maximum profit (US$/ha)*
		Sowing to recovering	Jointing	Booting	Heading to milky filling	Maturing		
Dry	Average rainfall (mm)	30.7	3.5	6.3	12.9	6.4	59.6	182
	Simulated irrigation (mm)	60	0	60	60	0	180	
Normal	Average rainfall (mm)	52.3	10.9	17.4	16.3	8.1	105	189
	Simulated irrigation (mm)	0	60	0	60	0	120	
Wet	Average rainfall (mm)	67.9	17.4	22.8	34.2	12.1	154	213
	Simulated irrigation (mm)	0	0	60	0	0	60	

*Based on current prices and costs

In most years, the water content (0-200 cm) at sowing time is about 85 percent of field capacity. This value was used for initial soil water content. At the beginning of the first growth stage, available irrigation water is equal to the planned irrigation water for the whole growth period.

An asymptotic approximation method was used to programme the number of irrigations and their timing. Table 7 lists the simulated scheduling with maximum net profits for different seasonal rainfall conditions. The simulated results were similar to those from the field experiments. The irrigations were timed when winter wheat is most sensitive to water stress.

CONCLUSIONS

Crop yields and net profits are important considerations in selecting an irrigation management policy in the water deficient NCP region of China. Winter wheat, has a high water requirement. Supplemental irrigation is essential. Farmers generally irrigate for maximum yield but sometimes over irrigate, reducing the yield. With the increasing shortage of water in the NCP, irrigation water fees may rise, whereas grain prices may decrease because of current overproduction in China. The simulated results showed that a single irrigation in wet years, two irrigations in normal years and three in dry years produced maximum profits. The timing of the irrigations would be: at jointing to booting for the single irrigation, at jointing and heading to milky filling for the two irrigations; and before over wintering, jointing, and heading to milky filling for the three irrigations.

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Scheduling deficit irrigation of fruit trees for optimizing water use efficiency

SUMMARY

Regulated deficit irrigation (RDI) of fruit trees in the Goulburn Valley of southeastern Australia has increased water use efficiency by approximately 60 percent with no loss in yield or substantial reductions in vegetative vigour. Original techniques to schedule RDI were based on a 12.5 percent (peach) and 20 percent (pear) replacement of US Class A pan evaporation. Subsequent research into soil moisture measurement led to a recommended soil suction of 400 kPa to trigger irrigation. To extend the application of RDI to other environments and fruit crops, practical scheduling steps have been developed. Firstly, fruit growth is measured to determine when to apply RDI. Secondly, an irrigation plan is developed to estimate irrigation run time and interval based on soil type, root distribution, wetting pattern and average daily water use. Thirdly, soil moisture sensors are installed and irrigation is applied when soil suction reaches 200 kPa. Irrigation run time is adjusted by measuring soil moisture immediately following irrigation. Finally, US Class A pan evaporation is measured or reference crop evapotranspiration is calculated to estimate irrigation interval for scheduling in later years.

Regulated deficit irrigation (RDI) was developed to improve control of vegetative vigour in high-density orchards in order to optimize fruit size, fruitfulness and fruit quality. RDI is usually applied during the period of slow fruit growth when shoot growth is rapid. However, it can also be applied after harvest in early-maturing varieties. Furthermore, RDI can generate considerable water savings. Thus, it is useful for reducing excessive vegetative vigour, and also for minimizing irrigation and nutrient loss through leaching.

Increasingly, orchards are being planted with compact, closely spaced trees. Higher density improves profitability as trees bear earlier, yields are higher, and production costs are lower (Chalmers, 1986). While the benefits of high-density orchards are well known, excessive vegetative vigour in badly managed high-density orchards can lead to shading and associated barrenness (Chalmers *et al.*, 1981). Fruitlet retention, fruit size and fruit colour can be reduced in the current season while fruit-bud formation in the following season can be inhibited (Purohit, 1989). Therefore, when full canopy cover is reached, it is critical that excessive vegetative growth minimized.

Techniques for controlling vegetative vigour include branch manipulation, mechanical shoot and root pruning, the application of chemical growth regulators, manipulating crop load, fertilizer management, and RDI (Chalmers *et al.,* 1984). Of these, RDI is arguably the most economical, as less water is applied with no loss in fruit size or total yield. Genetic control methods such as

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the use of dwarfing rootstocks will control vegetative vigour for the life of an orchard and are widely used in apple production. However, vigour management based on cultural practices ensures that trees remain inherently vigorous and are capable of rapidly filling their allotted space and producing high early yields (Chalmers *et al*).

Extensive research means that the effects of regulated water deficits on tree growth and development are well understood. Most studies have shown that mild water stress applied during the period of slow fruit growth controlled excessive vegetative growth while maintaining or even increasing yields. These included studies on peach (*Prunus persica*) (Li *et al.*, 1989; Williamson and Coston, 1990), European pear (*Pyrus communis*) (Brun *et al.*, 1985a, 1985b; Chalmers *et al.*, 1986; Mitchell *et al.*, 1984, 1986, 1989), Asian pear (*Pyrus serotina*) (Caspari *et al.*, 1994) and apple (*Malus domestica*) (Irving and Drost, 1987). In addition, water stress applied after harvest reduced vegetative growth of early-maturing peach trees (Larson *et al.*, 1988; Johnson *et al.*, 1992). RDI applied to olives over a ten-week period following pit hardening had no adverse effect on oil production (Alegra *et al.,* 1999). Moderate levels of water stress applied to prunes (*Prunus domestica*), by withholding irrigation in a deep soil during stage II of fruit growth, increased return fruit bloom, crop load, and total fruit dry matter yield (Lampinen *et al.,* 1995).

The application of RDI improves water use efficiency (WUE). Mitchell and Chalmers (1982) found WUE, expressed as yield per unit irrigation, increased from 4.9 to 8.0 t/Ml under RDI in canning peaches that yielded 48 t/ha. Similarly, Mitchell *et al.* (1989) found WUE increased from 12.5 to 22 t/Ml under RDI in WBC pears that yielded approximately 90 t/ha. In the Goulburn Valley in southeastern Australia these improvements in WUE would lead to water savings of 3 Ml/ha and 2 Ml/ha for peaches and pear, respectively. Even larger water savings have been reported for peaches in China (Goodwin *et al.,* 1998). In this case, total irrigation applied was reduced from 3.0 Ml/ha to 1.4 Ml/ha without any effect on yield. Goldhamer (1999) reported water savings of 25 percent for RDI applied to olives in California, United States of America. with no yield reduction.

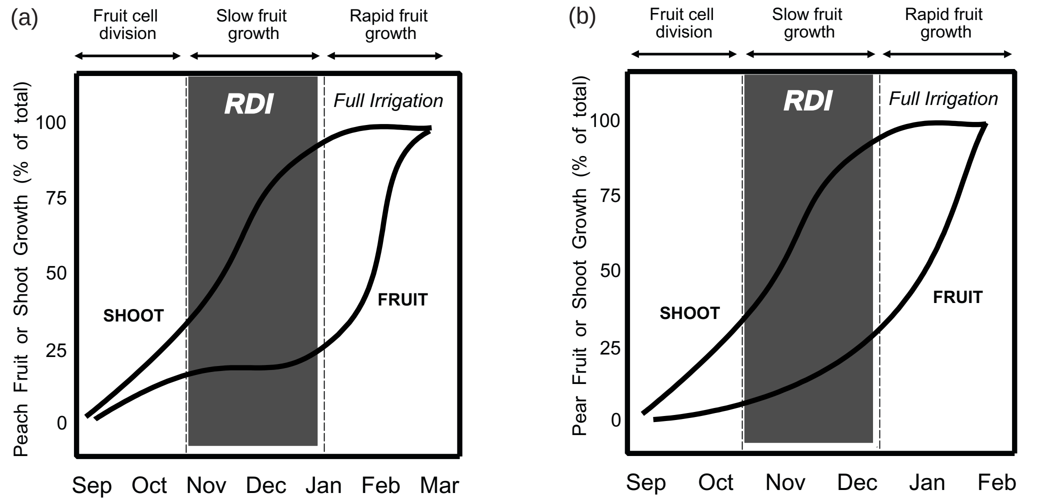
Increased WUE under RDI is due largely to reductions in transpiration, which might be as much as 50 percent (Boland *et al.,* 1993b). Reduced transpiration appears attributable to partial stomatal closure. Despite reduced transpiration, measured increases in fruit osmotic potential (Jerie *et al.,* 1989) indicate that fruit dry weight accumulation is not impaired. This also holds for Asian pear (Behboudian *et al.*, 1994), grapefruit (Cohen and Goell, 1988) and apple (Failla *et al.*, 1992), and is thought to be a mechanism of adaptation to water stress (Mitchell *et al.*, 1994).

Both the timing and level of water stress are critical to the success of RDI. These factors need to be considered in relation to what is understood of the growth and development of the species in question. In addition, it is necessary to adopt modern techniques for scheduling irrigation that allow adequate assessment of water stress in any environment. This paper describes how to determine the timing and frequency of RDI, and it presents practical scheduling techniques for estimating water application rates.

Timing of RDI

The development of RDI was not possible without first understanding patterns of tree and fruit growth. Initially, RDI experiments focused on peach and pear, and a comparison of the development of these fruits illustrates the importance of the timing of RDI application. Although patterns of growth and development may vary in other horticultural crops, the basic principle of applying RDI when fruit growth is minimal remains the same.

Figure 1
Typical shoot and fruit growth pattern for (a) peach and (b) European pear



The growth curve of peach is double-sigmoidal with two periods of increasing growth rate. Three phases are commonly attributed to fruit growth. Stages I and III are separated by a phase of decreasing growth rate (Stage II) known as the lag phase (Chalmers and van den Ende, 1975, 1977). Changes in the relative sink strengths of the seed and pericarp govern development. Only 25 percent of total fruit growth occurs when vegetative parts are growing rapidly; the majority of fruit growth occurs in the final 6-8 weeks before harvest when vegetative growth is almost complete (Chalmers *et al.*, 1975, 1984) (Figure 1a). This asynchronous growth of fruit and shoots reduces competition for resources at critical stages, and provides a sound basis for the application of the RDI, which relies on water stress during Stage II having a small effect on fruit growth but a significant effect on vegetative growth.

The growth of pear fruit is curvilinear with less than 20 percent occurring by midway from bloom to harvest (Mitchell, 1986). The majority of shoot growth occurs during this period of slow fruit growth (Mitchell *et al.,* 1986). Thus, RDI is applied for the first 70-80 days after bloom. The majority of fruit growth occurs in the remaining 6-8 weeks to harvest (Figure 1b).

The above generic descriptions of fruit and shoot growth of peach and pear are useful for explaining the theoretical basis for RDI and the general timing of RDI. However, to implement RDI for a particular variety requires a more accurate description of the growth periods. Stages of fruit growth for different fruit varieties can be readily determined by tagging several fruit and shoots on a tree and making weekly determinations of their circumference (or diameter) and length with a tape measure. Fruit circumference can be converted to relative volume by cubing.

Scheduling RDI — history

Understanding of when and how to apply RDI has improved substantially over the past 20 years. Scheduling has evolved from the initial recommendations based on US Class A pan evaporation (E_{pan}) toward measuring both soil moisture and tree responses before making management decisions. Although the original simple recommendations may still work for many orchards, the emphasis on measuring soil moisture to estimate orchard water use and tree water stress allows more precise control over vegetative vigour and fruit growth.

Under trickle irrigation, the original recommendation for scheduling RDI was to irrigate daily and calculate irrigation amount from a percent replacement of E_{pan}. The formula used to calculate irrigation run time was:

$$Run\ time(h) = \frac{(E_{pan} - Rain)(mm) \times \%\ Replacement \times Row\ spacing\ (m) \times Tree\ spacing\ (m)}{Emitter\ rate\ per\ tree\ (litres\ /\ h)}$$

Replacement amounts were derived from the original RDI experiments at Tatura (Mitchell *et al.,* 1989). For peaches, the recommended replacement was 12.5 percent from flowering until the start of rapid fruit growth. From the start of rapid fruit growth to harvest, the recommended replacement was 100 percent. The start of rapid fruit growth was based on a date for different varieties, e.g. Golden Queen was mid-January. With William Bon Chretien (WBC) pears the strategy was slightly different, consisting of a period of withholding irrigation during spring until attaining a cumulative deficit of 100-125 mm of evaporation from 1 October. After this, a replacement of 20 percent E_{pan} was used until mid-December to calculate required irrigation application. From mid-December to harvest, the recommended replacement was 100-120 percent for pears.

Adapting these recommendations to fit other irrigation systems concentrated on altering the interval between irrigations. During the RDI period, the recommended intervals were 7 days for microjets (40 litres/h/tree in 3x5 m planting) and 21 days for sprinklers (120 litres/h/tree in 6x6 m planting) (Goodwin, 1995). Applying RDI using flood irrigation was based on increasing the interval between irrigations or irrigating every second row.

The next improvement was to estimate irrigation interval for systems other than trickle. Estimates were based on the volume of water in the rootzone and average daily water use, and utilized the measurement of soil moisture to adjust the interval. Calculation of run time was essentially unchanged, although soilmoisture measurements following irrigation were recommended to adjust run time. Mitchell and Goodwin (1996) recommended a formula to calculate interval based on average daily pan evaporation:

$$Interval\ \ (days) = \frac{Volume\ \ of\ \ water\ \ in\ rootzone\ \ (litres)}{Average\ \ daily\ \ water\ \ use\ (litres\ \ /\ day)}$$

Where: volume of water in rootzone (litres) = width of wetted strip (m) x tree spacing (m) x 0.3 m wetting depth (m) x soil type factor ranging from 60 (sandy soils) to 80 (loams and clays) average daily water use (litres/day) = row spacing (m) x tree spacing (m) x replacement factor x average daily E_{pan} (mm).

This method of scheduling remains well suited to the Goulburn Valley. However, it is not applicable to other soil types and climates. RDI experiments in China on peaches, with root systems up to 2.5 m deep, emphasized the need to measure soil moisture over the entire rootzone depth to trigger the initial irrigation in spring or early summer (Goodwin *et al.,* 1998).

In conjunction with the above formulae to estimate run time and interval based on pan evaporation, recommendations to measure soil moisture were developed to ensure soil dryness was sufficient but not excessive. Measurements of rootzone soil moisture were included in the scheduling of RDI to adjust irrigation interval and run time. Recommendations were based on intensive soil suction monitoring with gypsum blocks in an RDI experiment on pears at Tatura (Goodwin *et al.,* 1992). Under trickle irrigation, soil suction of 400 kPa at 0.1-0.25 m depth, 0.15 m from the emitter, was recommended to trigger irrigations with irrigation run time based on the above formula. Soil moisture measurements after irrigation at 0.6 m from the tree line were recommended to adjust irrigation run time.

Work undertaken on RDI of wine grapes across a range of climates and soil types (Goodwin and Jerie, 1992) highlighted the need for adjustments in soil moisture values to trigger irrigation depending on rootzone depth, soil texture and climate. Recommendations for wine grapes were as follows. In sandy soils with shallow rootzones (<0.4 m) and hot climates (e.g. average January daily evaporation >8 mm), soil suction under RDI should not exceed 100 kPa. In loam soil with intermediate rootzones (0.4-0.8 m) and mild climates (e.g. average January daily evaporation 5-8 mm), soil suction under RDI should not exceed 200 kPa. In clay soil with deep rootzones (>0.8 m) and cool climates (e.g. average January daily evaporation <5 mm), soil suction under RDI should not exceed 400 kPa.

Scheduling RDI — current recommendations

The following is a list of necessary steps implementing RDI successfully:

- Measure fruit and shoot growth to determine the RDI period for fruit species/varieties in an orchard.
- Dig up a tree to determine the rootzone distribution — width and depth (80 percent of total).
- Determine the wetting pattern of the irrigation system and estimate wetted rootzone.
- Develop a season irrigation plan for run time and interval based on soil type and average E_{pan} or reference crop evapotranspiration (ET_o).
- Install soil moisture sensors (preferred measure is soil suction using gypsum blocks)
  - at 0.3 m and bottom of rootzone in shallow soil,
  - at 0.3 m, 0.6 m and bottom of rootzone in deep soil.

During RDI period

1. Measure and record soil suction and irrigate when the entire rootzone dries out to a minimum of 200 kPa.
2. Irrigate to wet the top 0.3 m of the root zone.
3. Measure and record soil moisture 6-12 h after irrigation and, where necessary, adjust the amount applied in previous irrigations.
4. Irrigate when the wetted rootzone soil at 0.3 m depth dries out to 200 kPa.
5. Measure evaporation (or ET_o) interval between irrigations — irrigate in future years based on this evaporation interval.
6. Repeat steps 3-6.

During rapid fruit growth

1. Irrigate to wet at least the top 0.6 m of rootzone.
2. Measure and record soil suction 6-12 h after irrigation, and, if the soil is dryer than 30 kPa (sandy soil) or 50 kPa (clay soil) at 0.6 m, apply more irrigation.
3. Irrigate when the wetted rootzone soil suction at 0.3 m depth dries out to 30 or 50 kPa.
4. Measure evaporation (or ET_o) interval between irrigations — irrigate in future years based on this evaporation interval.
5. Repeat steps 2-5.

Measuring shoot and fruit growth

An understanding of the changes in fruit and shoot growth for different varieties is critical for the timing of RDI. Water stress should be applied only during the vegetative growth period when fruit is growing slowly. Water stress must be avoided or minimized (where water is limited) during rapid fruit growth. The stages of fruit growth for a given variety can be determined by tagging several fruit and shoots and weekly measuring their circumference and length with a tape measure. Converting fruit circumference to volume [volume = 0.02 x $(\text{circumference})^3$] gives a true indication of fruit weight. This technique is simple and the measurements are useful for adjusting irrigations, especially where shoot growth continues despite high soil water deficits.

Root distribution

Root distribution is an important component for RDI scheduling because of the potential store of available moisture in the soil. The best method for determining root distribution is to dig a pit next to an orchard tree and estimate the amount of roots in 0.2-m depth increments until the bottom of the rootzone (80 percent of roots). Root depth is important for determining the volume of water in the rootzone when the profile is wet from rainfall, and for deciding where to site soil moisture sensors.

Wetted root zone

It is critical to determine the volume of the wetted rootzone. This can be estimated from the root distribution and the wetted volume of soil. To determine the wetting volume, it is necessary to observe the wetted surface area and depth following an irrigation event.

A hole is dug to observe wetting at depth. The wetted rootzone is then estimated from the volume of roots that are wet following irrigation. The calculation in the following irrigation plan assumes that the wetting pattern is a continuous strip of soil with a wetting depth of 0.3 m. This wetted strip pattern will occur with closely spaced microjets or drippers where the wetting pattern overlaps. For other irrigation systems where the wetting patterns are separate, the wetted rootzone is calculated assuming the shape of a cylinder.

Irrigation plan

The aim of setting out a season irrigation plan for the approximate interval and run time is to provide a theoretical basis for irrigation scheduling and water budgeting. For each month of a growing season, the interval between irrigations is calculated based on the equation:

$$Interval\ (days) = \frac{Volume\ of\ water\ in\ root\ zone\ (litres\ /\ tree)}{Average\ daily\ water\ use\ (litres\ /\ tree\ /\ day)}$$

At the start of the season, the interval between irrigations is equivalent to the withholding irrigation period where the volume of water in the rootzone (i.e. stored soil moisture) can be calculated by substituting the wetted volume with the root volume:

Volume of water in rootzone (litres/tree) = Lateral root distribution width (m) x Tree spacing (m) x Root depth (m) x Deficit available water ranging from 9 percent (sandy soils) to 13 percent (loams and clays) x 1 000.

Once irrigation commences, the volume of water in the root zone is equivalent to the irrigation amount to be applied:

Volume of water in rootzone (i.e. irrigation amount) (litres/tree) = Width of wetted strip (m) x Tree spacing (m) x 0.3 m wetting depth (m) x Deficit available water ranging from 9 percent (sandy soils) to 13 percent (loams and clays) x 1 000

Run time calculations use the emitter rate per tree and the system irrigation efficiency:

$$Run\ time(h) = \left[\frac{Vol.\ of\ water\ in\ rootzone(litres)}{Emitter\ rate\ per\ tree(litres/h)}\right] \Big/ \left[Efficiency(\%)/100\right]$$

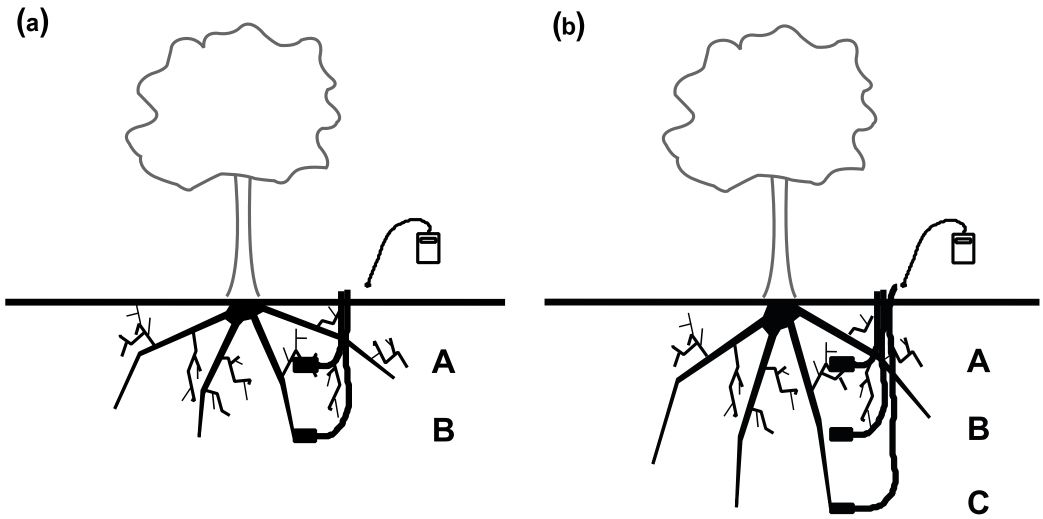
To estimate average daily water use, the plan uses local long-term average USA Class A pan evaporation data and appropriate crop factors for RDI (Mitchell and Goodwin, 1996). Alternatively, it is possible to use ET_o and crop coefficients (K_c) (Allen *et al.,* 1998) and appropriate percent replacements for RDI to estimate daily water use.

Soil moisture

RDI scheduling requires measurements of soil moisture. In shallow rootzones, soil moisture is measured at two depths (Figure 2). In deep rootzones (>0.6 m), soil moisture is measured at three depths. The aim is to dry out the soil throughout the rootzone to a minimum suction of 200 kPa by withholding irrigation (positions A, B and C). If there is no rain, the soil in the upper rootzone (positions A and B) will become much drier than the soil towards the bottom of the rootzone (position C). If the entire rootzone becomes drier than 200 kPa, stress levels on the tree will cause loss in productivity. Irrigation is necessary.

Once irrigation commences, the objective is to maintain a moderate level of stress on the trees. This is best achieved by irrigating with less water than the usual full recommendation. Irrigations should aim to wet to 0.3 m depth (position A).

FIGURE 2
Position of soil moisture sensors in (a) shallow and (b) deep rootzone soils



It is necessary to measure soil moisture 6-12 h after irrigation to adjust the amount of water applied in proceeding irrigations. If the soil in the top rootzone (position A) remains dry then the irrigation amount must be increased. If the soil in the mid-rootzone (position B) becomes wet immediately following irrigation then irrigation amount must be cut back.

The gypsum block is preferred over other methods of determining moisture because it measures soil water suction, which relates to the level of water stress on the trees. It is the only instrument capable of measuring soil suction in the range suitable for RDI. It is relatively inexpensive, robust to handle, and simple to install. It requires a portable hand-held meter to measure the resistance between the two electrodes embedded in the block of gypsum. The electronics in the meter convert the resistance automatically to suction. The measurement is simple: requiring the connection of the two wires to the meter and a button to be pushed to directly measure soil suction.

Alternatively, soil samples may be collected with an auger and the moisture content assessed. This is much less accurate than the gypsum block method, but may be useful to assess wetted depth and moisture below the top 0.05 m depth.

RDI in practice

As part of an extension programme in the Goulburn Valley, sites were established on growers properties to demonstrate RDI. Growers were interested in controlling vegetative vigour in high-density orchards and saving water. One site consisted of 6-year-old Golden Queen peach trees on Tatura Trellis (van den Ende *et al.,* 1987) irrigated with 45 litres/h microjets (one every second tree). Thirty trees (three rows each of ten trees) received normal irrigation and 30 (also three rows of ten) received the deficit irrigation. Measurements recorded to indicate WUE and vigour control included water applied, soil moisture (tensiometers and gypsum blocks), butt diameter and fruit growth (mm).

RDI was applied from the first week of November to the last week of December, to provide approximately 40 percent of evaporation; control trees received full irrigation. Soil suction was maintained between 0 and 65 kPa on the control treatment and between 0 and 200 kPa on the RDI treatment. For the remainder of the season, soil suction was maintained between 0 and 50 kPa on all of the trees.

Fruit growth was measured over the season (four fruits per tree, 120 per treatment). There was no apparent difference in fruit size between the RDI-treated trees and the controls. Tree butt size was used as an indicator of vigour. The 30 trees irrigated under the RDI strategy exhibited an overall reduction in measured butt diameter at the end of the season. The grower also noted a reduction in tree vigour, with more fruiting wood established. There was a reduction in the water applied under RDI management with a saving of 2.3 Ml/ha: total irrigation for the control was 7.9 Ml/ha, whereas that for the RDI treatment was 5.6 Ml/ha.

The demonstration site showed that RDI can generate considerable savings. Fruit size and yield were maintained, and vegetative vigour appeared to be reduced.

Other issues related to RDI — root volume and salinity

It is evident that root volume is an important factor in the tree growth response to RDI. Some studies have suggested that the success of RDI in controlling vigour and maintaining yield arises from both an adaptation to moderate water stress developed in a shallow soil volume (Jerie *et al.*, 1989) and/or restricted wetted root volume (Richards and Rowe, 1977a, 1977b).

To further explore this effect, an experiment was established to determine the interaction of RDI and root volume on Golden Queen peaches (Boland *et al.*, 1994, 2000a, 2000b). This study demonstrated that the effect of root volume was independent of the RDI water stress response. However, there are important implications for the practical application of RDI under various conditions. In the Goulburn Valley, shallow root volume assists the development of water stress under RDI. In a deep soil with an unrestricted root system, it takes considerably longer to develop water stress; under these conditions it may be necessary to physically restrict the volume of roots.

Therefore, the control of vegetative growth and establishment of RDI depends on the interaction between rainfall/evaporation, available soil volume for root exploration and the readily available water (time taken to develop water stress).

The application of RDI in a saline environment presents potential advantages and disadvantages. Management of orchards irrigated with saline water has traditionally relied on leaching to prevent accumulation of salts, in order to maintain a soil volume that will permit root development. Leaching is regarded as the key to salinity control (Hoffman and van Genutchen, 1983). Although, RDI does not provide the same degree of leaching, it does have the potential to improve salinity management, firstly by a reduction in the importation of salt, and secondly by control of the rising water table (Shalhavet, 1994).

An experiment that assessed the impact of saline irrigation when applying RDI (Boland *et al.*, 1993a) demonstrated significant adverse effects on the productivity of peach trees, with similar results expected on other fruit trees that are generally sensitive to salinity. Therefore, while RDI may lessen the volume of drainage and applied salts, the detrimental effects on productivity would generally outweigh these benefits. Where RDI is applied in a saline environment to either save water or control vegetative vigour, it is necessary to adopt specific management strategies: strategic leaching irrigations (e.g. every five to seven irrigations), and careful monitoring of soil salinity.

Conclusion

Although the control of vegetative vigour in high-density orchards was the original objective of RDI, increased WUE has become a critical issue in areas where water scarcity is a problem. RDI is an ideal water saving technique. Its application and adaptation in various environments have led to improved understanding of the process, the benefits, and the requirements for adoption. Scheduling has evolved to include weather and soil-based monitoring. As a consequence, this wealth of knowledge has enabled the implementation of a practical and achievable programme for grower adoption of RDI.

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Regulated deficit irrigation and partial rootzone drying as irrigation management techniques for grapevines

Summary

Regulated deficit irrigation (RDI), an irrigation scheduling technique originally developed for pome and stone fruit orchards, has been adapted successfully for winegrape production. Water deficit is applied during the post-set period of berry development to reduce vegetative growth and, as necessary, berry size of red-winegrape varieties. However, water deficit is avoided during the berry-ripening period, and precise irrigation management is required to ensure minimal competition between ripening berries and vegetative growth. For the variety Shiraz, in particular, this irrigation practice has resulted in significant improvements in wine quality. Partial rootzone drying (PRD) is a new irrigation technique that improves the water use efficiency of winegrape production without significant crop reduction. The technique was developed on the basis of knowledge of the mechanisms controlling transpiration, and requires that approximately half of the root system be always in a dry or drying state while the remainder is irrigated. The wetted and dried sides of the root system are alternated on a 10- to 14-day cycle. PRD irrigation reduced significantly stomatal conductance of vines when compared with vines receiving water to the entire root system. Both systems require high management skills, and accurate monitoring of soil water content is recommended. Drip and other forms of micro-irrigation facilitate the application of RDI and PRD.

There is increasing global demand for high-quality wine and declining demand for wines of lower quality and lower value. Therfore, the challenge facing winegrowers is to improve winegrape quality.

In many regions, in particular in New World vineyards, irrigation is an integral feature of winegrape production. Traditionally, winegrowers have used irrigation maximizes productivity, as is reflected in recommended crop coefficients (FAO, 1977; FAO, 1998). Such coefficients help predict peak water requirement, and therefore are useful in the design stage of vineyard development. However, use of these values will result in water application rates in excess of those that may be optimal for the most appropriate balance between vegetative and reproductive development required for the production of premium quality grapes.

The key to improving winegrape quality in irrigated vineyards is to achieve an appropriate balance between vegetative and reproductive development, as an excess of shoot vigour may

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have undesirable consequences for fruit composition. Water stress has a major influence on shoot growth, and, in general, vegetative growth is more sensitive to water stress than is berry (fruit) growth. For some winegrape varieties, control of berry size is of importance. However, rrigation is not the only vineyard practice contributing to an inappropriate balance between vegetative and reproductive growth. Others include the use of rootstocks that impart high shoot vigour, improved plant nutrition and soil management, and the tendency to grow vines in cooler regions, which may favour vegetative growth at the expense of fruit growth. However, in many localities, the key to achieving the correct balance is irrigation management.

In recent years, the two main approaches for developing practical solutions to manipulate grapevine vegetative and reproductive growth have been: regulated deficit irrigation (RDI) and partial rootzone drying (PRD). However, these developments have been possible only as a consequence of better understanding of physiological responses to water deficit and the widespread use of drip and other forms of micro-irrigation that enable the precise control of water application rate and timing. RDI and PRD have become established water management techniques, both in New and in some Old World regions.

Regulated deficit irrigation

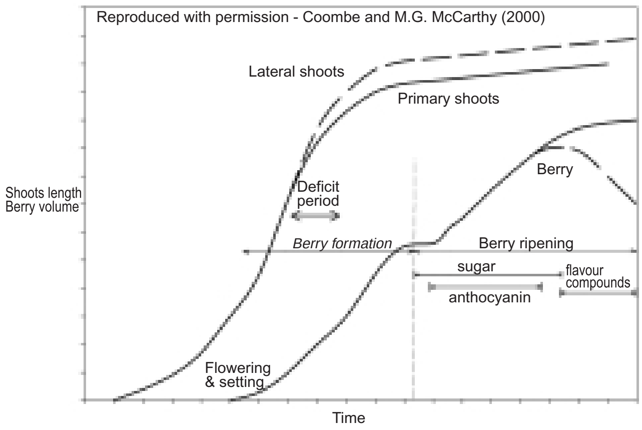
RDI uses water stress to control vegetative and reproductive growth. It was initially applied in peach and pear orchards to control growth by imposing water stress at key stages of fruit development. In an experiment on pear trees (Mitchell *et al.*, 1989), irrigation application was reduced from 93 percent of the water evaporated from free water surface equivalent to the tree planting square to either 23 or 46 percent for a period of 19 d between November and December (southern hemisphere). After rapid fruit growth commenced, irrigation amount was returned to 120 percent. Compared with non-RDI trees, fruit growth was stimulated and vegetative growth reduced. The effectiveness of the RDI treatments was greater at higher tree density with the associated increased root competition.

In grapevines, reduced irrigation prior to veraison caused a greater reduction in berry size than did less irrigation after veraison, compared with control vines (Matthews *et al.*, 1987). Wine made from fruit of continually drip-irrigated vines was unlike wine from early- or late-season deficit treatments, and distinctions were evident between 'early-deficit' and 'late-deficit' wines in appearance, flavour, taste and aroma (Matthews *et al.*, 1990). Tasters of these wines indicated that 'late-deficit' wines had a greater intensity of blackcurrant aroma compared with 'fully irrigated' counterparts. The concentrations of anthocyanins and phenolics were higher in 'deficit' wines although levels of residual sugar, titratable acid, pH and ethanol were similar to 'fully irrigated' wines. The volume of water applied weekly to the least stressed treatment was about 50 percent of ET_o for the site, and the most stressed vines received about 11 percent of ET_o (Matthews and Anderson 1988).

In an experiment on winegrapes, Goodwin and Macrae (1990) reported that reduced irrigation during defined periods of berry growth after veraison reduced berry fresh and dry weights and sugar concentration. However, control vines in the experiment were not irrigated at full crop replacement and, consequently, in comparison to the initial work with RDI on stone and pome fruit, were deficit irrigated for the whole of the experiment. The question arises as to whether this practice is actually RDI. Less than full ET_o replacement is often practised for the entire growing season in vineyards where water supply may be limited or in cooler districts where cropping level needs to be controlled to ensure adequate ripeness levels. In such situations, irrigation practice should perhaps more correctly, and simply, be termed 'deficit irrigation.'

To compare the effects of water stress during berry developmental stages with well-irrigated vines, a large long-term field experiment was established on mature vines near Waikerie in the South Australian Riverland in the Murray-Darling Basin. Water stress treatments were imposed by withholding irrigation during four periods of berry development after flowering of *Vitis vinifera* cv. Shiraz. Control vines were irrigated such that water stress was minimized by regular monitoring of soil water content throughout the growing season and the use of a modern irrigation system that supplied water on demand (McCarthy 1997a, b, 1999, 2000). Coombe and McCarthy (2000) integrated these and previous findings into the figure reproduced here (Figure 1), with the addition of lines representing vegetative growth and the suggested period of water deficit. These findings were:

FIGURE 1
Idealized curves of vegetative and reproductive growth of *Vitis vinifera*



Note: dashed berry growth line represents weight loss period in Shiraz berries

- Berry growth was most sensitive to water stress during pericarp cell division.
- Higher levels of water stress were needed to reduce berry size compared with vegetative growth.
- A reduction in berry size and, hence cropping level, resulted in earlier fruit maturity.
- Smaller berries resulted in higher anthocyanin concentration.
- Water stress during the early stages of berry ripening may enhance anthocyanin concentration.
- Water stress during the ripening period (post veraison) reduced solute accumulation in berries.
- Accumulation of flavour compounds occurred relatively late in the ripening process and was sensitive to water stress.
- With modern irrigation systems, it was possible to manipulate soil water availability to the degree necessary to influence vegetative and reproductive growth precisely.

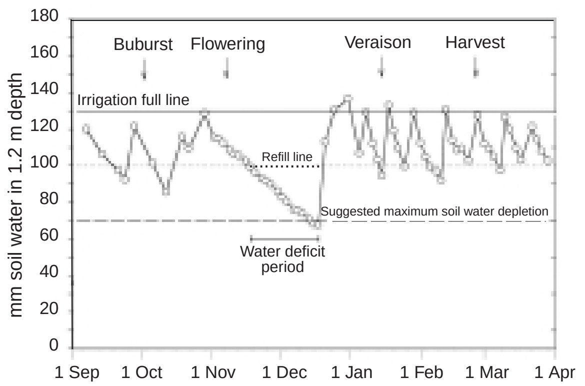
Practical application

Many Australian winegrape vineyards normally use soil water monitoring to assist in the implementation of RDI. A variety of proven instrumentation is available. Where soil water content is measured with a neutron probe, for example, the available rootzone soil water content is kept below the irrigation refill line during the period of water deficit. The total available water in the rootzone should not decline by an amount greater than the difference between the full and refill lines (Figure 2). In practice, this may necessitate a light irrigation to prevent excessive water deficit. To control vegetative and reproductive growth, water stress should be limited to the period after fruit set in winegrape vineyards. This strategy is more applicable for red-wine varieties rather than white for which control of berry size and canopy size is considered less important. Monitoring shoot extension or comparing the rate of increase in berry weight with non-stressed vines can assess the effectiveness of the water deficit.

In practice, reduced irrigation application during the post-set period may not achieve the desired outcome. The site may be unresponsive to irrigation due to factors such as:

- the presence of perched or regional water tables,
- deep soil with high water-holding capacity from winter rainfall,
- weather conditions such as rain and/or low temperatures resulting in low evaporative demand,
- inadequate knowledge of changes in soil water content during periods of reduced irrigation, due to lack of reliable soil water monitoring.

FIGURE 2
Use of a neutron probe to monitor changes in soil water content



There are various approaches for making sites with high water-holding capacity from winter rainfall responsive to post-set deficit:

- use of deep-rooted, spring-active cover crops to remove soil water,
- mounding soil along vine rows to increase evaporation from the soil,
- root pruning to reduce water uptake,
- high plant density,
- minimal pruning to increase crop water use early in the growing season as a result of an earlier canopy development.

The use of irrigation water containing moderate to high levels of salt (sodium chloride) may necessitate monitoring soil salinity during periods of reduced irrigation, and potentially the application of a leaching irrigation at the end of the period of reduced application. Other factors that may limit the successful adoption of water deficit during the post crop-set period are:

- inability to re-schedule irrigation and application quantities,
- excessive variability in soil water-holding characteristics within each irrigation shift,
- poor distribution uniformity of the irrigation system,
- excessively high soil water availability from furrow and flood irrigation systems,
- general management skills; a more-than-basic understanding of vegetative and berry growth is required in relation to the effects of water abundance or deficit during each stage of vegetative and fruit growth, for example the effect of excessive water stress on floral initiation.

Conclusions — RDI

In Australia, numerous vineyards have adopted the concept of applying water stress immediately after fruit set to control vegetative growth, and, in particular for the variety Shiraz, to control berry size. In many instances this practice has resulted in significant improvement in red-wine quality, albeit sometimes at the expense of yield. In addition, experimental work has demonstrated that, contrary to the existing practice in many vineyards, controlled irrigation is recommended to avoid water stress during the fruit ripening period (post veraison). Minimizing water stress, whilst controlling vegetative growth, has resulted in more rapid ripening and a changed wine flavour profile. The continuance of controlled levels of irrigation during berry ripening is more necessary in drip-irrigated vineyards, where, as a result of drying of deeper soil layers and a reduced wetted soil volume compared with furrow irrigation, drought stress can rapidly develop during periods of high evaporative demand. This is particularly relevant in parts of Australia, United States of America, South America and South Africa, where the ripening period occurs under warm and dry conditions. Maintenance of higher levels of soil water content prior to, and after, harvest is now considered beneficial to post-harvest root growth and ensures vines do not enter dormancy under water stress, a condition that results in susceptibility to damage from cold weather. As a consequence, winegrape growers are now encouraged to use the term 'strategic irrigation management' rather than RDI.

Partial rootzone drying

PRD uses biochemical responses of plants to water stress to achieve a balance between vegetative and reproductive development. By doing so, it achieves a secondary goal of significant improvement in production per unit of irrigation water applied. It has been a consistent feature of all trials that, even though the irrigation amount was halved, there was no significant reduction in yield due to PRD treatment. This contrasts with RDI experiments, where savings in irrigation application have often been at the expense of yield.

Research into the physiological changes that occur during water stress has led to improved understanding of plant response to stress in terms of chemical signals passing from roots to leaves. The vine's first line of defence when faced with water shortage is to close its stomata to conserve moisture. One of the principal compounds that elicits this response is abscisic acid. As soil water availability falls following the cessation of irrigation, this acid is synthesized in the drying roots and transported to the leaves in the transpiration stream (Loveys *et al.,* 1999). Stomata respond by reducing aperture, thereby restricting water loss. Improvement in WUE results from partial stomatal closure. However, an inevitable consequence is reduced photosynthesis, as carbon dioxide and water vapour share the stomatal pathway through the leaf surface.

The challenge was to devise ways of controlling the amount of water available to grapevines, to maximize the production of root-derived chemical signals that reduce canopy transpiration, and, therefore, improve WUE. A methodology was developed to permit drying of part of the root system while keeping the remainder well watered. However, early attempts with grapevines were confounded by the transient nature of the response to drying part of the root system. By simply switching the wet and dry sectors of the rootzone on a regular basis, this transient response was overcome (Dry *et al.,* 1996; Dry and Loveys, 1998).

A number of long-term, large-scale field experiments on Shiraz, Cabernet sauvignon, and Riesling, using a range of irrigation methods, have now been completed (Loveys *et al*., 1997, 1998, 1999; Dry *et al.,* 2000). These included standard drip emitters (2 or 4 litres/h), two per vine in the inter-vine space and placed about 450 mm from the vine trunk (Figure 3) and subsurface drip lines, one on each side of the vine row at a depth of 200-250 mm and 350-400 mm from the centre of the row. In all cases, the intention was to create two wetted zones per vine that could be alternately irrigated on a cycle of approximately two weeks, i.e., while one zone was wetted, the other zone would be dried. Soil moisture sensors installed within each wetted zone assessed whether water applied to one side infiltrated to the other, supposedly dry, side. In all cases, there was satisfactory separation of wet and dry zones in a range of soil types under field conditions. Partial rootzone drying with furrow/flood irrigation has been successful in experiments with pears and citrus and in commercial vineyards in the Riverina district of New South Wales, Australia (Clancy, 1999), and with other perennial row-crop fruits.

In vines subject to PRD, there were reductions in vegetative growth as measured by pruning weight (Table 1). Much of the reduction in canopy biomass was due to reduced leaf area associated with lateral shoots. Total leaf area of PRD vines was significantly ($P<0.05$) less, largely the result of reduction in the area of leaves on lateral shoots (Figure 4). In another trial, minimally pruned Riesling vines were subjected to PRD and in July (southern hemisphere) the canes from three control panels (fully irrigated) and three PRD panels were removed and allocated to three length categories. Only the current season's growth was removed. The PRD treatment resulted in a significant reduction in the weight of canes in the >500-mm-size category and in the total pruning weight. Another measure of canopy density is the amount of light reaching the bunch zone and this figure was consistently higher in PRD than in control vines.

FIGURE 3
Partial rootzone drying using two above-ground drip lines in a vineyard

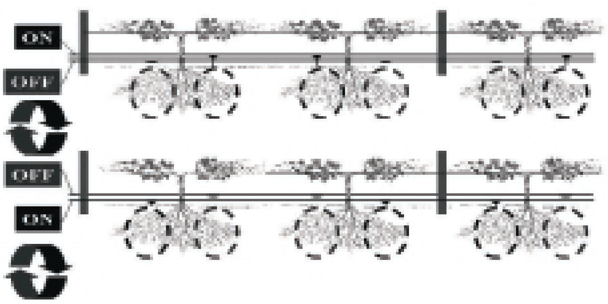
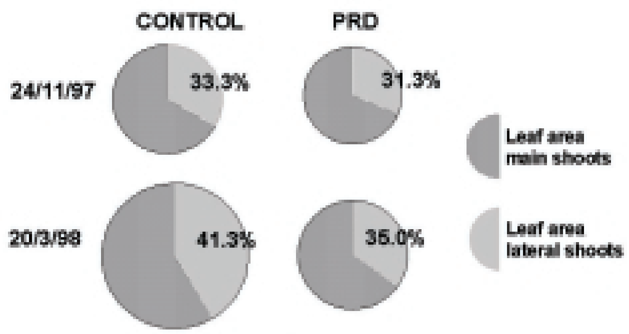


TABLE 1
Effect of PRD on pruning weight of vines, percent of control

Cabernet sauvignon – mean of four seasons	77
Minimally pruned Riesling (total all lengths)	60**
canes >500 mm	47**
canes 250–500 mm	82^{ns}
canes <250 mm	103^{ns}

**Significantly different from control, $P<0.01$
^{ns}Not significant

FIGURE 4
Main and lateral leaf area of control and PRD vines, post flowering and near harvest



A consistent feature of all trials was that there was no significant reduction in yield due to PRD treatment, even though irrigation amount was halved. As a result, yield per unit of water applied doubled in response to PRD (Table 2). Moreover, there was no effect on berry size in response to a halving of irrigation amount whereas there is usually a significant decrease in berry size in response to a substantial reduction in the amount of irrigation applied (Smart and Coombe, 1983; Williams and Matthews, 1990), particularly with deficit imposed between flowering and veraison (McCarthy, 1997a).

The results of PRD on fruit composition in respect to wine-making attributes indicate that quality is at least maintained if not improved. Some experiments revealed no apparent effect on

TABLE 2
Yield and water use of winegrapes

Variety/Location/Season	Variable	Control	PRD
Shiraz, Adelaide, 1997–98	Yield (t/ha)	22.6	21.5
	Water applied (Ml/ha)	1.4	0.7
	Yield/Ml irrigation	16.1	30.7
Cabernet sauvignon, Adelaide, 1997–98	Yield (t/ha)	15.2	15.4
	Water applied (Ml/ha)	1.4	0.7
	Yield/Ml irrigation	10.9	22.0
Riesling, Waikerie, 1996–97	Yield (t/ha)	29.1	28.9
	Water applied (Ml/ha)	4.5	2.4
	Yield/Ml irrigation	6.4	11.9
Riesling, Waikerie, 1997–98	Yield (t/ha)	30.6	28.7
	Water applied (Ml/ha)	5.2	2.6
	Yield/Ml irrigation	5.9	10.9

fruit quality as indicated by concentrations of anthocyanins and phenolics in fruit. In these cases, the control vines were well balanced with relatively open canopies: PRD did not substantially alter the canopy microclimate. In earlier experiments, the PRD treatment qualitative changes in the anthocyanin pigments of Cabernet sauvignon. For several seasons and at two sites, the concentration of the derivatives of delphinidin, cyanidin and petunidin in berries from PRD vines increased relatively more than the derivatives of malvidin and peonidin. Furthermore, PRD enhanced the formation of the coumarate forms of anthocyanins. This may be a response to bunch exposure, because shading of Shiraz bunches in a hot climate was found to enhance the proportion of coumarate forms.

Commercial trials have shown that if PRD is applied properly, there should be no significant yield reduction, although irrigation amount may be halved. A critical irrigation management practice with PRD is to ensure adequate rewetting of the dry side. Failure to ensure adequate replenishment of deep soil layers after switching sides may result in water stress, which may significantly reduce berry size during the early stages of berry development. Provided an overall favourable vine water status is maintained with PRD, berry size, and thus yield, will be maintained, despite reductions in water of up to 50 percent of conventional irrigation. A simple indication of whether the soil moisture status of the wet side was adequately maintained is the absence of reduction in berry weight. Similar to RDI, the responsiveness of the site to irrigation determines the successful application of PRD. Where the site is not responsive to irrigation, it is unlikely that part of the rootzone can be dried sufficiently during the initial stages of vegetative growth to control primary and lateral shoot extension. While savings in irrigation application may occur later in the season they may not be sufficient to economically justify the higher capital cost of installing PRD.

Conclusions — PRD

There has been much interest from New World viticultural industries in the PRD concept and its potential for influencing water use, vine vigour and grape quality. The implications for sustainable and profitable winegrape production are, well recognized. The successful adoption of PRD on a large scale has a number of consequences.

A reduction in consumption of water for irrigation is desirable from an economic viewpoint, although market forces will determine whether this ultimately translates to a reduction in district use or to the planting of additional vines or of other crops, to use the water saved. Further restrictions in water availability are probable and, in order to maintain productivity, irrigation practices and WUE will have to improve. Nevertheless, PRD does provide the vineyard manager with an additional management tool for tailoring crop quality to market needs.

The cost of implementing PRD varies depending on the irrigation system employed and whether it is applied to a new or existing vineyard. One of the most successful experiments in these projects utilized a pre-existing irrigation system consisting of two subsurface drip lines, one on each side of the row. In this case, the implementation cost was restricted to a few valves to allow switching water from one side to the other. At the other end of the cost scale, a development with the addition of a second drip line may cost about US$1 100/ha to install. Drip irrigation is in widespread use in vineyards throughout the world and, for example, in Australia a drip irrigation system may constitute half of the capital development cost. The additional outlay of installing PRD, is economical where the cost of irrigation water is high and as water becomes an increasingly valuable and scarce resource. The true environmental cost of irrigation water justifies the cost of implementing PRD.

The evaluation of PRD has progressed beyond the experimental stage with significant areas of PRD installed in vineyards in Australia, New Zealand, Spain, Israel, the United States, and South Africa. To date, most installations have involved a second drip line either above or below ground. Several irrigation-equipment manufacturers are working to eliminate the need to install two separate drip lines and to improve methods of installation and reduce root penetration in buried systems. Further research is underway in Australia to determine the optimum configuration for above- and below-ground installations, such as spacing of 'on' and 'off' drippers relative to vine spacing.

Table 3
Relevant factors in choosing RDI or PRD as a vineyard management system

RDI	PRD
Site must be responsive to irrigation	
Can be used with furrow irrigation	Drip irrigation preferred, alternate row furrow possible
Water must be available on demand	
Control of berry size	No effect on berry size
Vegetative growth control	Vegetative growth control
Potential for yield loss	No loss of yield
Positive effects on grape and wine quality	Possible improvement in grape and wine quality
Marginal water savings	Significant water savings
No irrigation hardware modification	Significant changes required. Can be retrofitted.
Soil water monitoring recommended	
High-level management skills required	

General conclusion

Table 3 summarizes the factors that determine the choice of RDI and/or PRD as an irrigation method in an individual vineyard.

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Regulated deficit irrigation as a water management strategy in *Vitis vinifera* production

Summary

An initial six-year study in a commercial vineyard located in the Columbia River Valley of Washington State, United States of America, examined the management practices and potential benefits of regulated deficit irrigation (RDI) on *Vitis vinifera* cv. Sauvignon blanc. The objective of the treatments was to evaluate the effect of deficit irrigation prior to, compared with after, veraison. Each of four irrigation treatments was applied to 1.6 ha and replicated four times for a total 27.0 ha. Irrigation treatments were based on desired soil moisture levels in the top metre of the profile where most of the root system is found. Soil moisture was monitored using a neutron probe and the information was combined with calculations of evaporative demand to determine the irrigation required on a weekly basis. Vine growth, yield, fruit quality and cold hardiness were monitored throughout the study. The results indicated that RDI prior to veraison was effective in controlling shoot growth, as determined by shoot length and elongation rate, as well as pruning weights. Sixteen wine lots, each of approximately 12 000 litres, were prepared each season. Although there was some effect on berry weight, yield was not always significantly reduced. Full irrigation prior to veraison resulted in excessive shoot growth. RDI applied after veraison to vines with large canopies resulted in greater water deficit stress. Fruit quality was increased by pre-veraison RDI compared to post-veraison RDI based on wines made. Regulated deficit irrigation applied at anytime resulted in better early-season lignification of canes and cold hardening of buds. There was a slight improvement in mid-winter cold hardiness of vines subjected to RDI. However, this effect was inconsistent. Studies on Cabernet Sauvignon and White Riesling are underway to confirm these results and to investigate the impact of RDI on fruit quality and winemaking practices.

The introduction of grapevines, especially *Vitis vinifera* cultivars, into new growing regions, has led to an increasing focus on irrigation to maintain or increase vine productivity and fruit quality. Irrigation and the developing strategies for using irrigation as a management tool in winegrape production have been ongoing for at least 20 years. Therefore, an understanding of plant water relations and soil water management is essential to use irrigation successfully to produce consistent yields of high-quality grapes. Effective irrigation management results in better control of plant growth and more efficient and economical crop production. A number of studies examining the effects of decreasing levels of irrigation on vine growth and physiology (Smart and Coombe, 1983; Mullins, *et al*., 1992; Williams and Matthews, 1990; Goldberg *et al.,* 1971) have found that drip irrigation resulted in improved WUE based on fruit production and pruning weights per unit of water applied.

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In 1972, Peacock *et al.* (1977) compared drip, sprinkler and flood irrigation, and found that drip used less water while achieving good vine vigour, fruit production and quality. However, there was evidence of salt accumulation in a smaller wetted rootzone compared to flood and sprinkler irrigation. In 1985, Bucks *et al*. (1985) reported similar results for the production of table grapes in Arizona. Finally, Araujo *et al.* (1995a, 1995b) found that similar crop production of Thompson Seedless could be achieved with either furrow or drip irrigation. However, they reported a reduction in the nitrogen content of drip irrigated fruit and they found a restricted rootzone associated with daily applications of drip irrigation. This led them to propose the use of drip irrigation to control vine vigour by restricting nitrogen uptake and restricting root volume.

In a study examining the potential benefit of using drip irrigation on Concord vines trained to various trellis systems, Cline *et al.* (1985) found that during dry years in New York, United States of America, drip irrigation improved yields, especially on higher density plantings and with trellis-training systems with higher cropping potential. They found drip to be more compatible than sprinkler irrigation on heavier clay soils with lower infiltration rates. Neja *et al.* (1977) found that timing of irrigation when combined with variations in trellis type resulted in differences in yield and quality of Cabernet Sauvignon grown in the Salinas Valley, California, United States of America. However, their results showed a higher yield with an intermediate level of irrigation when combined with a more elaborate trellis system.

Bravdo and Hepner (1987) showed that drip irrigation was an effective way to apply fertilizer to grapevines with the potential for influencing fruit and must composition. They found a significant response to phosphorus applied through the irrigation system, with higher yields, higher cluster numbers, improved wine sensory characteristics, wine colour and monoterpene levels in the must. They suggested that restriction of the rootzone by irrigation management could be used to control grapevine vigour. Irrigation systems have also had limited success for the application of herbicides (Fourie, 1988).

Irrigation management as a tool for use in the production of grapes has continued to receive attention in many regions of the world. In Australia, the use of regulated deficit irrigation (RDI) has been explored to control vegetative growth and improve the consistency of fruit production and quality (Goodwin and Jerie, 1992). In Spain, Nadal and Arola (1995) reported increased yield, malic and total acidity, and earlier ripening of irrigated Cabernet Sauvignon.

There is a growing need and desire to understand the effects of irrigation (water management) on grapevine growth, development, productivity, and fruit quality. The continued expansion of agriculture, including grape production, into low-rainfall regions compels a response to these issues. Furthermore, increased competition for this increasingly scarce resource will impose greater efficiency in irrigation management practices.

When considering using irrigation management as a tool, it is essential to establish a clear set of goals and to determine where water management may have an impact on them. Possible goals may include controlling vine vigour, preventing occasional water deficit stress, attempting to manage fruit development (berry size), or attempting to alter fruit quality by influencing soluble solids, pH, or titratable acidity. Careful selection of the most appropriate irrigation system for the vineyard site is also a high priority. The irrigation system must match soil type, depth, water holding capacity, infiltration rate, and the effective rooting zone of the vines. This latter point may require detailed knowledge of the cultivar or the rootstock in question. The amount of water available and its cost also demand careful consideration. Vineyards planted on hillsides or rolling terrain are not amenable to furrow or flood irrigation practices. Soils with low infiltration rates and significant slope also present runoff problems for overhead sprinkler systems with high delivery rates. Drip irrigation can accommodate all of these situations, but has higher initial capital investment costs and generally requires a higher level of management. Additional factors that warrant consideration are water quality, filtration requirements, system automation, and local availability of equipment, supplies, and support. Because of the number of variables involved, growers should contact companies dealing in irrigation design and equipment for recommendations tailored to the vineyard site.

Deciding when and how much to irrigate requires a thorough understanding of the factors that contribute to vine water status and the effects of various water management strategies on grapevine development and productivity. Grapevine water stress develops when the supply of water from the soil through the root system to the growing shoots is less than the evaporative demand. The cause for this imbalance may be: low available soil moisture; a poorly developed, injured, or otherwise restricted root system; unbalanced development of shoot and root systems; and/or high evaporative demand conditions. Salts in the irrigation water or in the soil can also reduce the water available to vines. Extensive trellis systems may contribute to leaf exposure and consequently a higher rate of transpiration than can be supplied by the roots. This latter type of stress is more likely to be transient in nature and less of a concern when adequate soil moisture is available.

The following are some observations and comments regarding the response of grapevines to water stress/management. Some of these statements are supported by research, whereas others are observations that appear to be consistent over several production regions.

Grapevines, especially *Vitis vinifera*, do not generally exhibit immediate signs of water stress, but will show symptoms of repeated stress by cumulative effects on shoot or fruit development. Williams *et al*. (1994) reviewed the effects of water stress and other environmental factors on grapevines. Depending upon the phenological stage at which it occurs, water stress has a wide range of effects on grapevine growth, development and physiology.

Water stress occurs infrequently during bud break and early shoot development due to low water use. However, water stress during this time may result in uneven bud break and stunted shoot growth. More severe and prolonged water stress may result in poor flower-cluster development and reduced pistil and pollen viability and subsequent berry set (Hardie and Considine, 1976). Nutritional deficiencies, especially in N, Mg and Ca, might also become evident under severe water stress (Falcetti *et al*., 1995). Most of the nutrients required by grapevines early in the season are derived from stored sources, thus reducing the likelihood of early-season deficiency symptoms. Early-season deficiencies in Zn and or B are often the result of water stress the previous season, causing reduced root growth and nutrient uptake (Christensen, 1962).

Following berry set, severe water stress may cause flower abortion and cluster abscission, possibly associated with hormone changes (During, 1986). Uncorrected water stress during this stage of development may result in reduced canopy development and, consequently, insufficient leaf area to adequately support fruit development and maturation. Because initiation of clusters at nodes 1-4 for the following season begins about two weeks prior to full bloom and continues for about two weeks, water stress during this stage may reduce the following season's crop potential. The predominant effect at that stage is believed to be a reduction in the number of clusters per shoot and not the number of flowers per cluster, which develop later in the season and throughout the dormant season as conditions permit.

Immediately after fruit set, water stress may restrict berry cell division and enlargement, resulting in smaller fruit and lower yield. The lag phase of berry development, which follows early berry development, is less susceptible to water stress. However, shoot development, which normally continues during this stage of development, would be reduced by water stress. Insufficient canopy development during this time will limit the photosynthetic capacity of the vine and may restrict fruit development and quality. Aside from reduced yield potential and fruit soluble-solids accumulation, the fruit may have higher pH, decreased acidity, and reduced colour development in red varieties. Problems associated with fruit sunburn are also more likely.

Rapid senescence of lower leaves, leaf abscission, and progressive loss of canopy, are consequences of water stress that may occur at any stage of development, but are more likely where a larger canopy is present. Sunburn of both red and white varieties can be a consequence of sudden fruit exposure caused by senescence of lower leaves and sudden loss of canopy and reduced canopy cooling caused by low evapotranspiration. Slow development of stress is associated with a loss of acidity and a rise in pH and soluble solids. More rapid onset of stress causes these processes to be arrested as fruit dehydration and raisining occur. Late-season water stress contributes to acclimation of one-year-old wood that begins from the base towards the tip of the cane. High levels of stress will result in abscission of shoot tips, which, if followed by over-irrigation, may stimulate lateral shoot growth. Such growth creates a competitive sink for photosynthates and delays fruit maturation. Late-season irrigation, following water stress, can also reduce cane and vine acclimation increasing the potential for low-temperature injury. Such vines are unlikely to have adequate viable buds the following season. Were exposed to extremely low temperatures, they often show reduced survival of buds, trunks and cordons.

The most detrimental effect of water stress following harvest is the potential for reduced root growth, resulting in decreased nutrient uptake and micronutrient deficiencies the following spring. Low-temperature injury of roots is also a concern if the soil remains dry, thereby increasing the depth of frost during long periods of cold weather. This is more likely in areas with lighter soils and little or no precipitation prior to winter conditions. Root injury is often expressed the following spring as delayed and erratic bud break, and eventual collapse of the developing shoots.

Careful water management is recognized as a tool for achieving some control of grapevine growth and development. The adoption of such a management strategy involves moderate stress at specific stages of development to achieve specific results. The decision to use such an irrigation strategy requires well-defined goals including effects on yield, grape quality, canopy structure, and protection against winter injury. To achieve these goals in the face of variable weather conditions requires both a thorough understanding of the effects of water stress on grapevines at various phenological stages, and also a good understanding of soils and soil water management. This understanding must include knowledge of total and available water holding capacities of the soil and the potential, as well as actual, rooting depths. The role and water use characteristics of cover crops also require careful consideration. Where most of the available moisture during root development is from irrigation water, irrigation methodology and scheduling can influence the distribution of the roots, both vertically and horizontally. Vineyard managers should be familiar with the characteristics of the rootstocks they use.

It is possible to use established crop coefficients (Kc) and measurements or calculations of potential evapotranspiration to estimate water use by vines (ET_p). Grapevine crop coefficients have been developed in several different locations (Evans *et al*., 1993; Grimes and Williams, 1990; FAO, 1977) and reflect the development of leaf surface area and vine water demand as the growing season progresses. The Kc represents the fraction of the potential evapotranspiration used by the vines, and its value is typically less than one. Variability in vine development from year to year has resulted in referencing the values of Kc with accumulated growing-degree-days (GDD) rather than calendar dates. Crop coefficients are low early in the season due to small leaf area and hence low water use, and approach unity as the canopy reaches maximum development in July and August in northern climates (January and February in the southern hemisphere). The calculation of daily water use (DWU) uses the published Kc for the appropriate accumulated GDD multiplied by the ET_p, a value based on the water use of a well watered, mowed, grass-covered area:

$$DWU = ET_p \times Kc$$

The availability and use of computers make these calculations and record keeping easy, and facilitate improved water management. The calculations must also account for any rainfall that occurs during the irrigation cycle. It is important to recognize that not all rainfall reaches the vine's rootzone, and may, therefore, be considered as effective rainfall.

On a worldwide basis, the estimated range for total water use for wine-, table- and raisin-grape production, with or without irrigation, might vary from 10 to 31 ha-cm/year. Recognizing that grapevine water use increases through the season to a peak shortly after veraison, it is possible to further estimate the fractional water use during the major phenological stages (Table 1).

TABLE 1
Water use by stage of development

Stage of development	Fraction of annual water use
Bud break to flowering	<5%
Flowering to fruit set	15%
Fruit set to veraison	60%
Veraison to harvest	20%
Harvest to leaf fall	3-5%

Using these estimates in conjunction with the annual precipitation for a given geographical location provides a sound basis for determining when and how much irrigation may be necessary in that area. It is also necessary to consider the suitability of the precipitation pattern for grape production.

MATERIALS AND METHODS

The study took place in the period 1992 - 1997, with the objective of evaluating the potential of using irrigation management to control wine grape vegetative growth and development, while maintaining yield and potentially improving fruit quality. The general approach to achieving these goals was to utilize the inherent growth characteristics and physiology of *Vitis vinifera* in combination with various irrigation schedules.

The vineyard site is in the rain shadow of mountains, and consequently receives about 20-25 cm of precipitation per year; the majority occurs between October and April. Rainfall during the growing season is considered to be ineffective as it occurs in small amounts and is frequently followed by high winds that increase evaporative demand. The number GDD (base 10°C) accumulated at the vineyard site averaged 1 600, with extremes of around 1 400 and 1 800.

The vineyard, 27 ha of Sauvignon blanc, is located at the Columbia Crest Estate Vineyard and Winery in south-central Washington, near Paterson, United States of America,. It was planted in 1979 with a 3.1x1.8 m spacing. Vines were trained to a bilateral cordon system, and spur pruned. The vineyard, originally irrigated using a centre-pivot system, was converted to drip irrigation in the mid-1980s. Drip irrigation lines consisted of pressure compensating 2-litre/h emitters at a 100-cm spacing.

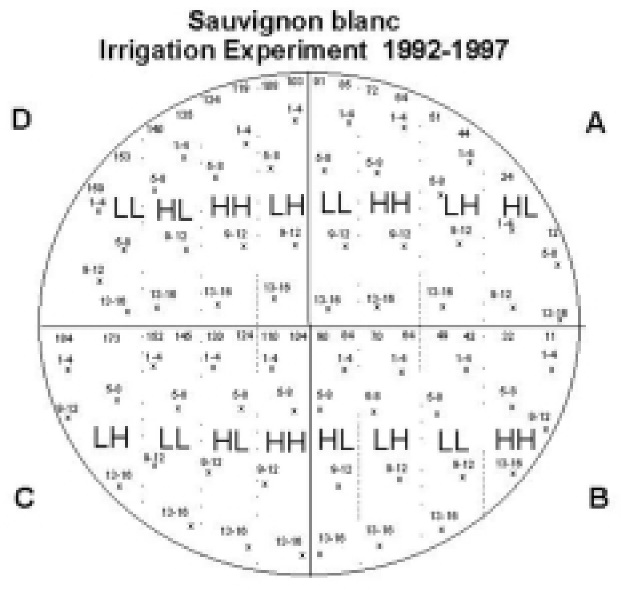
Irrigation strategies were applied from 1992. They involved high irrigation (H) defined as 5.6 cm of water and low irrigation (L) defined as 3.1 cm of water per 30 cm of soil in the top 1 m of the soil profile. The H treatment is near field capacity, while the L treatment is near the permanent wilting point for the Quincy soil type found on most of this vineyard. The strategies were:

- (HL) High irrigation applied early in the growing season followed by low irrigation from the point when control of canopy development was achieved in the early-season low-irrigation treatment. The high-irrigation treatment phase typically occurred from bud break to early or mid-July, which is similar to the standard irrigation practice for wine grapes in the State.
- (HH) High irrigation maintained throughout the growing season. This extreme treatment was applied primarily for comparative purposes. However, it was suspected that some growers were using this practice.
- (LL) Low irrigation applied throughout the growing season. This extreme treatment was applied primarily for comparative purposes.
- (LH) Low irrigation applied early in the growing season until control of canopy development was achieved, which typically occurred by early to mid-July, followed by high irrigation through harvest.

At the end of each season, all treatments were irrigated to bring the top 40-60 cm of soil to near field capacity. This provided winter protection for the root system and adequate moisture for early season growth the following year. It was anticipated that there would be sufficient precipitation during the dormant season to fill the soil profile to the 1-m level. Where adequate precipitations did not occur, additional irrigation was applied prior to, or during, budbreak, to fill the soil profile to a depth of one metre.

There were four replicates of each treatment of 1.6 ha each. Treatments were randomized within each 6.5-ha set of replicates (Figure 1). Each 1.6-ha replicate was irrigated independently and equipped with a flow meter. Sixteen neutron-probe sites within each replicate (128 in total) provided weekly readings during the growing season. At each of the neutron-probe sites, four vines were selected for collection of data on growth and yield, i.e. a total of 512 data vines. Vines were spur pruned, leaving 36-40 buds per vine for all treatments. Pruning weights were taken from designated plot vines and randomly selected vines within each treatment-replicate.

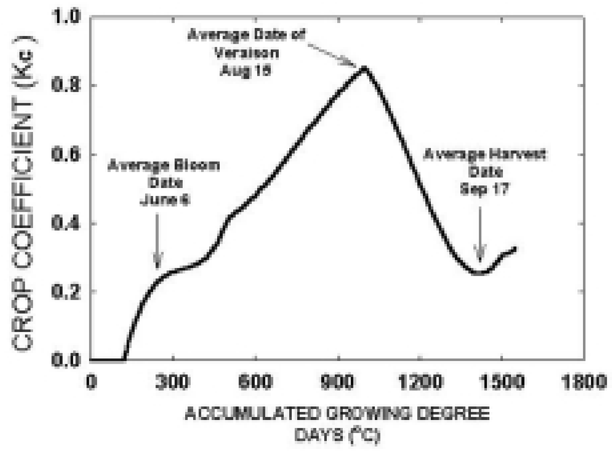
FIGURE 1
Experimental plot design of the Clore vineyard irrigation experiment



RESULTS AND DISCUSSION

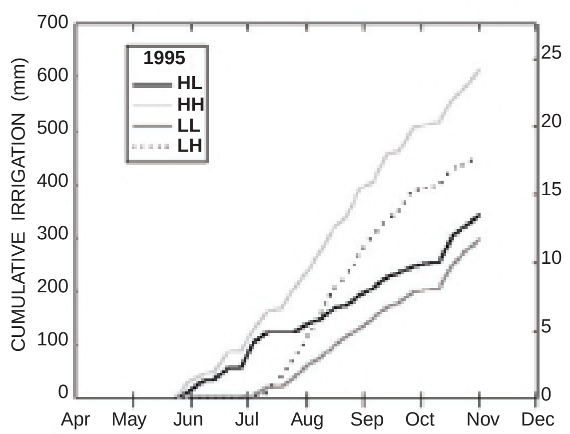
Over the six years of the study, soil moisture measurements taken during the third week of April indicated no differences among treatments in the top 1 m of the soil. Hence, there was uniform soil moisture for early-season growth, and a uniform starting point for irrigation planning. Irrigation schedules were determined using a combination of established Kc for winegrapes in Washington,United States of America (Figure 2) and (ET_p). The product of these values estimated the actual evapotranspiration ET_a. The ET_a and measured soil moisture were used to determine the hours of irrigation to achieve the desired soil moisture. The average cumulative irrigation over six years for the HH vines was about 50 ha-cm. The average for the LH vines was about 40 ha-cm, while the LL vines received about 30 ha-cm and the HL vines about 36 ha-cm. The HL vines received only about 2.5-5.1 ha-cm more than the LL vines because of low irrigation requirements early in the season (the Kc and ET_p values are lower during April - June than in July and August). Although the HH vines received 50 ha-cm of water, this was still considerably less than the 76-90 ha-cm typically used previously in the Yakima Valley. The data provided in Figure 3 are indicative of the amounts of water applied annually to each of these treatments.

FIGURE 2
Crop coefficient for determining irrigation requirements



Modified from Evans *et al.*1993

FIGURE 3
Cumulative irrigation applied to the four treatments in 1995

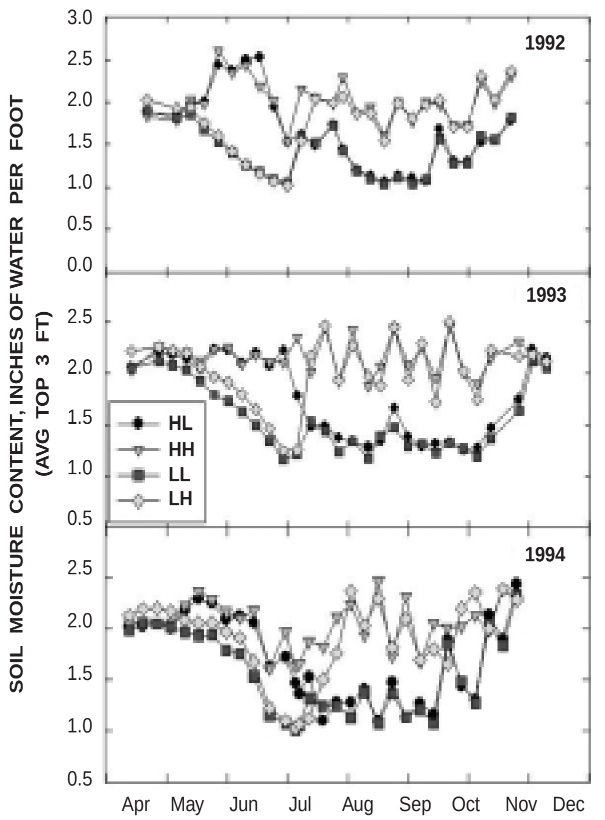


Irrigation maintained the HH and HL soils near 5.6 cm of water per 33 cm of soil until the first week of July, whereas the moisture in the LL and LH soils declined to 3.0 cm of water per 33 cm of soil in the top 1 m of the soil profile as determined by neutron-probe measurement. Irrigation, based on weekly consumption, was applied to maintain this level of soil moisture. Once shoot growth decreased in the LL and LH vines, the transitions in irrigation treatments were made, generally during the first or second week of July (Figure 4).

Measurements of shoot length and node number were taken from data vines located near the neutron-probe sites. Individual shoots were selected on each cordon and marked for repeated measurements taken on a weekly basis. Shoot length of current-season growth was measured from the junction with 1-year-old wood to the shoot tip. Node number included all nodes from the base of the shoot to the last discernable node at the tip of the cane.

Leaf area measurements, achieved non-destructively by measuring the widest part of the leaf, were regressed against measured leaf area each season as determined with a LiCor leaf area meter. Repeated measurements taken weekly from the same shoots and leaves provided an indication of dynamic vine growth and development.

Figure 4
Soil moisture profiles determined by neutron-probe analysis 1992-94



Fruit and wine quality analyses were based on harvesting the fruit from the various irrigation treatments at 23 percent soluble solids. All replicates were sampled and data were kept separate for statistical purposes. Harvest was based on the average of all replicates for a treatment reaching 23 percent soluble solids. Harvests commenced at about 2100 hours, with completion by 0900 hours the next day. The fruit of each replicate was kept separate for yield and winemaking purposes, thus allowing statistical analysis of these large-scale plots. Fruit from each treatment-replicate was crushed and pressed separately and a 114-h/litre sample placed in separate fermentation tanks. Plot vines for any given treatment were hand-harvested before mechanical harvest. Cluster counts and weights were based on hand-harvested fruit. Post-harvest soluble solids measurements were based on samples taken from the fermentation tanks for each of the four replicates of each treatment.

Measurements of shoot length, node number and pruning weight all demonstrated the ability to control shoot growth by irrigation management. Plates 1 and 2 represent typical differences in canopy development between the HH and LL irrigation treatments.

Data indicate that, regardless of the previous year's irrigation, there was essentially no difference in shoot length from bud break until approximately 30 d after bloom. This was despite significant differences in weather conditions over the four years and the lower irrigation in the LL and LH treatments. This suggests several things. First, water was not a limiting factor early in the season. Second, because there were nearly 20 nodes present by the time differences in shoot growth developed, there was sufficient leaf area to mature the crop. Third, as even the HH irrigation treatment showed a change in shoot length around 30 d after bloom, fruit set and early cluster development reduced shoot growth. In general, the HL vines stopped initiating nodes shortly after the change in irrigation treatment, whereas there was an increase in shoot growth in the LH vines. Leaf area measurements also showed that the sizes of leaves up to about leaf-number 15 were similar regardless of irrigation treatment. This further supports the suggestion that early-season soil moisture was not limiting and that there was little difference in the water status of the irrigation treatments until late June or early July. Leaf area development was more sensitive to soil moisture depletion with differences occurring 10-14 d prior to differences in shoot elongation. Thus, changes in leaf area enlargement can serve as an early indicator of

Plate 1
Canopy characteristics of the high irrigation (HH) treatment, August 1996

Plate 2
Canopy characteristics of the continuously low (LL) treatment, August 1996

soil moisture depletion and, if carefully monitored, may be of use in scheduling irrigation. By mid- to late August, there was interior leaf senescence and defoliation in the HL treatment associated with water stress. However, in the LL vines there was less leaf senescence, indicating physiological adjustments resulting in increased WUE. From late July until the end of the season, following the change in irrigation, although there was no difference in soil moisture between the LH and HH treatments, the LH vines showed less stress as indicated by leaf and xylem water potential measurements. This is presumed to be the result of smaller canopy and physiological adjustments associated with the early-season low irrigation. Although the LL treatment often showed high levels of water stress, these vines showed less leaf senescence and loss than the HL vines.

The irrigation treatments had little effect on the number of clusters. The similarity in cluster number indicates that early-season low irrigation was not detrimental to the cluster initiation process.

During the first year of the study, which was very hot, the LL and LH vines averaged 1.5-2 t/ha less yield than the HH vines (Table 2).

Higher yields in the HH vines were due primarily to larger berries. Throughout the study, there tended to be more berries per cluster in the LL and LH treatments.

Table 2
Fruit yield for each of the four irrigation treatments

Treatment	1992	1993	1994	1995	1996
	(t/ha)				
HL	9.2^{B}*	14.6^{A}	9.2^{A}	12.0^{B}	12.1^{A}
HH	10.6^{A}	16.3^{A}	9.2^{A}	16.0^{A}	14.3^{A}
LL	6.5^{C}	14.5^{A}	7.8^{B}	11.5^{B}	13.3^{A}
LH	6.7^{C}	15.2^{A}	7.1^{B}	12.0^{B}	13.3^{A}

*Numbers in a column followed by the same letter are not significantly different

Fruit and wine-quality analyses were based on harvesting the fruit from the different irrigation treatments at the same soluble solids content. Post-harvest soluble solids measurements were based on samples taken from 114-hl tanks for each of the four replicates of each treatment. There were no differences among treatments in any of the five years of the study (Table 3). In 1995, the HH treatment was harvested at about 22 percent soluble solids, while the other treatments were all near 23 percent. Late-season high irrigation (HH and LH) tended to delay harvest and lower the soluble solids slightly, throughout the study. In 1993, the HH vines were harvested nearly a week after the LH vines which tended to be the first to reach 23 percent soluble solids. In cool, wet years like 1995, earlier harvest can be an advantage by avoiding fruit-rot problems.

The eitratable acidity of 1995 tank samples was significantly higher in the HH and LH must (1.0) than in the HL and LL must (0.7) (Table 4). Although this was due in part to the lower soluble solids for the HH treatment in 1995, this trend was seen in at least four of the five years. The lack of significant effects in 1992 was probably due to the high temperatures that prevailed throughout the season. Differences were generally accompanied by lower pH in the HH and LH musts than in the HL and LL musts (Table 5). Fruit and must analyses over the past five years have shown similar results. The lack of differences in soluble solids, while consistent differences occurred in pH and acidity, seems to indicate the effect of irrigation practices on these fruit, and potentially on wine characteristics.

TABLE 3
Influence of the four irrigation treatments on fruit soluble solids

Treatment	1992	1993	1994	1995	1996
	(% soluble solids)				
HL	22.6^{A}*	22.5^{A}	22.6^{A}	23.2^{A}	22.4^{A}
HH	22.3^{A}	22.2^{A}	22.3^{A}	21.9^{A}	22.1^{A}
LL	22.9^{A}	23.0^{A}	23.2^{A}	23.3^{A}	22.9^{A}
LH	23.4^{A}	23.1^{A}	21.8^{A}	22.8^{A}	23.8^{A}

*Numbers in a column followed by the same letter are not significantly different

TABLE 4
Influence of the four irrigation treatments on fruit titratable acidity

Treatment	1992	1993	1994	1995	1996
	(mg tartaric acid equivalents per 100 ml of juice)				
HL	0.73^{A}*	0.75^{BC}	0.60^{B}	0.68^{B}	0.76^{B}
HH	0.81^{A}	0.93^{A}	1.07^{A}	1.01^{A}	1.03^{A}
LL	0.74^{A}	0.67^{C}	0.59^{B}	0.70^{B}	0.67^{C}
LH	0.68^{A}	0.78^{B}	0.90^{A}	0.96^{A}	0.84^{B}

*Numbers in a column followed by the same letter are not significantly different

TABLE 5
Influence of the four irrigation treatments on fruit acidity (pH)

Treatment	1992	1993	1994	1995	1996
	(pH)				
HL	3.38^{A}*	3.28^{A}	3.40^{A}	3.41^{A}	3.17^{AB}
HH	3.31^{A}	3.11^{B}	3.27^{A}	3.16^{B}	3.10^{B}
LL	3.40^{A}	3.35^{A}	3.43^{A}	3.30^{A}	3.23^{A}
LH	3.41^{A}	3.28^{B}	3.29^{A}	3.20^{B}	3.13^{B}

*Numbers in a column followed by the same letter are not significantly different

Vine evaluation during early August typically showed that treatments involving reduced irrigation had more lignified nodes than did HH. This was consistent over the five years of the study, indicating better cold hardiness during late summer and early fall. Although not important in most years, it could be a significant advantage in a year with an exceptionally early killing frost. Evaluations of cold hardiness of buds, undertaken each year from October to March, indicated no differences as a function of irrigation treatment.

The information produced by this study demonstrates that, given the variety and location, it is possible to produce a satisfactory crop of winegrapes with between 30 and 50 ha-cm of water per year including a post-harvest irrigation to bring the soil to a moisture level that will protect the root system from cold injury.

Several points from this study are applicable to vineyard water management in general. First, the water requirements of grapevines change as the season progresses and, second, their responses to changes in water availability at different stages of development are an important consideration.

The decision to adopt the concept of irrigation as a management practice should be based on well-defined objectives and on a clear idea of how irrigation management will overcome any problems. Where the problem is vine water stress, and irrigation water is available, the question is one of economics associated with the installation of an appropriate irrigation system and the expected improvement in vine growth and productivity. Depending upon when and why the stress occurs, soil and site characteristics, and grape variety, the decision to irrigate and the choice of irrigation system will vary significantly.

Based on information derived from this study, the only vine-related expense of using regulated deficit irrigation as a management tool is a potential loss of yield if stress becomes excessive. Leaving more buds at pruning can compensate for this, although it would be preferable to improve water management. Other costs are those associated with establishing, maintaining and operating the irrigation system. These costs require careful evaluation based on the potential for more consistent, balanced vine growth and fruit production of higher quality that would result in higher net returns to the grower. In addition to direct improvements in fruit quality, additional benefits observed in this and other studies include improved control of disease and pests. This is associated with a more open canopy that is less susceptible to pathogens and insects. Such an open canopy also facilitates better coverage with chemical sprays. In red varieties, there are increases in phenolics and tannins that contribute to flavour and complexity of the wine. Some remaining concerns include the development of undesirable flavour compounds in some white varieties and possible reduction in vine productivity. Additional studies are underway in Washington, United States of America, and at other North American locations in order to address these problems.

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The scope for further irrigation development to meet food requirements in the coming years has been strongly diminished as a result of decreasing water resources and growing competition for clean water. The great challenge for the future will be the task of increasing food production with less water, particularly in countries with limited water and land resources. In the context of improving water productivity, there is a growing interest in “deficit irrigation” – an irrigation practice whereby water supply is reduced below maximum levels and mild stress is allowed with minimal effects on yield. This publication presents a range of studies, carried out for several crops and under different ecological conditions, showing the various options and practices of deficit irrigation and the impacts of reduced irrigation water supply on crop yield. The synthesis shows that deficit irrigation can result in substantial water savings with little impact on the quality and quantity of the harvested yield. However, to be successful, an intimate knowledge of crop behaviour is required, as crop response to water stress varies considerably.

ISBN 92-5-104768-5 ISSN 1020-1203

9 789251 047682

TC/M/Y3655E/1/5.02/1300