OPTIMIZATION OF IRRIGATION MANAGEMENT IN MANGO TREES BY DETERMINATION OF WATER AND CARBON DEMANDS TO IMPROVE WATER USE EFFICIENCY AND FRUIT QUALITY

by

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EXECUTIVE SUMMARY

Background

The production of agricultural crops and in particular subtropical fruits for the export market is a very important contributor to the South African economy. Production of these crops of high value is influenced by the amount of water the crops receive at certain growth stages. Due to the low and erratic rainfall, irrigation is widely practiced in South Africa. However, water resources in South Africa are scarce and the demand by agricultural, domestic, and industrial users is increasing continuously. Irrigation strategies are, therefore, changing and shifting towards increasing water use efficiencies instead of obtaining maximum yields accompanied by low water use efficiencies. In other words, the goal of modern agriculture is to use less water for irrigation without a decrease in fruit quality and yield and to conserve water.

The research objectives were:

- to manage irrigation for minimum water and nutrient losses in mango trees, simultaneously maintaining or even improving fruit quality and shelf life, by manipulating the water supply to trees,
- to determine vegetative and reproductive growth patterns critical for the application of regulated deficit irrigation treatments, and to expose trees to water deficits at specific growth periods to reduce excessive vegetative growth while not affecting fruit growth,
- to study photosynthesis and tree water relations, stem water potential and stomatal conductance, in response to different irrigation regimes in mango trees under field conditions over the season, and
- to adapt the PEACH growth model to mango trees.

An economical evaluation of the various irrigation strategies was not conducted, since this would require a separate study and was not part of our aims. Mango was chosen as an example for subtropical tree crops, since Hans Merensky Holdings provided the necessary field facilities.

The research was carried out in a commercial mango orchard (1 ha) of the Westfalia Estate Moriah (Hans Merensky Holdings) in Hoedspruit (latitude: 24ºS, longitude: 31°E), Limpopo Province, and in laboratories of the Department of Plant Production and Soil Science, University of Pretoria. Five to eight year old mango (*Mangifera indica* L. cv. 'Kent' trees grown on 'Sabre' rootstock) trees planted at a density of 1.5 x 6 m were used in the study. Cultural practices, such as pruning, fertilizing, and harvesting, were conducted as in commercial orchards. Fertilization was applied separately from irrigation applications.

Irrigation Water Use Efficiencies

During the first two years irrigation was conducted with a drip irrigation system, since it was used on the farm. The following irrigation treatments (drip irrigation system, 2 emitters, 4 L h^{-1} per tree) were implemented from November 1999 until February 2002 (Table 2.4):

Co: Control (82 ± 8 and 87 ± 11% of FC in 2000/2001 and 2001/2002, respectively)

DI-1: Continuous deficit irrigation (83 ± 6% of irrigation water applied to Co)

DI-2: Continuous deficit irrigation (64 ± 4% of irrigation water applied to Co)

RDI: Regulated deficit irrigation (like Co, except that irrigation water was withheld for 5 weeks in May/June 2000 and for 4 weeks in December 2000/January 2001, and reduced for 4 weeks to 1/3 of Co in May/June 2001 followed by 2 weeks of 1/2 of Co and 3 weeks of 1/3 of Co in January 2002)

Co-F: Farm control (one 8 L h^{-1} emitter per tree), full irrigation according to daily tensiometer readings at 30 and 60 cm depth, trees were irrigated once per day when soil moisture was lower than -5 KPa in 2000/2001, irrigation was reduced for 5 weeks in April/May 2001 reaching -20 KPa followed by full irrigation (about -7 KPa) until February 2002.

Trees of the treatments Co, DI-1, DI-2, and RDI, were irrigated in 3-5 applications each day, and the amounts were based on weekly soil moisture readings. The amount of water applied to each irrigation treatment was measured by hydrometers.

The soil profile in the control treatment (Co) was supposed to be filled up to field capacity (FC), however this goal was not completely achieved because of technical and field circumstances. Treatments DI-1 and DI-2 were implemented to evaluate the effect of continuous deficit irrigation on tree growth, physiology, yield, and fruit quality on a long-term basis. In the RDI treatment, positive and negative impacts of water deficits (either water withholding or reduction) during specific growth periods (before flowering and during the last fruit growth stage) were assessed with respect to the above mentioned tree parameters.

From June 2002 onwards, soil water measurements were taken on a daily basis in order to obtain more accurate water uptake data and amounts of water to be irrigated daily. From March until May 2002 Co and RDI were irrigated to about 76% ± 6% of FC, while DI-1 and DI-2 received 83 and 64%, respectively, of the amount of irrigation water applied to Co. From June until the middle of July the treatments Co, DI-1, DI-2, and RDI, were irrigated to 73 ± 6% of FC followed by 2 weeks of full irrigation (98 ± 6% of FC). The farm control was irrigated when tensiometer readings reached values of -10 KPa from March until the beginning of June 2002 and from then on until the third week in July 2002 when soil moisture was lower than about -20 KPa. In August the drip irrigation system was replaced by microjets (1 microjet between 2 trees), since the lateral distribution of water in the coarse textured soil under drip irrigation was too small to ensure an adequate water supply. The following irrigation treatments were applied from August 2002 until February 2003 (Table 2.4):

Co: Control (95 ± 3% of FC)

DI-1: Continuous deficit irrigation (when 30 mm was extracted the profile was filled up to 89 mm, ± 20 mm below FC, ± 79% of FC)

DI-2: Continuous deficit irrigation (when 40 mm was extracted the profile was filled up to 83 mm, ± 30 mm below FC, ± 69% of FC)

RDI: Regulated deficit irrigation (like Co, except that irrigation water was withheld for 2 weeks in December 2002/January 2003)

Co-F: Farm control, full irrigation according to daily tensiometer readings at 30 and 60 cm depth; trees were irrigated once per day when soil moisture was lower than -10 KPa

Table 2.4 Phenological cycle of 'Kent' mangoes and irrigation treatments during 2000-2003. Depending on season phenological stages can shift by ± 2-4 weeks (NI = no irrigation).

	Phenological Cycle											
	Vegetative Flush			Flower Development	Flowering and Fruit Set		Fruit Development					Harvest
	Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
IRRIGATION SCHEDULING												
2000-2001												
Co	82% of FC											
DI-1	83% of irrigation water applied to Co											
DI-2	64% of irrigation water applied to Co											
RDI	82% of FC		NI	82% of FC							NI	82% FC
Co-F	-5 KPa											
2001-2002												
Co	87% of FC											
DI-1	83% of irrigation water applied to Co											
DI-2	64% of irrigation water applied to Co											
RDI	87% of FC			1/3, 1/2 of Co	87% of FC						1/3 of Co	87% of FC
Co-F	-7 KPa	-20 KPa		-7 KPa								
2002-2003												
Co	76% of FC			73% of FC	FC	95% of FC						
DI-1	83% of Co			73% of FC	FC	79% of FC						
DI-2	64% of Co			73% of FC	FC	69% of FC						
RDI	76% of FC			73% of FC	FC	95% of FC					NI	95% FC
Co-F	-10 KPa			-20 KPa		-10 KPa						

Deficit irrigation represented a suitable irrigation method to save water and to simultaneously achieve acceptable yields, especially under conditions of water shortages. However, the implementation of deficit irrigation scheduling would require a regular monitoring of soil water content on a daily basis. The highest irrigation water use efficiency was found for treatment DI-2 where the maximum soil water content at any time was the lowest of all treatments. The RDI treatment, receiving the same irrigation practice as Co except for one or two periods during the season when irrigation water was reduced or withheld, provided storage space for eventual rainfall, particularly in summer, leading to a saving of irrigation water of 12-24% compared to the control. However, the period of water reduction before flowering in the RDI treatment could be further optimized by taking place slightly earlier (May) than in our studies in order to minimize or eliminate effects on flower development, flowering, fruit set, and consequently yield. The effect of the alternate bearing habit of mango trees observed during this research was in part responsible for the relatively low yields every other year. In addition, the trees were still relatively young, especially during the first two years, and their production is expected to increase further. Another season would smooth the effect of alternate bearing and probably accentuate the effects of the different treatments even more, especially water savings and irrigation water use efficiencies, in trees that are in full production.

The current irrigation practice by the farm clearly showed that the trees were over-irrigated as indicated by capacitance sensor readings and similar yields across all treatments during the 2000/2001 and 2002/2003 seasons, although the farm slightly reduced the amount of irrigation water applied by raising the threshold from -5 to -10 KPa. However, those reductions were not reflected in the yearly total amount of irrigation water applied, since the trees were coming into production and because of a fairly dry season during 2002/2003 in comparison to the first two seasons. Water and nutrient losses due to drainage as a result of over-irrigation on these coarse textured soils were very high primarily because of the use of drip emitters of high volume (8 L hr^{-1}) and only one long time application of irrigation water per day by the farm. Pulse irrigation (several applications of irrigation water per day) would be advisable when using a drip irrigation system to minimize water losses if technically feasible. The inefficient irrigation practice by the farm was further illustrated by generally low irrigation water use efficiencies over the years in comparison to the other treatments.

The drip system was replaced in August 2002 by a microjet system. Its effect on irrigation water, yield, and irrigation water use efficiencies will be more noticeable from the next growing season on. However, over-irrigation by the farm was drastically reduced as indicated by capacitance sensor readings. Considering the technical conditions/restrictions on the farm (electricity, labor, soil properties, etc.), the microjet system appeared to be better than the drip irrigation system. As a larger area is wetted by the microjet system compared to the drip system, it is expected that the root system will expand considerably and hence influence water requirements and yields. It would have been very interesting if the effects could have been monitored over a longer time period.

Physiological Tree Responses

Photosynthesis, stomatal conductance, and stem water potential were measured in response to the different irrigation regimes in mango trees under field conditions over the seasons of 2000-2003 to determine when and to what extent the trees were stressed. Stomatal conductance (g_s) and photosynthetic rates (Pn) of fully exposed leaves were measured on sunny days at midday using a porometer and an Infrared Gas Analyzer. Stem water potential was determined on covered leaves close to the main stem at midday using a pressure bomb. The potential to use stem water potential as indicator of tree water status in mango under various irrigation regimes and field conditions has not been evaluated yet.

Seasonal patterns of photosynthesis, stomatal conductance, and stem water potential, were described in 'Kent' mango trees under field conditions. Stem water potential in the farm control and in part in the Co and RDI treatments during the 2002/2003 season showed that stem water potential values for non-stressed mangoes fluctuated between -0.4 and -0.6 MPa over the season in a subtropical climate.

Stress responses to water deficits were detected after the trees were exposed to irrigation water reductions in May/June (pre-flowering stress) by stem water potential followed by stomatal conductance indicating that they were more sensitive stress indicators than photosynthesis. Since the trees needed 1-2 months to recover from severe water deficits during pre-flowering (May/June 2000) in the RDI treatment and reaching, therefore, in part into the growth phase of flower bud formation, it appeared to be advisable to reduce irrigation water application to some extent but not to completely withhold the water before flowering. Low photosynthetic rates and stomatal conductances as well as low stem water potentials during the months August-December 2002, appeared to be associated rather with environmental factors than with irrigation management. Over-irrigation (Co-F) or even optimum irrigation (Co) during 2002 did not improve photosynthesis at that time of the year, since the water uptake by the trees appeared to be limited by low stomatal conductance. The deficit irrigation treatment DI-2 followed by DI-1 displayed the lowest stem water potentials especially during the months August-November 2002 in contrast to the other treatments indicating that during this period of tree growth severe irrigation water reductions in addition to limiting environmental factors might affect tree productivity substantially.

Based on the physiological measurements, RDI and at some periods during the season DI-1 seemed to present possible irrigation scheduling practices that could be adopted by the growers. Furthermore, our studies showed that stem water potential can be used as a water status indicator in mango trees.

Vegetative and Fruit Growth, Yield, and Fruit Quality

The annual vegetative and reproductive development of trees is for the grower useful in the planning of management procedures like spraying, fertilization, and irrigation. Vegetative growth of mango and other tropical trees is not continuous but occurs as intermittent, short lasting flushes of terminal buds, before returning to a quiescent state. The effect of deficit irrigation on mango tree growth and crop production was evaluated to identify periods during the year to initiate water deficits that will reduce vegetative growth while not affecting fruit growth.

The irrigation treatments Co, DI-1, DI-2, and RDI did reduce vegetative growth in comparison to the farm control (Co-F) over the years. High increases in TCA, shoot number per tree, and light interception in Co-F apparently indicated that large amounts of irrigation water were used for vegetative growth leading to generally low irrigation water use efficiencies in Co-F over the years in comparison to the other treatments. Fruit yield was significantly reduced in DI-2 and RDI compared to the other treatments in 2002 but not in the other years. In comparison to the various irrigation strategies, high crop loads had a larger effect on fruit growth. However, it cannot be excluded that with increasing tree age and crop load fruit growth might be affected in addition by irrigation. During fruit development, differences in irrigation scheduling were not clearly reflected in concentrations of nonstructural carbohydrates, since differences between the various treatments were inconsistent.

Flesh color of mangoes is commonly used as maturity index to determine the optimum time for harvest by South African mango growers. Among the studied maturity indices (flesh color, firmness, total soluble solid concentration - TSS, titratable acid concentration - TA) TSS and TA provided the most sensitive ones to assess quality at harvest followed by firmness. A comparison between TSS concentration and flesh color showed no relationship between them at harvest suggesting that flesh color might not be the most suitable index for maturity determinations in mango and might need to be re-evaluated. Differences between irrigation treatments were detected only in fructose concentrations at harvest but disappeared as soon as the fruits ripened. Comparing concentrations of fructose, glucose, and sucrose, 6 days after the fruits were harvested (local) or taken out of the shipping simulation (export) showed that the ripening process took its course much faster in export compared to local fruits as indicated by the higher concentrations of nonstructural carbohydrates in export fruits. Although the study was conducted over three years conclusive suggestions about the effect of the various irrigation treatments on vegetative and fruit growth and quality can only be made after a longer time period because of seasonal differences in climate and the alternating growth habit of mangoes.

Adaptation of the PEACH Model to Mango

To facilitate integration of information about the carbon budget of mango trees, the PEACH model is being converted to a mango model. The results of the model will be used to examine factors that limit mango crop yield and to make recommendations to improve management of mango production. Conversion of the PEACH model to simulate mango growth required information on fruit and vegetative growth, tree biomass, photosynthetic capacity, respiration by all organs, and weather information. The PEACH model assumes optimal irrigation and fertilization and is not designed to simulate suboptimal and other environmental conditions directly. Data that had been collected in South Africa on mango photosynthesis, vegetative and fruit growth, and climatic data (temperature and solar radiation) were used in the model. Fruit and leaf respiration rates were obtained from data collected by A. González in Darwin, Australia. A ‘hybrid peach-mango’ growth model has been developed using mango parameters wherever possible and substituting peach parameters where mango parameters were not available.

The conversion of the PEACH model has produced a ‘hybrid peach-mango model’ that simulates fruit growth accurately and provides testable hypotheses regarding changes in reserve carbohydrate and vegetative growth. The mango model might provide useful information for scientists to enhance the understanding of growth and development of mango trees as an example for subtropical fruit trees as affected by environment and cultural management practices. It is anticipated that the information gained with the model will help to optimize cultural management practices, such as irrigation, pruning, etc. and to direct scientists in planning their research.

Conclusions and Recommendations for the Practice

Deficit irrigation represented a suitable irrigation method to save water and to simultaneously achieve acceptable yields, especially under conditions of water shortages. However, the implementation of deficit irrigation scheduling would require a regular monitoring of soil water content on a frequent basis. Since low rainfall during the season of 2002/2003 might indicate the beginning of a drought period, many of the results obtained in this study might be quite useful for the near future. During a drought period and consequent water shortages, farmers might have to consider to either irrigating with lower water applications (deficit irrigation) or not irrigating for periods of time. The worst possible scenario would be to take out of production part of their orchards resulting in a loss of highly valuable orchards. Deficit irrigation practices might offer an acceptable solution before loosing orchards under conditions of severe water shortages.

With respect to water savings and irrigation water use efficiencies RDI followed by DI-1 appeared to be the most advantageous irrigation treatments among the ones evaluated. RDI and at some periods during the season DI-1 seemed to represent possible irrigation scheduling practices that could be adopted by the growers. The RDI treatment, receiving the same irrigation practice as Co except for one or two periods during the season when irrigation water was reduced or withheld, provided storage space for eventual rainfall, particularly in summer, leading to a saving of irrigation water of 12-24% as compared to the control. The period of water reduction before flowering could be further optimized by taking place slightly earlier (May) than in our studies in order to minimize or eliminate effects on flower bud development, flowering, fruit set, and consequently yield.

The current irrigation practice by the farm clearly showed that the trees were over-irrigated. Water and nutrient losses due to drainage as a result of over-irrigation on these coarse textured soils were very high primarily because of the use of drip emitters of high volume (8 L hr^{-1}) and only one long time application of irrigation water per day by the farm. Pulse irrigation (several applications of irrigation water per day) if technically feasible and using 2 emitters of a lower volume than 8 L hr^{-1} would be advisable when using a drip irrigation system to minimize water losses. The replacement of the drip with the microjet system drastically reduced the over-irrigation by the farm. Considering the technical infrastructure and soil properties on the farm, microjet irrigation appeared to be the more appropriate system in comparison to drip irrigation.

Stem water potential can be used as a water status indicator in mango trees. Stem water potential values for non-stressed mangoes fluctuated between -0.4 and -0.6 MPa over the season in a subtropical climate. Stress responses to water deficits were detected after the trees were exposed to irrigation water reductions in May/June 2002 (pre-flowering stress) by stem water potential followed by stomatal conductance indicating that they were more sensitive stress indicators than photosynthesis.

Flesh color of mangoes is commonly used as maturity index to determine the optimum time for harvest by South African mango growers. Among the studied maturity indices (flesh color, firmness, total soluble solid concentration - TSS, titratable acid concentration - TA) TSS and TA provided the most sensitive ones to assess quality at harvest followed by firmness. A comparison between TSS concentration and flesh color showed no relationship between them at harvest suggesting that flesh color might not be the most suitable index for maturity determinations in mango and might need to be re-evaluated.

The PEACH model is being converted to a mango model to facilitate integration of information about the carbon budget of mango trees. The results of the mango model will be used to examine factors that limit mango crop yield. Recommendations to the farmers can then be made to improve the management of mango production.

Capacity Building

This project provided five students the opportunity to receive training towards fulfillment of the requirements for their Master and Bakkalaureus degrees:

MAC Damaske*

GJ Mthembu

KO Neluheni*

MF Rabothata*

AJ De Villiers

* in the process of completing their studies and Master theses

The Master students received training in planning and conducting scientific experiments, i.e. taking measurements with the instruments that were used in this project, as well as data analysis procedures, interpretation and presenting of results. MF Rabothata gained experience in taking measurements with the various instruments and in cultural management practices, such as irrigation, fertilization, and pruning, among others.

1. General Introduction

1.1. Background and Objectives

Man has practised the use of irrigation to produce agricultural crops since biblical times. However, the methods in irrigation have changed dramatically over the last few decades, with more emphasis being placed on water use efficiency and water conservation. The goal of modern agriculture is to use less water for irrigation without a decrease in yield and fruit quality.

South Africa has very limited water resources. In recent years various factors have contributed to greater uncertainty in the environment (global change in climate), and decisions need to be taken for agricultural water management (Backeberg and Odendaal, 1998). In the Blyde River valley, where the irrigation experiment was conducted, the current form of irrigation distribution (earth-lined canals) has led to a tremendous loss of water before it reached the farmer. Because of this immense loss and change in political environment, farmers and government had to re-examine cultural practices of the past. They have committed themselves to build an underground pipeline in order to distribute water. This will lead to a higher percentage of water available not only for irrigation but also for informal settlements (Backeberg and Odendaal, 1998). Thus, to utilize irrigation water efficiently farmers have to optimize irrigation management.

In many areas of South Africa drought and growing water demands by other sectors endanger the potential development and sustainability of irrigated agriculture. Among irrigated crops, fruit trees are of high economic value and can suffer the most from poor water management because of the carry-over effects into subsequent years. Irrigation applied at rates below the maximum evapotranspiration demand usually results in reduced fruit yield in many tree crops (Fereres and Goldhamer, 1990). However, water deficits applied at specific growth periods (regulated deficit irrigation, RDI) do not negatively affect production. In some cases, they even improve fruit yield and quality (Chalmers et al., 1984; Mitchell et al. 1989). At the same time, RDI may reduce water use and excessive vegetative tree growth resulting in major savings. Positive responses to RDI strategies have been reported in peaches (Chalmers et al., 1984) and pears (Mitchell et al., 1989). To our knowledge, RDI has not been applied to commercial mango orchards in summer rainfall areas of South Africa except for one study (Mostert and Hoffman, 1996).

Knowledge about seasonal vegetative and reproductive growth patterns and water requirements of fruit trees is essential for irrigation scheduling. Growth of fruit trees is affected by water supply/stress. Analyses of fruit tree growth over the season as well as the effect of crop load upon tree water requirements and fruit quality are necessary for optimizing and evaluating different irrigation applications.

Mango was chosen as an example for subtropical tree crops, since the necessary field facilities were provided by Hans Merensky Holdings. An economical evaluation of the various irrigation strategies was not conducted, since this would require a separate study and was not part of our aims.

Our research objectives were:

- to manage irrigation for minimum water and nutrient losses in mango trees, simultaneously maintaining or even improving fruit quality and shelf life, by manipulating the water supply to trees,
- to determine vegetative and reproductive growth patterns critical for the application of regulated deficit irrigation treatments, and to expose trees to water deficits at specific growth periods to reduce excessive vegetative growth while not affecting fruit growth,
- to study photosynthesis and tree water relations, stem water potential and stomatal conductance, in response to different irrigation regimes in mango trees under field conditions over the season, and
- to adapt the PEACH growth model to mango trees.

2. Optimizing Irrigation Water Use Efficiencies in Mango Trees by Improving Irrigation Management

2.1. Introduction

The production of agricultural crops and, in particular, subtropical fruits for the export market is a very important contributor to the South African economy. The performance of these crops is highly influenced by the amount of water they receive during the growing season. Therefore, irrigation management plays a vital role in stabilizing production and facilitating the cultivation of these crops. Despite many advantages, irrigation has taken its toll on the limited water resources of the country. About 53.6% of the total water available in South Africa is being used in agriculture with the Limpopo Province being the second highest consumer (Backeberg and Odendaal 1998). In view of this problem, improving irrigation water use efficiencies of tree crops poses a major challenge.

The Lowveld of South Africa (Mpumalanga and Limpopo Province) is one of the most suitable areas for the cultivation of subtropical fruit. This is of particular importance considering the fact that South Africa has a very low percentage of arable land and is characterized by low and variable (unreliable) rainfall for the cultivation of these crops. The objective of this experiment was to optimize irrigation water use efficiencies of mangoes by means of more efficient irrigation strategies.

2.2. Materials and Methods

The research was carried out in a commercial mango orchard (1 ha) of the Westfalia Estate Moriah (Hans Merensky Holdings) in Hoedspruit (latitude: 24ºS, longitude: 31°E), Limpopo Province, and in the laboratories of the Department of Plant Production and Soil Science, University of Pretoria. Five to eight year old mango (*Mangifera indica* L. cv. ‘Kent’ trees grown on ‘Sabre’ rootstock) trees planted at a density of 1.5 x 6 m were used in the study. Cultural practices, such as pruning, fertilizing, and harvesting, were conducted as in commercial orchards. Fertilization was applied separately from the irrigation applications.

Physical and chemical soil properties were analyzed by the Soil Science laboratory (Dept. of Plant Production and Soil Science, University of Pretoria). In each replicate, soil depth was measured and soil samples were collected at two different depths in the profile (15cm and 60 cm) for analyses of particle size distribution, pH, and water holding capacity. Particle size distribution was determined using the hydrometer method as described by Day (1950). Chemical soil analysis included basic element concentration and pH level according to methods described by the soil testing advisory manual (Anonymous, 1990). Soil water holding capacity was determined using the pressure plate method at various pressures (0.1, 0.3, 1, 10, and 15 bars) (Richards and Weaver, 1944). Values obtained at a pressure of 0.1 bar represented field capacity, and at 15 bars water was unavailable to the plants. The difference between 0.1 and 15 bars indicated when water was available to the plants. Soil infiltration rate was measured at six locations in the orchard using a double-ring infiltrometer as described by Marshall et al. (1999).

The experimental orchard exhibited differences in soil depth: the middle of the orchard was more shallow (70-80 cm) in comparison to the sides (90-110 cm). The orchard soil, belonging to the Glenrosa series (Lithic Ustochrept), displayed two horizons: an A horizon consisting of a shallow layer of well-weathered material with low organic matter content and a B horizon consisting of well to partly weathered rock. Mean soil particle size was very similar for the different depths (Table 2.1). The soil type is on the boundary of loamy sand and sand with an average depth of 70-90 cm followed by a layer of semi-weathered saprolite. The soil profile was homogeneous and horizons were not distinguishable.

Table 2.1 Soil particle size distribution of the experimental orchard across the soil profile (mean ± SD, n=16).

Depth	Sand (%)	Silt (%)	Clay (%)
0 – 30 cm	82.3 (± 4.1)	5.1 (±3.2)	11.6 (±3.1)
30 – 100 cm	80.0 (± 8.7)	5.4 (±6.4)	13.6 (±5.7)

Mean infiltration rate was 213 ± 95 mm h^{-1} across all treatments. The high infiltration rate indicated that the chance of stagnant or run-off surface water in the treatments was extremely low. Mean soil water-holding capacity was low as expected from a loamy sand/sand soil (Table 2.2).

Table 2.2 Soil water-holding capacity (water/soil: mm/m) of the experimental orchard (mean ± SD, n=16).

Depth	Field Capacity ($mm\ m^{-1}$)	Plant Available ($mm\ m^{-1}$)	Unavailable ($mm\ m^{-1}$)
0 – 30 cm	120 (±18)	83 (±16)	37 (±5)
30 –100 cm	138 (±36)	98 (±23)	41 (±20)

High sand and low clay contents, high infiltration rates, and low water holding capacities of the orchard soil indicated its suitability for frequent irrigation applications under a drip irrigation system to save water and minimize nutrient losses.

Nutrient concentrations of the soil were at desirable levels (Table 2.3) as indicated by Tomlinson and Smith (1998). Soil pH amounted to 6.3 ± 0.3 throughout the profile.

Table 2.3 Nutrient levels in the experimental orchard across the soil profile (mean ± SD, n=16).

Depth	P ($mg\ kg^{-1}$)	Ca ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)	Na ($mg\ kg^{-1}$)
0–30 cm	26 (±12)	754 (±488)	103 (±24)	129 (±26)	63 (±30)
30–100 cm	16 (±18)	881 (±666)	94 (±46)	162 (±33)	50(±15)

Soil water measurements were taken by means of a neutron hydroprobe (CPN 503, Campbell Pacific Nuclear Corp., CA, USA) and calibrated *in situ* at depth intervals of 10 cm (0-90 cm depth). Neutron probe access tubes were inserted to a depth of 1 m at about 20 cm from the tree in each replicate of the various irrigation treatments. Field capacity (FC, 103 mm up to a depth of 90 cm) was determined in the field as described by Vanassche and Laker (1989) and used for irrigation scheduling rather than determinations conducted in the laboratory of disturbed soil. Capacitance sensor probes (Netafim) were installed at three depths (30, 60, and 90 cm) in the soil profile at a distance of about 20 cm from the tree in one replicate of each treatment.

Soil moisture was monitored daily in three hour intervals via a datalogger (Netafim). The irrigation system represented a single line drip system with two emitters (4 L h^{-1}) per tree located at a distance of 30 cm on each side of the tree, while the farm trees were irrigated by one emitter (8 L h^{-1}) per tree located at the trunk. The four irrigation treatments (four replicates of 18 trees each per treatment excluding border trees) were randomly distributed in a block design in 2 x three rows within the orchard. During the first two years the irrigation was conducted with a drip irrigation system, since it was used on the farm. The following irrigation treatments were implemented from November 1999 until February 2002 (Table 2.4):

Co: Control (82 ± 8 and 87 ± 11% of FC in 2000/2001 and 2001/2002, respectively)

DI-1: Continuous deficit irrigation (83 ± 6% of irrigation water applied to Co)

DI-2: Continuous deficit irrigation (64 ± 4% of irrigation water applied to Co)

RDI: Regulated deficit irrigation (like Co, except that irrigation water was withheld for 5 weeks in May/June 2000 and for 4 weeks in December 2000/January 2001, and reduced for 4 weeks to 1/3 of Co in May/June 2001 followed by 2 weeks of 1/2 and 3 weeks of 1/3 of Co in January 2002)

Co-F: Farm control, full irrigation according to daily tensiometer readings at 30 and 60 cm depths, trees were irrigated once per day when soil moisture was lower than -5 KPa in 2000/2001, irrigation was reduced for 5 weeks in April/May 2001 reaching -20 KPa followed by full irrigation (about -7 KPa) until February 2002.

Trees of the treatments Co, DI-1, DI-2, and RDI, were irrigated in 3-5 applications each day, and the amounts were based on weekly soil moisture readings. The amount of water applied to each irrigation treatment was measured by hydrometers. The soil profile in the control treatment (Co) was supposed to be filled up to field capacity (FC), however this goal was not completely achieved because of technical and field circumstances. Treatments DI-1 and DI-2 were implemented to evaluate the effect of continuous deficit irrigation on tree growth, physiology, yield, and fruit quality on a long-term basis. In the RDI treatment, positive and negative impacts of water deficits (either water withholding or reduction) during specific growth periods (before flowering and during the last fruit growth stage) were assessed with respect to the above mentioned tree parameters.

From June 2002 onwards, soil water measurements were taken on a daily basis in order to obtain more accurate water uptake data and amounts of water to be irrigated daily. From March until May 2002 Co and RDI were irrigated to about 76% ± 6% of FC, while DI-1 and DI-2 received 83 and 64%, respectively, of the amount of irrigation water applied to Co. From June until the middle of July the treatments Co, DI-1, DI-2, and RDI, were irrigated to 73 ± 6% of FC followed by 2 weeks of full irrigation (98 ± 6% of FC). The farm control was irrigated when tensiometer readings reached values of -10 KPa from March until the beginning of June 2002 and from then on until the third week in July 2002 when soil moisture was lower than about -20 KPa. In August the drip irrigation system was replaced by microjets (1 microjet between 2 trees), since the lateral distribution of the water in the coarse textured soil under drip irrigation was too small to ensure an adequate water supply. The following irrigation treatments were applied from August 2002 until February 2003 (Table 2.4):

Co: Control (95 ± 3% of FC)

DI-1: Continuous deficit irrigation (when 30 mm was extracted the profile was filled up to 89 mm, ± 20 mm below FC, ± 79% of FC)

DI-2: Continuous deficit irrigation (when 40 mm was extracted the profile was filled up to 83 mm, ± 30 mm below FC, ± 69% of FC)

RDI: Regulated deficit irrigation (like Co, except that irrigation water was withheld for 2 weeks in December 2002/January 2003)

Co-F: Farm control, full irrigation according to daily tensiometer readings at 30 and 60 cm depths, trees were irrigated once per day when soil moisture was lower than -10 KPa

Table 2.4 Phenological cycle of 'Kent' mangoes and irrigation treatments during 2000-2003. Depending on season phenological stages can shift by ± 2-4 weeks (NI = no irrigation).

	Phenological Cycle											
	Vegetative Flush			Flower Development	Flowering and Fruit Set		Fruit Development					Harvest
	Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
IRRIGATION SCHEDULING												
2000-2001												
Co	82% of FC											
DI-1	83% of irrigation water applied to Co											
DI-2	64% of irrigation water applied to Co											
RDI	82% of FC			NI	82% of FC						NI	82% FC
Co-F	-5 KPa											
2001-2002												
Co	87% of FC											
DI-1	83% of irrigation water applied to Co											
DI-2	64% of irrigation water applied to Co											
RDI	87% of FC			1/3, 1/2 of Co	87% of FC						1/3 of Co	87% of FC
Co-F	-7 KPa		-20 KPa	-7 KPa								
2002-2003												
Co	76% of FC			73% of FC	FC	95% of FC						
DI-1	83% of Co					79% of FC						
DI-2	64% of Co					69% of FC						
RDI	76% of FC					95% of FC					NI	95% FC
Co-F	-10 KPa			-20 KPa		-10 KPa						

The harvest of the experimental trees (10-12 trees per 4 replicates per treatment) followed normal farm procedures. Fresh weight of each individual fruit was measured at harvest for yield determinations. Yield data were analyzed with ANOVA (F-Test, one factor = irrigation), and means were compared using the Tukey-Test at P=0.05. The effect of irrigation on yield was evaluated by calculating the irrigation water use efficiency (WUE-I) for each treatment. Values of WUE-I were obtained by dividing the yield per tree by the amount of water applied per tree. Vanassche and Laker (1989) calculated WUE values for wheat and maize based on total water use by the plants, i.e. irrigation water and effective rainfall (WUE), and on applied water, i.e. irrigation water only (WUE-I). They found that WUE-I was a more useful value as it reflected the influence of irrigation treatments more clearly than WUE.

Ambient air temperatures (Appendix, Fig. A.1), solar radiation, relative humidity (Appendix, Fig. A.2), windspeed, and rainfall (Appendix, Fig. A.3), were monitored at a weather station located within 5 km of the study site. Daily evaporative demand (Appendix, Fig. A.4) was calculated using a modified Penman-Monteith equation (Allen et al., 1998). Contributions of rainfall to irrigation were estimated by taking the total rainfall for the growing season and converting it to liter per effective surface area. The latter was estimated by determining the distribution of roots within soil profiles parallel and perpendicular to the row (about 1.5, 2.25, and 3 m^2, respectively, for the three years).

2.3. Results and Discussion

2.3.1. Growing Season 2000/2001

During the 2000/2001 growing season, the amounts of irrigation water applied in the continuous deficit irrigation (DI-1 and DI-2) and in the regulated deficit irrigation (RDI) treatments were considerably less than those for the control treatment (Co) (Fig. 2.1, Fig. 2.2). The estimated contribution of rainfall to the irrigation was 1695 L $tree^{-1}$ and might represent a slight overestimation, since the bulk of roots were situated underneath the emitter at a radius of about 40 cm. The large amount of irrigation water (3787 L $tree^{-1}$) applied in the farm control treatment (Co-F) was related to large irrigation applications in time (2 hours per application vs. 1 hour per day) and in volume per unit time (8 vs. 4 L h^{-1}). The smallest amount of irrigation water was found in treatment DI-2 (1591 L $tree^{-1}$). Both treatments DI-1 and RDI received similar amounts of irrigation water (1893 and 1802 L $tree^{-1}$, respectively). The amount of irrigation water (2386 L $tree^{-1}$) for the Co treatment was considerably less than that for the farm control indicating that the farm might have over-irrigated at some times in addition to that the Co was only irrigated to 82 ± 8% of FC. Capacitance sensors were installed to monitor water drainage and water losses due to over-irrigation in all treatments.

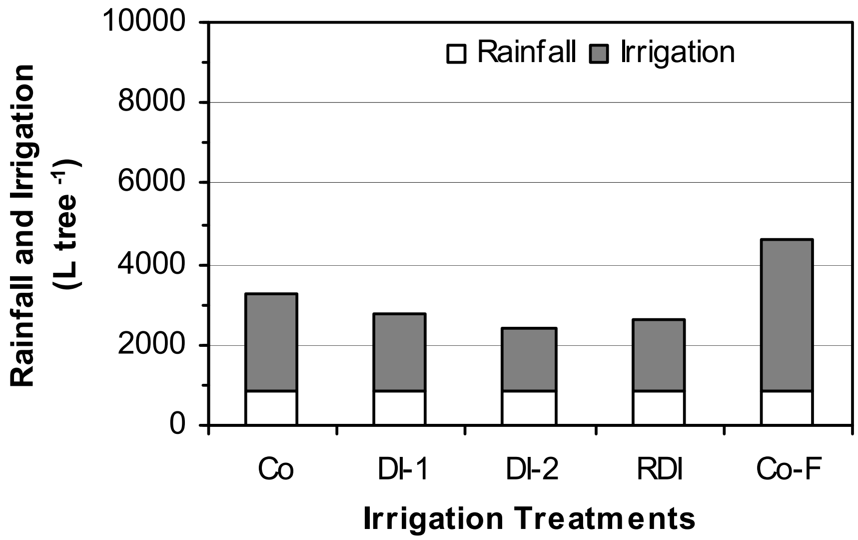

Fig. 2.1 Amounts of rainfall and irrigation water for the various treatments during the season of 2000/2001 (details of irrigation scheduling are outlined in Table 2.4).

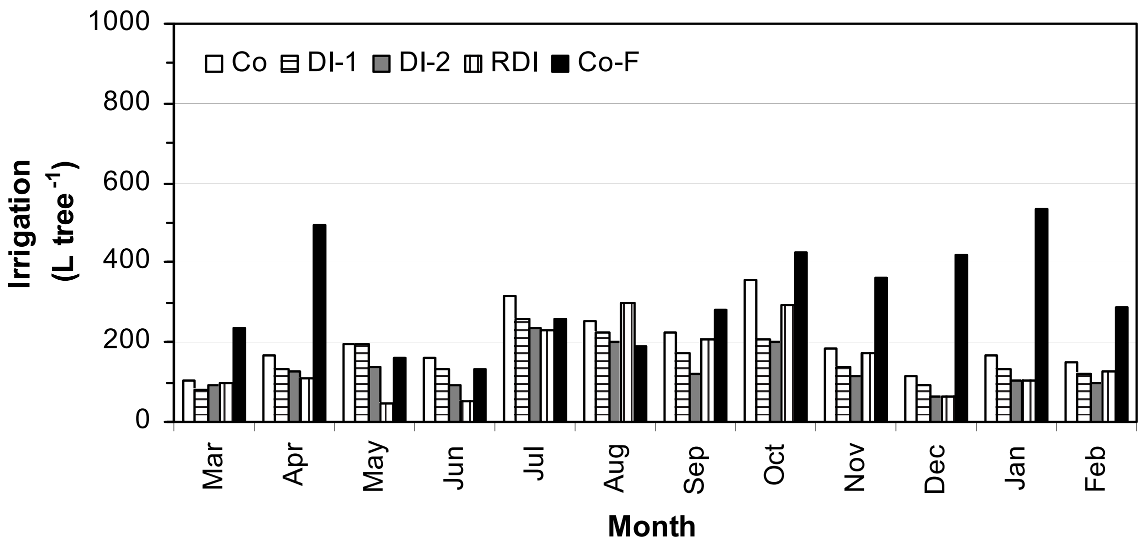

Fig. 2.2 Monthly amounts of irrigation water for the various treatments during the season of 2000/2001 (details of irrigation scheduling are outlined in Table 2.4).

The amounts of irrigation water saved for the various treatments ranged from 37% for Co, 50% for DI-1 and RDI, respectively, and to 58% for DI-2 in relation to the farm control (Fig. 2.3). These values were high but might be somewhat deceiving considering that Co was only irrigated to 82 ± 8% of FC and an over-irrigation in the farm control could not be excluded. When compared to the control treatment (Co) the savings of irrigation water ranged from 21% (DI-1 and RDI) to 33% (DI-2).

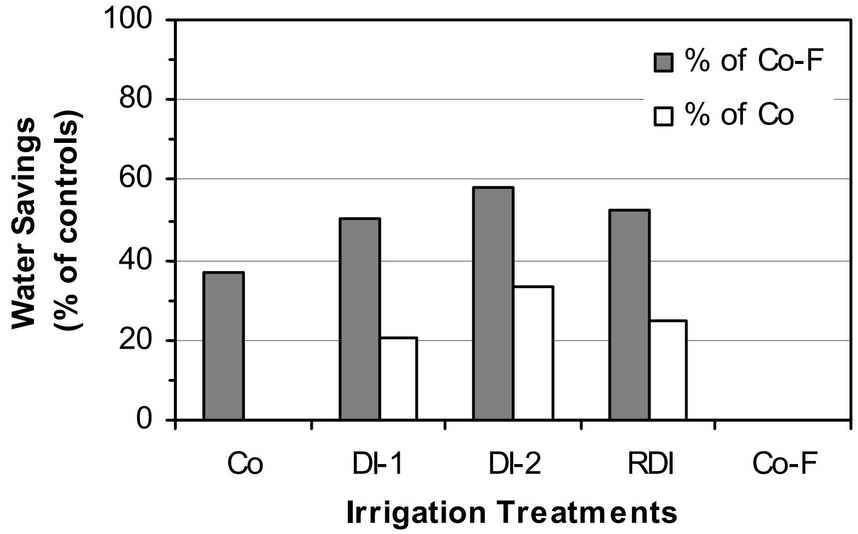

Fig. 2.3 Water savings for the various treatments with respect to the farm-control treatment (Co-F) and the control treatment (Co) during the season of 2000/2001 (details of irrigation scheduling are outlined in Table 2.4).

Yields for the 2000/2001 growing season were generally low for all treatments (Fig. 2.4), since the trees were not in full production yet. The highest yield was found for the control treatment (7.1 kg tree^{-1}) and the lowest yield was found for treatment DI-1 (3.9 kg tree^{-1}). Treatment RDI received a similar amount of water as treatment DI-1 but had a considerable higher yield than the latter (6.4 kg tree^{-1}) indicating that apparently not the amount of water was the most deciding factor for yield but rather the time when water was withheld. Although the farm control treatment (Co-F) received 52% more water than Co and Co was only irrigated up to 82 ± 8% of FC, the yield of Co-F (6.4 kg tree^{-1}) was still 11% lower than that of Co. This indicated that the additional amount of water applied to Co-F did not have any beneficiary effects on yield during the season of 2000/2001. On the contrary, it might have reduced the yield perhaps through nutrient leaching in these coarse textured soils. Yields of the farm control and RDI were the same, although RDI received half the amount of irrigation water.

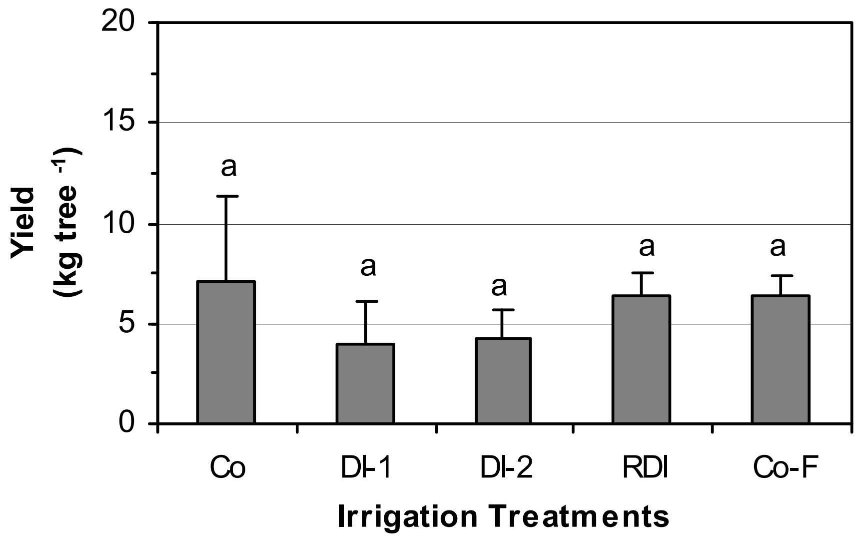

Fig. 2.4 Yield data for each treatment during the season of 2000/2001 (each bar represents the mean ± SE of 4 replicate tree samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Irrigation water use efficiencies (WUE-I) were low due to the relative low yields for all treatments (Fig. 2.5). The lowest WUE-I (1.7 g L^{-1} tree^{-1}) was found for the farm control treatment (Co-F), while RDI displayed the highest WUE-I (3.5 g L^{-1} tree^{-1}) followed by Co (3.5 g L^{-1} tree^{-1}). High irrigation water use efficiencies in Co and RDI might have been in part attributed to their irrigation scheduling (82 ± 8% of FC). The relatively high WUE-I in the RDI treatment (about 18% in comparison to Co-F) was to a large extent associated with savings in irrigation water during the two periods (May/June 2000 and December 2000/January 2001) when no irrigation took place. Irrigation water use efficiencies were fairly low in the treatments DI-1 and DI-2, although considerable amounts of irrigation water were saved in both treatments. The low yields in both treatments might have been a result of water stress conditions due to an underestimation of the irrigation needs for those treatments. The very low WUE-I value for the farm control treatment (Co-F) was most likely the result of the high amount of irrigation water applied, since the yield was the same as for the RDI treatment indicating that the farm seemed to over-irrigate.

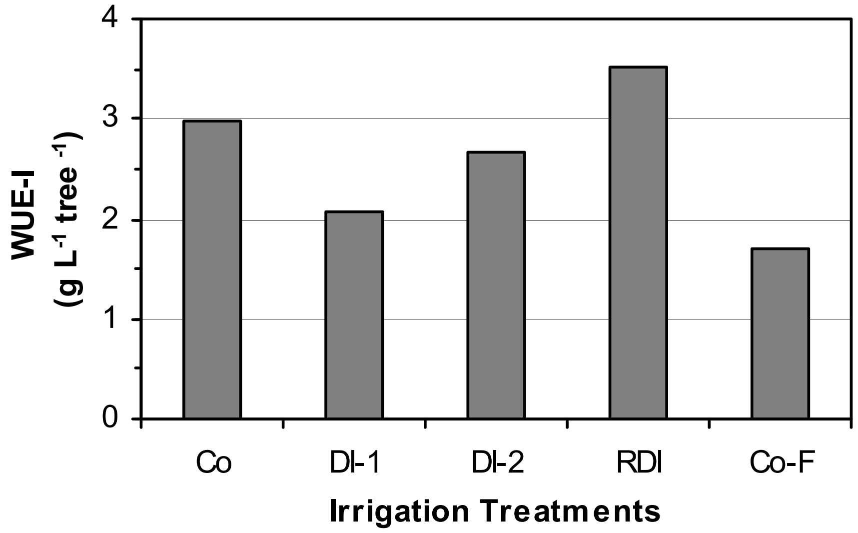

Fig. 2.5 Irrigation water use efficiencies for each treatment during the season of 2000/2001 (details of irrigation scheduling are outlined in Table 2.4).

2.3.2. Growing Season 2001/2002

The amounts of irrigation water applied during the 2001/2002 growing season (Fig. 2.6, 2.7) were similar for the control treatment (Co) compared to the previous growing season (2345 and 2386 L tree^{-1}, respectively) but higher for the other treatments (DI-1, RDI, and Co-F) (Fig. 2.1, 2.6). However, identical trends were found as during the previous season: DI-1 and RDI received similar amounts of water (2049 and 2073 L tree^{-1}, respectively), the farm control treatment (Co-F) received the highest (4441 L tree^{-1}) and DI-2 the lowest amount of irrigation water (1421 L tree^{-1}). The estimated contribution of rainfall to irrigation amounted to 1631 L tree^{-1} and might represent a slight overestimation.

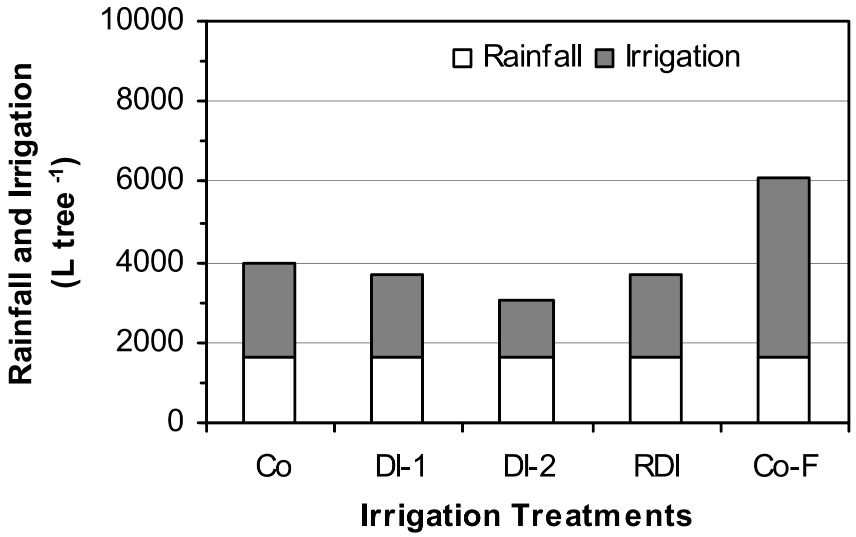

Fig. 2.6 Amounts of rainfall and irrigation water for the various treatments during the season of 2001/2002 (details of irrigation scheduling are outlined in Table 2.4).

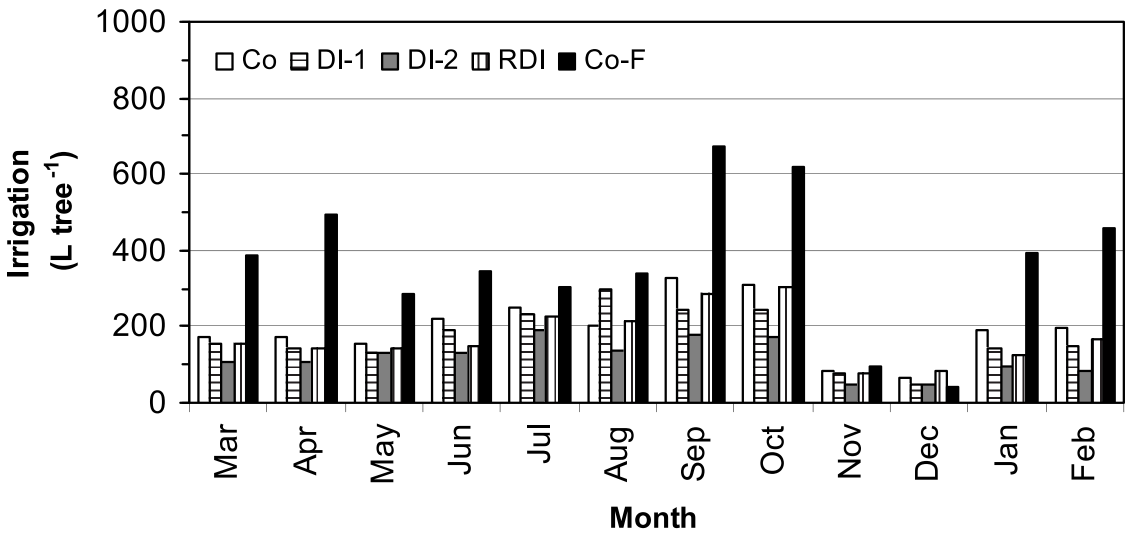

Fig. 2.7 Monthly amounts of irrigation water for the various treatments during the season of 2001/2002 (details of irrigation scheduling are outlined in Table 2.4).

Soil moisture readings with capacitance sensors showed clearly the apparent over-irrigation in the farm control treatment (Co-F) (Fig.2.8). The capacitance sensor readings showed a nearly constant water loss due to drainage in the farm control (Co-F) as displayed by the records of the probe at a depth of 90 cm in contrast to those of the control treatment (Co). Capacitance sensor readings were only depicted for the farm control (Co-F) and the control (Co) treatments, since soil water contents of the deficit irrigation treatments were lower than that of the control treatment and no drainage took place in those treatments.

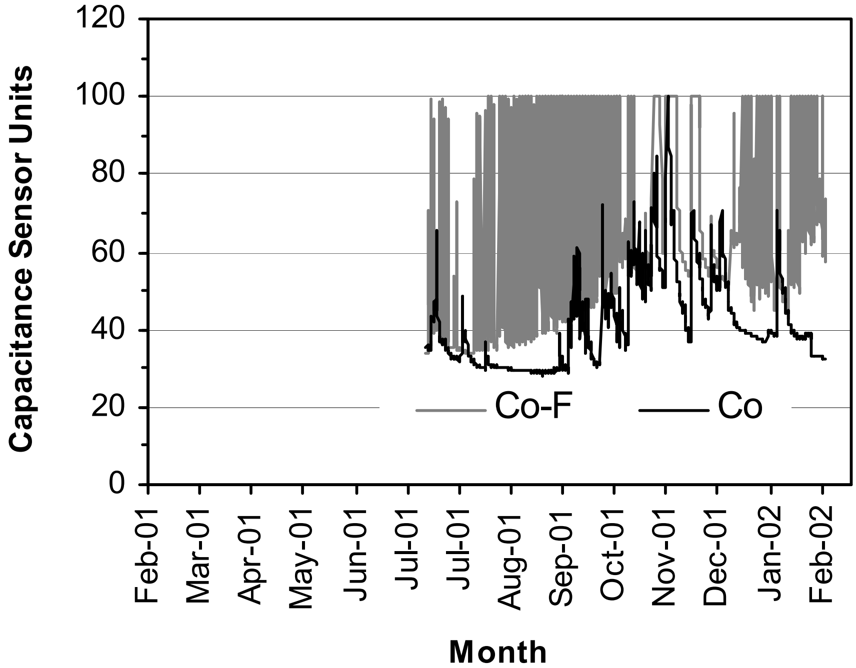

Fig. 2.8 Capacitance readings for treatments control (Co) and farm control (Co-F) at a soil depth of 90 cm (a value of 100 indicates leaching) during the season of 2001/2002 (details of irrigation scheduling are outlined in Table 2.4).

Water savings in the season of 2001/2002 followed a similar trend as observed during the previous season (Fig. 2.9). The highest water savings were found for treatment DI-2 (39% compared to Co and 68% compared to Co-F). Treatments DI-1 and RDI again showed similar savings (13% and 12%, respectively compared to Co). They were however lower than those of the previous growing season (Fig. 2.3) whereas the savings for treatment DI-2 had increased by 20%.

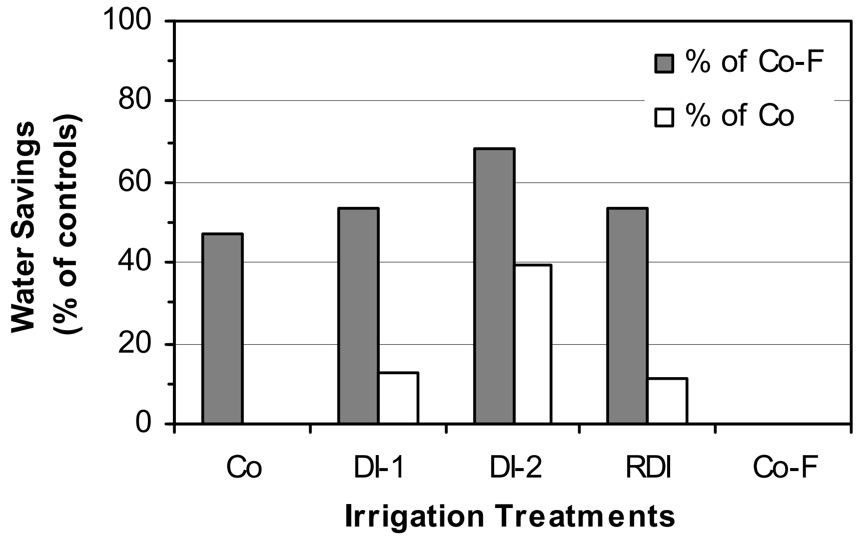

Fig. 2.9 Water savings for the various treatments with respect to the farm-control treatment (Co-F) and the control treatment (Co) during the season of 2001/2002 (details of irrigation scheduling are outlined in Table 2.4).

Yields during this season were markedly higher compared to the previous season. This was mainly due to the fact that the trees were coming into production and to a lesser extent that mangoes exhibit an alternate bearing habit, i.e. a year of high yield is normally followed by a year of a low one and vice versa. Significant differences in yield were found between treatments Co, DI-1,DI-2, and RDI on the one side and treatment Co-F on the other side, the latter having the highest yield (30.6 kg tree^{-1}) among all treatments (Fig. 2.10). DI-1 yielded 2.4 kg tree^{-1} more fruit than the RDI treatment, with both treatments receiving the same amount of water ($\pm$2500 L tree^{-1}) during the growing season. The difference in yield, despite the same amount of irrigation water applied in both treatments, could be explained that different amounts of water were applied at different times resulting in different soil water contents at different times in both treatments. More intense soil water monitoring during the 2002/2003 season should be implemented to give a clearer picture of the situation in the soil profile. A similar situation was found during the 2000/2001 season; however, RDI had then a markedly higher yield than DI-1 (Fig. 2.4, 2.10). The lower yield for the RDI treatment in this season might be attributed in part to carry-over effects of irrigation practices of the previous season and to the alternate bearing habit of mango trees.

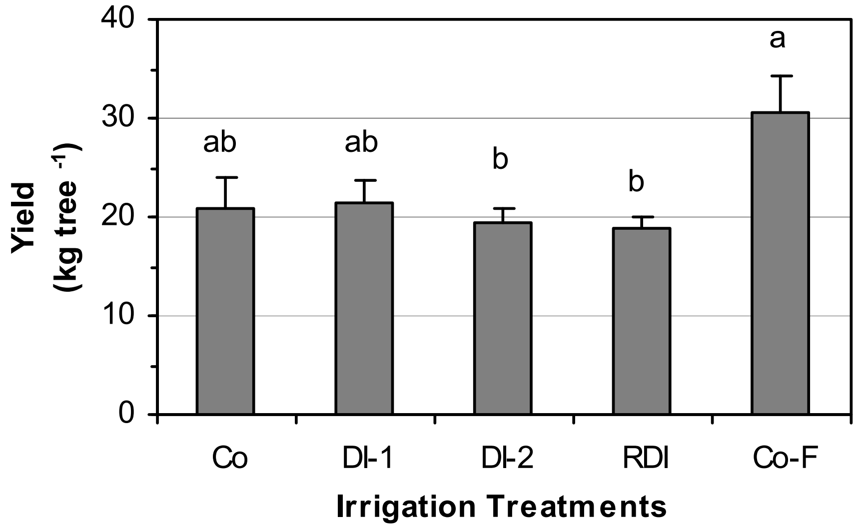

Fig. 2.10 Yield data for each treatment during the season of 2001/2002 (each bar represents the mean ± SE of 4 replicate tree samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Although the Co-F treatment showed the highest yield, the WUE-I was the lowest of all treatments (Fig. 2.11). The high amount of irrigation water applied (over-irrigation) resulted in high drainage losses as illustrated by the capacitance readings (Fig. 2.8). The highest WUE-I was found for DI-2 as a result of both a relatively high yield and small amount of applied water. This treatment also allowed for efficient use of rainfall water, which could have been temporarily stored in the soil profile for later consumption by the trees.

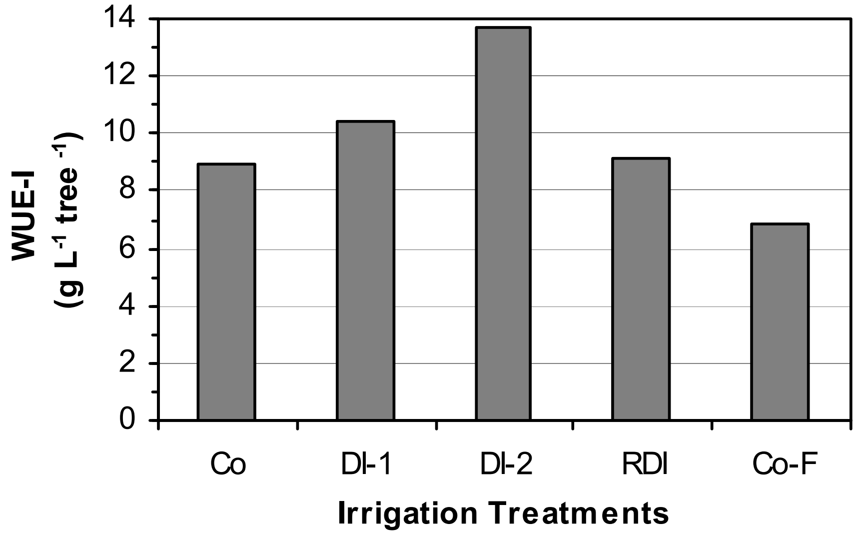

Fig. 2.11 Irrigation water use efficiencies for each treatment during the season of 2001/2002 (details of irrigation scheduling are outlined in Table 2.4).

2.3.3. Growing Season 2002/2003

The amounts of irrigation water applied during this season were considerably higher than those during the previous growing season (Fig. 2.6, 2.12, 2.13, Table 2.5) most likely because the season of 2002/2003 was characterized by a much lower rainfall than the previous season (307 mm vs. 725 mm) (Table 2.5).

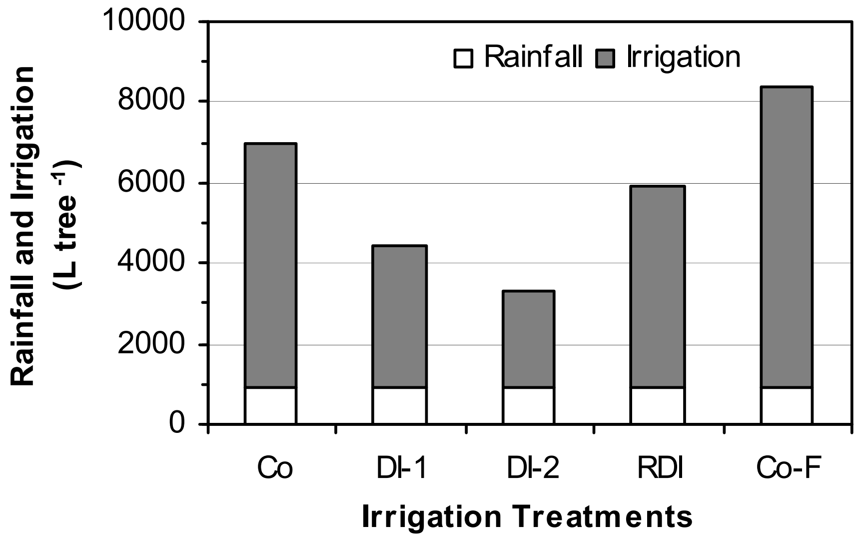

Fig. 2.12 Amounts of rainfall and irrigation water for the various treatments during the season of 2002/2003 (details of irrigation scheduling are outlined in Table 2.4).

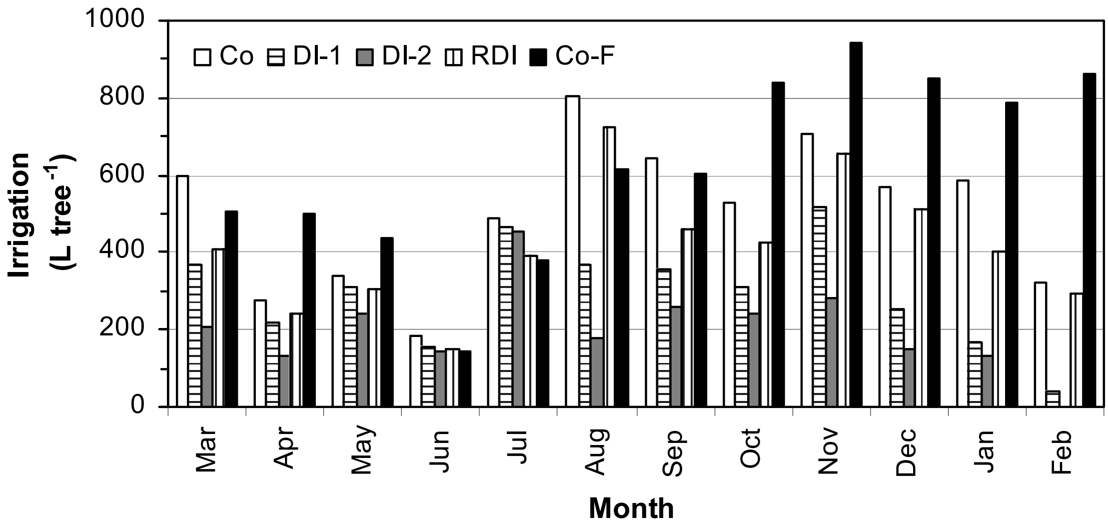

Fig. 2.13 Monthly amounts of irrigation water for the various treatments during the season of 2002/2003 (details of irrigation scheduling are outlined in Table 2.4).

Additionally, during August 2002 the drip system was replaced by a microjet system as it was found that the drip system could no longer supply the trees with adequate amounts of water. The microjet system wetted a much larger surface area than did the drip system, hence the higher amounts of irrigation water that had to be applied.

While for treatments Co, RDI, and Co-F, the total amount of water received per tree was much higher for the 2002/2003 season than the previous one, the amounts for the continuous deficit irrigation treatments (DI-1 and DI-2) were only slightly increased in 2002/2003 compared to 2001/2002. This would suggest that these irrigation scheduling practices are more efficient than the control treatment (Co, 95 ± 3 of FC). The higher amounts of irrigation water for these two treatments were caused by the low contribution of rainfall during this season compared to the previous one (Table 2.5).

Table 2.5 Amounts of irrigation water and estimated contribution of rainfall water for the various treatments for the seasons of 2001/2002 and 2002/2003 (L $tree^{-1}$) (details of irrigation scheduling are outlined in Table 2.4).

Treatment	**2001/2002**			**2002/2003**		
	Irrigation	**Rain**	**Total**	**Irrigation**	**Rain**	**Total**
Co	2345	1631	3976	6046	921	6967
DI-1	2049	1631	3681	3537	921	4458
DI-2	1421	1631	3052	2421	921	3342
RDI	2073	1631	3704	4965	921	5886
Co-F	4441	1631	6073	7467	921	8388

The installation of the microjets on the farm in August 2002 had one important and positive consequence: it reduced considerably the loss of irrigation water in the farm control treatment (Co-F) (Fig. 2.14). There were only four occasions of subsurface drainage in the farm control treatment whereas previously subsurface drainage was constantly observed in this treatment during the previous season (Fig. 2.8) as well as for the time period (Mar-Jun 2002) before the microjets were installed (Fig. 2.14).

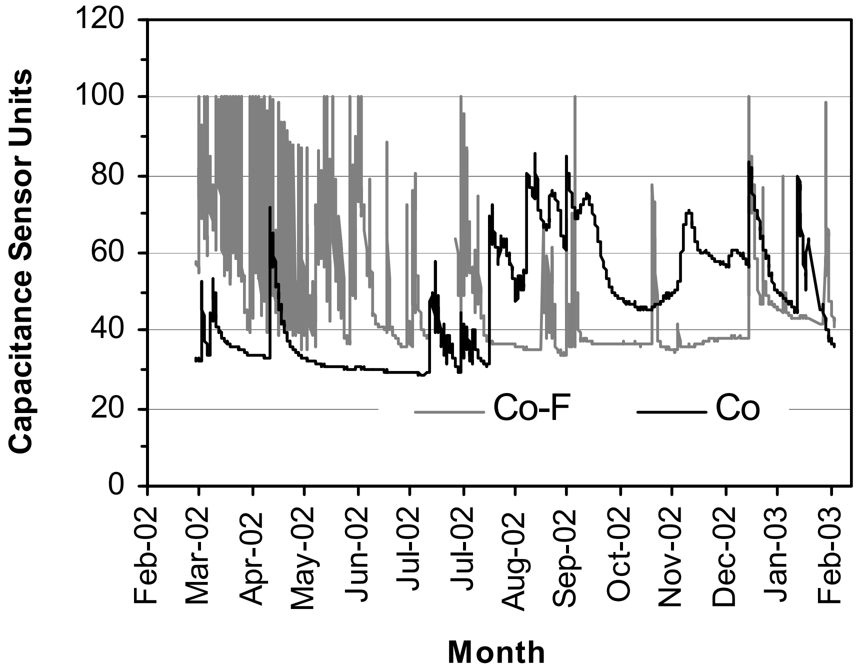

Fig. 2.14 Capacitance readings for treatments control (Co) and farm control (Co-F) at a soil depth of 90cm (a value of 100 indicates leaching) during the season of 2002/2003 (details of irrigation scheduling are outlined in Table 2.4).

Water savings were the highest for the deficit irrigation treatments DI-1 and DI-2 (53% and 68%, respectively) when compared to the farm control treatment. The savings for the control were 19% and for RDI 34% in comparison to Co-F (Fig. 2.15). Both treatments (Co and RDI) were full irrigation treatments (each irrigation profile was refilled to 95 ± 3 of field capacity) except for one period in January 2003 in the RDI treatment. The difference in water savings was mostly due to the period when no irrigation was applied in the RDI treatment in December 2002/January 2003. The comparison in water savings between the treatments Co and Co-F clearly showed that the farm control treatment (Co-F) was over-irrigated as 24% more water was applied than in the control treatment.

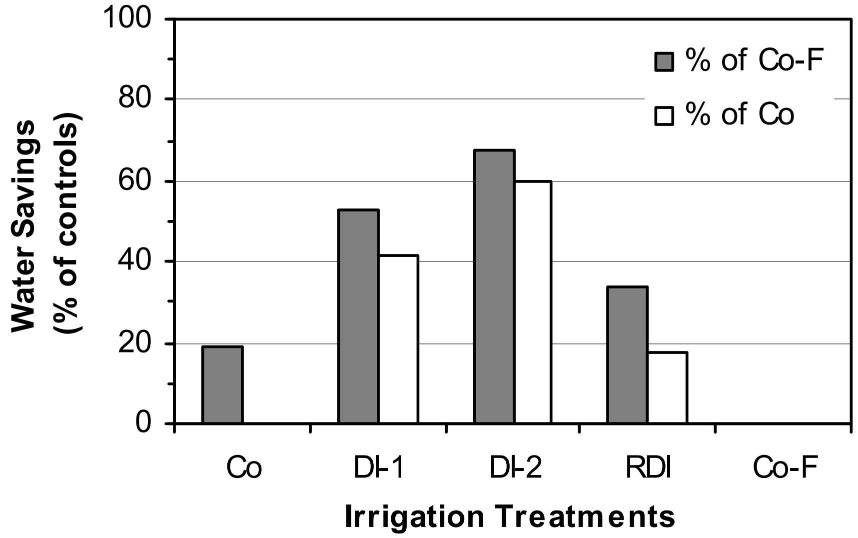

Fig. 2.15 Water savings for the various treatments with respect to the farm-control treatment (Co-F) and the control treatment (Co) during the season of 2002/2003 (details of irrigation scheduling are outlined in Table 2.4).

Yields were low for all treatments, ranging from 6.5 to 12.7 kg tree^{-1} (Fig. 2.16) in comparison to the previous season (Fig. 2.10) indicating the alternate bearing habit of mango trees. The highest yield was obtained in the farm control followed by RDI and Co. The lowest yields were found for the deficit irrigation treatments DI-1 and DI-2. The yield pattern of the different irrigation treatments was similar compared to the previous seasons (Fig. 2.4, 2.10).

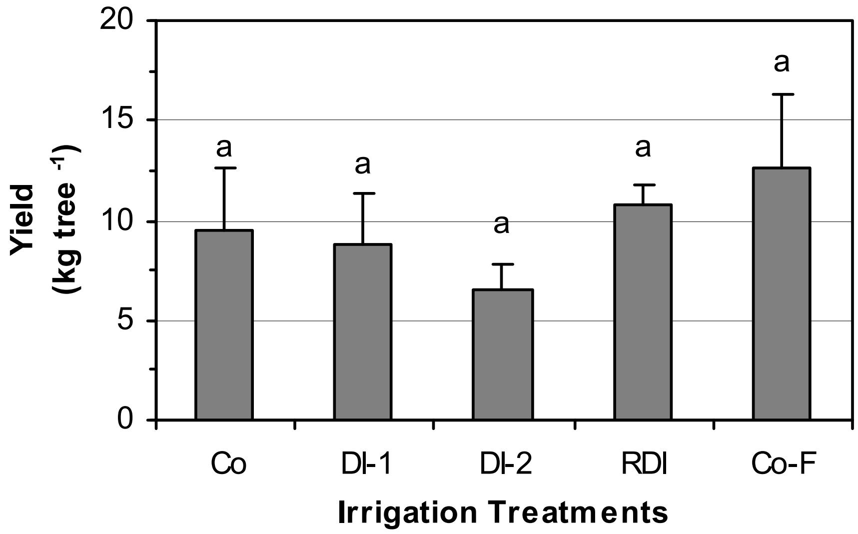

Fig. 2.16 Yield data for each treatment during the season of 2002/2003 (each bar represents the mean ± SE of 4 replicate tree samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

The highest irrigation water efficiencies were found for the deficit irrigation treatments (DI-1, DI-2, RDI) as a result of the low amounts of irrigation water applied despite the lower yields (Fig. 2.17). Both control treatments showed similar values of WUE-I (1.7 g L^{-1} $tree^{-1}$) and were the lowest across all treatments.

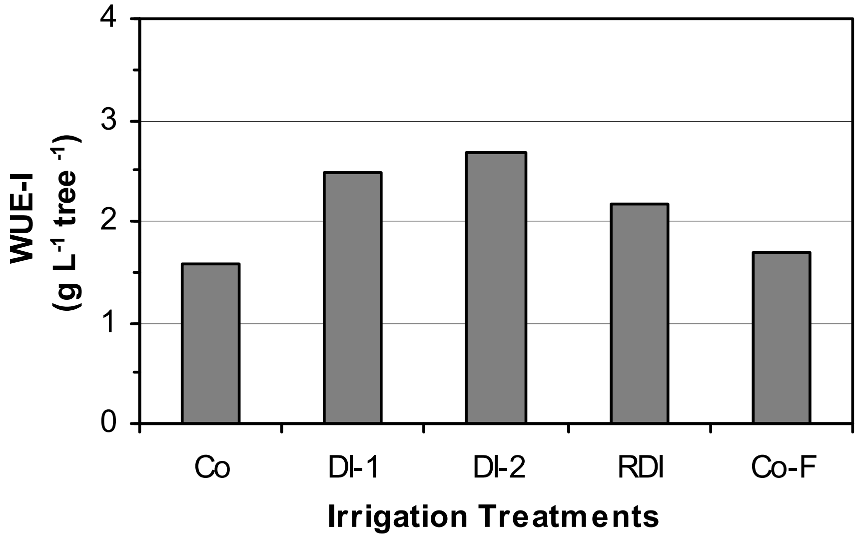

Fig. 2.17 Irrigation water use efficiencies for each treatment during the season of 2002/2003 (details of irrigation scheduling are outlined in Table 2.4).

2.4. Conclusions

Deficit irrigation represented a suitable irrigation method to save water and to simultaneously achieve acceptable yields, especially under conditions of water shortages. However, the implementation of deficit irrigation scheduling would require a regular monitoring of soil water content on a daily basis. The highest irrigation water use efficiency was found for treatment DI-2 where the maximum soil water content at any time was the lowest of all treatments. The RDI irrigation treatment, receiving the same irrigation practice as Co except for one or two periods during the season when irrigation water was reduced or withheld, provided storage space for eventual rainfall, particularly in summer, leading to a saving of irrigation water of 12-24% as compared to the control. However, the period of water reduction before flowering in the RDI treatment could be further optimized by taking place slightly earlier (May) than in our studies in order to minimize or eliminate effects on flower development, flowering, fruit set, and consequently yield. The effect of the alternate bearing habit of mango trees observed during this research was in part responsible for the relatively low yields every other year. In addition, the trees were still relatively young, especially during the first two years, and their production is expected to increase further. Another season would smooth the effect of alternate bearing and probably accentuate the effects of the different treatments even more, especially water savings and irrigation water use efficiencies, in trees that are in full production.

The current irrigation practice by the farm clearly showed that the trees were over-irrigated as indicated by capacitance sensor readings and similar yields across all treatments during the 2000/2001 and 2002/2003 seasons, although the farm slightly reduced the amount of irrigation water applied by raising the threshold from -5 to -10 KPa. However, those reductions were not reflected in the yearly total amount of irrigation water applied, since the trees were coming into production and because of a fairly dry season during 2002/2003 in comparison to the first two seasons. Water and nutrient losses due to drainage as a result of over-irrigation on these coarse textured soils were very high primarily because of the use of drip emitters of high volume (8 L hr^{-1}) and only one long time application of irrigation water per day by the farm. Pulse irrigation (several applications of irrigation water per day) would be advisable when using a drip irrigation system to minimize water losses if technically feasible. The inefficient irrigation practice by the farm was further illustrated by generally low irrigation water use efficiencies over the years in comparison to the other treatments.

The drip system was replaced in August 2002 by a microjet system. Its effect on irrigation water, yield, and irrigation water use efficiencies will only be noticeable from the next growing season on. However, over-irrigation by the farm was drastically reduced as indicated by capacitance sensor readings. Considering the technical conditions/restrictions on the farm (electricity, labor, soil properties, etc.), the microjet system appeared to be better than the drip irrigation system. As a larger area is wetted by the microjet system compared to the drip system, it is expected that the root system will expand considerably and hence influence water requirements and yields. It would have been very interesting if the effects could have been monitored over a longer time period.

Since low rainfall during the season of 2002/2003 might indicate the beginning of a drought period, many of the results obtained in this study might be quite useful for the near future, although the Co treatment was only irrigated to 82 and 87% of FC during the first two seasons. During a drought period and consequent water shortages, farmers might have to consider to either irrigating with lower water applications (deficit irrigation) or not irrigating for periods of time. The worst possible scenario would be to take out of production part of their orchards resulting in a loss of highly valuable orchards. Deficit irrigation practices might offer an acceptable solution before loosing orchards under conditions of severe water shortages.

3. Physiological Tree Responses to the Various Irrigation Regimes

3.1. Introduction

The productivity of a crop is dependent on the amount of carbon fixed by the process of photosynthesis during the season and the partitioning of these carbohydrates to various plant organs. The effect of environmental stress experienced by the plant can be determined by photosynthesis, stomatal conductance, and stem or leaf water potential. The rate of photosynthesis of a crop is greatly influenced by photon flux density, temperature, and vapor pressure deficit (Syvertsen, 1996), and will decline if water stress is experienced (Flore et al., 1985). During water stress most plants experience stress in the form of reduced vegetative growth, notably affecting leaf size, without significantly influencing photosynthesis of the plant (Hsiao, 1993). However as the stress intensifies, photosynthesis per unit leaf area will begin to decline (Boyer, 1970). This will only be noticed in the beginning of the stress period during the hottest part of the day (midday), but as the stress continues this becomes more apparent during the earlier parts of the day and the longer time it takes to recover during the afternoon. With photosynthesis restricted to fewer and fewer hours carbon accumulation declines affecting vegetative and fruit growth more negatively. The amount of carbon accumulation during water stress is closely correlated with stomatal conductance (g_s). Besides of the restriction of CO_2 uptake caused by the increased amount of closed stomata, the metabolic capacity for photosynthesis of cells in the affected leaves is also reduced, thereby reducing the rate of photosynthesis (Hsiao, 1993).

Caspari et al. (1994) showed in pears that, although water stress early in the season had no significant effect on g_s between controlled and stressed trees, the difference in g_s became more distinct as time progressed. Trees exposed for a significant amount of time to drought stress took more than two weeks to recover after full irrigation had been resumed indicating a lasting effect of stress on the plant (Behboudian et al., 1994). A similar pattern was found in litchi (Stern et al., 1998) where low irrigation frequency was associated with low g_s. In peach, Marsal and Girona (1997) showed the sensitivity of different phenological stages of the tree to deficit irrigation. Stomatal conductance in grape vines declined as stress intensified, and in most cases vine leaves did not recover during the night as sufficiently as the non-stressed ones did (Williams and Matthews, 1990). In some cases, trees exposed to deficit irrigation use water more efficiently than non-stressed ones. Girona et al. (1993) found that although stomata closed rapidly in peach when stress was experienced, the effect on photosynthesis was not as great in comparison to the control. Physiological stress responses of olives to water deficits and their subsequent recovery depended on the duration and severity of the stress period (Pavel and Fereres, 1998).

Stem water potential at midday, when the evaporative demand reaches usually a peak over the day, was found to represent the more sensitive detector for plant stress in comparison to predawn measurements (McCutchan and Shackel, 1992). Using water potential as indicator of water status has not been commonly used in mango trees because mango is a latex type sap conducting plant. When measuring water potential in mango using a pressure bomb, it is often not easy to distinguish between latex exudation and water outflow. Few studies of water potential have been conducted in mango, however, those studies were carried out with containerized trees and mainly leaf water potential was measured (Schaffer et al., 1994). To our knowledge little is known about the seasonal pattern of stem water potential in mango. The potential to use stem water potential as indicator of tree water status in mango under various irrigation regimes and field conditions has not been evaluated yet. The objective of this research was to study the photosynthesis and tree water relations, stem water potential and stomatal conductance, in response to different irrigation regimes in mango trees under field conditions over the season.

3.2. Materials and Methods

Details about the irrigation treatments and study site have been described in chapter 2.2.

Stomatal conductance (g_s) and photosynthetic rates (Pn) were measured in the different treatments over the seasons of 2000-2003 using a porometer (LICOR-1600, Licor Inc., NE, USA) and an Infrared Gas Analyzer (CIRAS, PP-Systems, UK). Measurements were taken on sunny days at midday using 5 fully exposed leaves per tree for Pn and g_s measurements. Stem water potential (Ψ_{stem}) was determined on 2-3 leaves per tree at midday using a pressure bomb (Soil Moisture Equipment, CA, USA). Leaves near to the main stem were covered with plastic bags coated with aluminium two hours before the measurements.

Data were analyzed with ANOVA (F-Test) with one factor (irrigation). Means were compared by using the Tukey-Test at P=0.05.

3.3. Results and Discussion

3.3.1. Growing Season 2000/2001

While there were no significant differences in leaf photosynthetic rates (Pn) at midday between Co, DI-1, DI-2, and RDI, during July, August, and September of 2000, Pn rates in DI-2 were significantly lower in October 2000 than in the other treatments indicating that the trees were stressed in this treatment because of water deficit (Fig. 3.1). Photosynthetic rates in winter were similar to those reported by Schaffer et al. (1994), i.e. mean photosynthetic rates of 10 μmol CO_2 m^{-2} s^{-1} for the winter in mango.

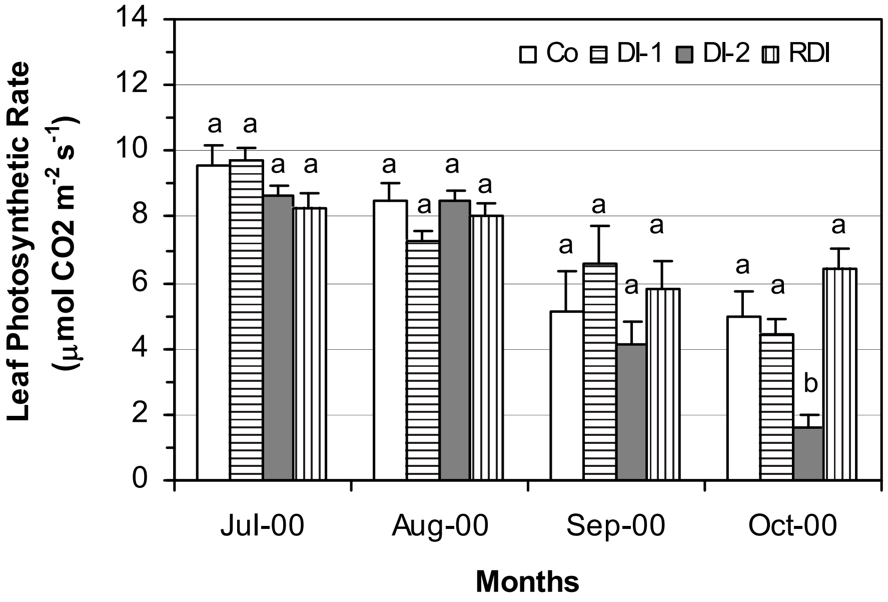

Fig. 3.1 Mean photosynthetic rates at midday in the various irrigation treatments from July to October 2000 (each bar represents the mean ± SE of 6 replicate leaf samples; different letters denote significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Stomatal conductance (g_s) in the RDI treatment was significantly lower than in the other treatments during July 2000 (Fig. 3.2) in contrast to photosynthetic rates (Fig. 3.1) implying those trees were still recovering from the water deficit the trees had been exposed to during the drying cycle from 23 May - 22 June 2000. Goldhamer et al. (1999) and Behboudian et al. (1994) reported similar results in peach and pear trees in response to water deficits. They suggested that the soil profile in field grown trees took a longer time to refill after resuming full irrigation leaving a deficit for two weeks after full irrigation.

Low g_s of the RDI treatment in comparison to the other treatments seemed not to be unusual for RDI as reported by Girona et al. (1994) in hazelnut and by Marsal and Girona (1997) in peach. Marsal and Girona (1997) showed also that responses of photosynthesis to water deficits were less sensitive than stomatal conductance in peach. In contrast to winter (May/June 2000), the stress period in summer (December 2000) had no significant effect on g_s. Stomatal conductances in December were, however, lower than those reported by Schaffer et al. (1994) for mango. Summer rainfall and root growth into the row (Schaffer et al., 1994) from where trees extracted water might have led to only a moderate stress in summer in the RDI treatment.

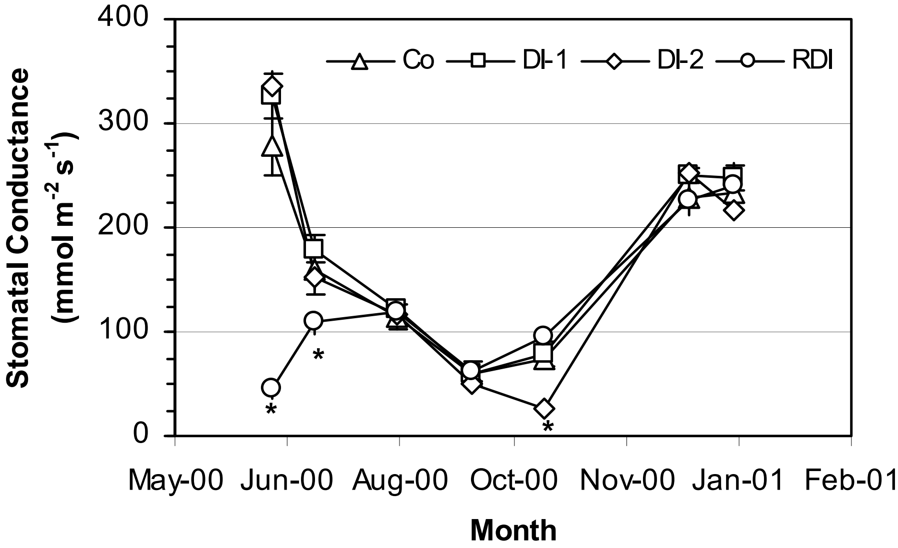

Fig. 3.2 Mean stomatal conductances in the irrigation treatments from June to December 2000 (each data point represents the mean ± SE of 6 replicate leaf samples; asterisks denote significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Concurrent with Pn rates, the DI-2 treatment displayed significantly lower g_s than the other treatments in October indicating that those trees encountered water deficits. In addition to low applications of irrigation water, high evaporative demands during September and October 2000 (Appendix, Fig. A.4) might have induced water deficits in those trees. Differences between Co and DI-1 over the season were minor. Stomatal conductances at a midday temperature of 30^{o}C during June and August were similar in magnitude as reported by Schaffer et al. (1994).

3.3.2. Growing Season 2001/2002

Mean photosynthetic rates declined in August and October 2001 across all treatments (Fig.3.3) in contrast to July 2001. Although there were some significant differences between treatments in photosynthetic rates, the differences were not consistent among treatments in July, August, and October. When comparing photosynthetic rates in July with those in August, it appears that there are large differences between months or days within a season. After the stress period the RDI trees were exposed to in June, trees recovered fairly rapidly as indicated by the higher photosynthetic rates in July and August compared to the other treatments.

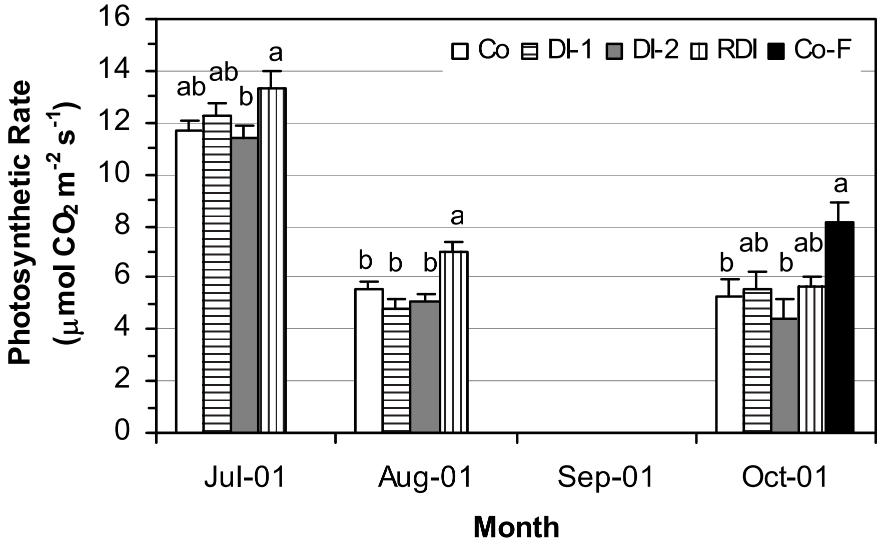

Fig. 3.3 Mean photosynthetic rates at midday in the various irrigation treatments from July to October 2001 (each point represents the mean ± SE of 6-8 replicate leaf samples; different letters depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Stomatal conductance was relatively low during the winter and spring months (May-October 2001) but increased in summer (December 2001) across all treatments (Fig. 3.4). Stomatal conductances over the season were comparable in magnitude with those reported by Schaffer et al. (1994) for mango in winter (about 100 mmol H_2O m^{-2} s^{-1}) but lower in summer (around 600 mmol H_2O m^{-2} s^{-1}). Except for July and December, significant differences in g_s were observed between treatments. The DI-2 treatment exhibited the lowest g_s during May, June, July, and October in contrast to the other treatments indicating that those trees were exposed to water deficit. Except for June (at the end of stress period) and December, g_s in the RDI treatment was generally higher than in the other treatments. In October significant lower stomatal conductances in the Co, DI-1, DI-2, and RDI treatments might indicate that at this particular day trees were slightly stressed at midday in comparison to the farm control (Co-F). Since the weather in Hoedspruit during late spring and summer is quite inconsistent in terms of evaporative demand (temperature, radiation, etc.), the trees might have been exposed to a short- or long-term stress depending on weather conditions.

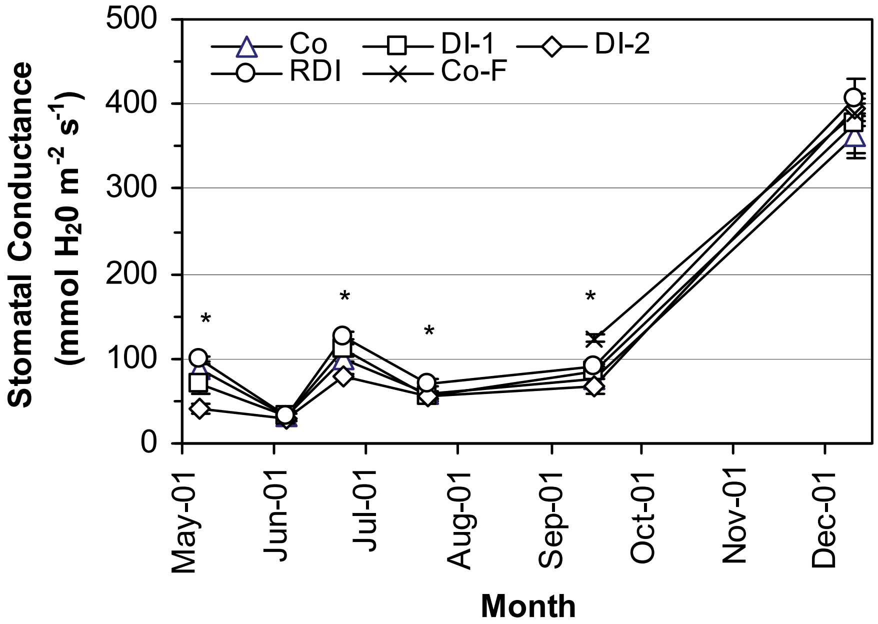

Fig. 3.4 Mean stomatal conductances in the different irrigation treatments from May to December 2001 (each data point represents the mean ± SE of 6-8 replicate leaf samples; asterisks depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Stomatal conductance was significantly lower in the RDI treatments after the trees had been exposed for 1 and 4 weeks, respectively, compared to the control (Fig. 3.5). Compared to the previous year, difference in stomatal conductances between the RDI treatment and control was minor (35% after week 1 and 31% after week 4). RDI trees appeared to be less stressed when a more moderate reduction in irrigation water was applied compared to the previous year (water was withheld completely for four weeks) (Fig. 3.2).

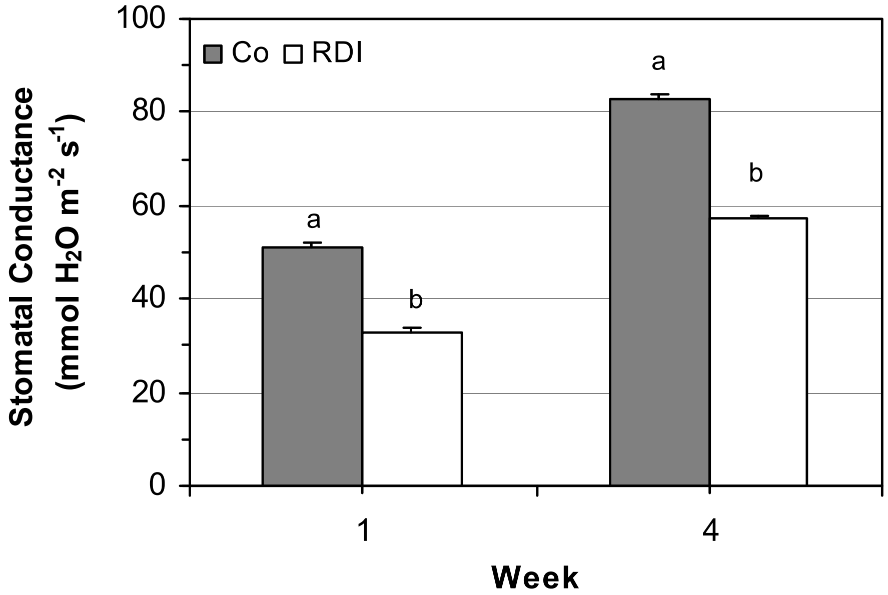

Fig. 3.5 Differences in mean stomatal conductance between the Co and RDI treatments at midday during the stress period before flowering 1 week (1 June 2001) and 4 weeks (22 June 2001) after the onset of reduced irrigation applications in the RDI treatment (each bar represents the mean ± SE of 6-7 of replicate leaf samples; different letters depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

According to McCutchan and Shackel (1992), midday stem water potential (Ψ_{stem}) represents a very sensitive stress indicator. In a manner similar to g_s, stem water potential was significantly lower in the RDI treatment compared to the control after the RDI trees had been exposed to reduced irrigation water applications for 1 and 4 weeks, respectively (Fig 3.6). The difference in the magnitude of reduction of Ψ_{stem} slightly decreased over the stress period (22% after week 1 and 20% after week 4) as observed in g_s (Fig. 3.5).

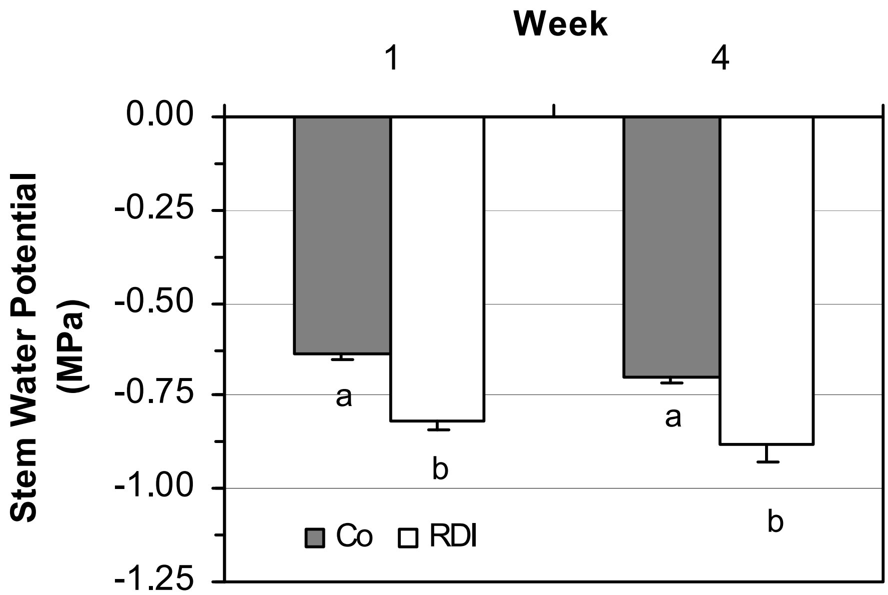

Fig. 3.6 Differences in mean stem water potential between the Co and RDI treatments at midday during the stress period before flowering 1 week (1 June 2001) and 4 weeks (22 June 2001) after the onset of reduced irrigation applications in the RDI treatment (each bar represents the mean ± SE 6-7 replicate leaf samples; different letters depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

In olive (Pavel and Fereres, 1998) among other fruit tree species, stem water potential in stressed and non-stressed trees was lower than those observed in mango. Schaffer et al. (1994) reported leaf water potentials (exposed leaves) of about -2.5 to -3.0 MPa in mango after a drying cycle of 40 days. They concluded that osmotic adjustment apparently took place as water deficit developed and attributed the osmotic adjustment to changes mediated through the latex inclusions.

Differences in Ψ_{stem} between the reduced irrigation treatments (DI-1, DI-2, RDI) and the control (Co) were not significant (Fig. 3.7) in December 2001 before the second stress period and after 24 days of stress exposure of the RDI trees (24 January 2002). Stem water potentials of the reduced irrigation treatments were lower than those of the control and significantly lower than those of the farm control. The similar response in Ψ_{stem} of the three reduced irrigation treatments might be attributed in part to rainfalls in November/December 2001 (Fig. A.3), although the three treatments received different amounts of water. Stem water potential measurements appeared to represent a suitable indicator of water status in mango trees.

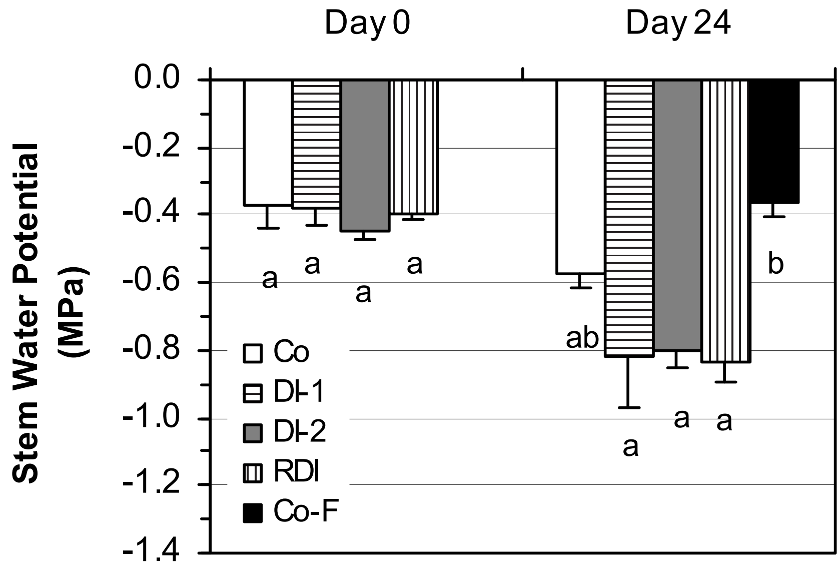

Fig. 3.7 Differences in mean stem water potential between the various irrigation treatments at midday before (31 December 2001) and after 24 days (24 January 2002) of the stress period in the RDI treatment during the last growth stage of fruit growth (each bar represents the mean ± SE of 4 replicate leaf samples; different letters depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

3.3.3. Growing Season 2002/2003

Patterns of photosynthetic rates (Pn) (Fig. 3.8) and stomatal conductances (g_s) (Fig. 3.9) were similar during the 2002/2003 growing season. Low Pn rates and g_s from June until November 2002 in the treatments Co, RDI, and Co-F (as observed in the previous years, Fig. 3.2, 3.4) might have been attributed in part to limiting environmental factors such as relative humidity (Fig. A.2) rather than irrigation since those treatments were fully irrigated to field capacity. Gonzalez (2003, personal communication) observed also low Pn rates and g_s in mangoes in spring and early summer in Australia associated with low VPD values. Generally, photosynthetic rates and stomatal conductances were highest in the farm control (Co-F) in comparison to the other treatments except for April 2003 and September (g_s only). During November 2002 until February 2003 Pn and g_s were significantly lower in the deficit irrigation treatments (DI-1 and DI-2) in comparison to the other treatments indicating lower irrigation rates affected Pn and g_s and, therefore, appeared to have reduced crop productivity (chapter 4, Fig. 4.10).

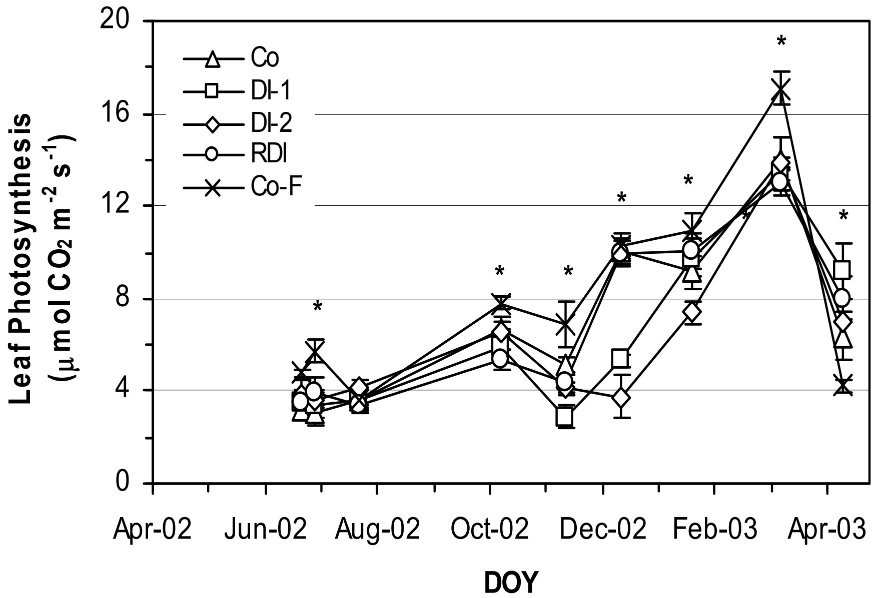

Fig. 3.8 Mean photosynthetic rates at midday in the various irrigation treatments from June 2002 until April 2003 (each point represents the mean ± SE of 4 replicate leaf samples; asterisks depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

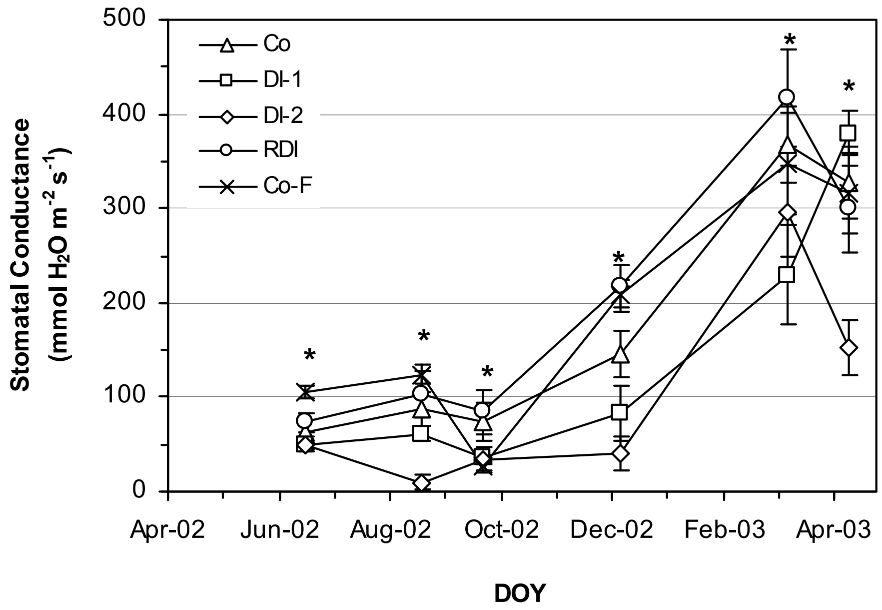

Fig. 3.9 Mean stomatal conductances in the various irrigation treatments from June 2002 until April 2003 (each data point represents the mean ± SE of 4-5 replicate leaf samples; asterisks depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

The difference in irrigation between treatments was to a large extent reflected in the Ψ_{stem} measurements (Fig. 3.10). The farm control usually displayed higher Ψ_{stem} values than the other treatments in a manner similar to Pn rates and g_s. Stem water potentials of the treatments Co and RDI were usually very similar in magnitude like the farm control except for May, Jun, and December. Stem water potential of the deficit irrigation treatments (DI-1 and DI-2) was lower than the other treatments indicating that those trees were stressed by low irrigation water applications. Lower stem water potentials in May and June 2002 in comparison to the farm control were apparently associated with reduced irrigation water application before flowering in the four treatments (Co, DI-1, DI-2, RDI).

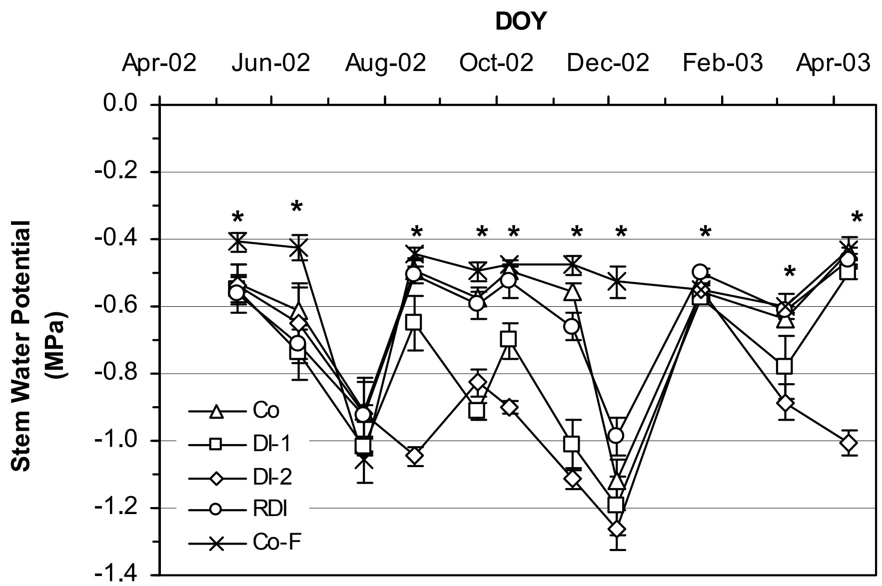

Fig. 3.10 Seasonal fluctuation in stem water potential in the various irrigation treatments from May 2002 until April 2003 (each data point represents the mean ± SE of 4-9 replicate leaf samples; asterisks depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

When comparing the three methods (stem water potential, photosynthesis, and stomatal conductance) with respect to their potential to detect plant water deficits, stem water potential appeared to be the most sensitive water status indicator followed by stomatal conductance. Similar observations have been made in tree crops by Moriana and Fereres (2002) in olives and by Girona et al. (1993) in peach among others.

3.4. Conclusions

Seasonal patterns of photosynthesis, stomatal conductance, and stem water potential, were described in 'Kent' mango trees. Stem water potential in the farm control and in part in the Co and RDI treatments during the 2002/2003 season showed that Ψ_{stem} values for non-stressed mangoes fluctuated between -0.4 and -0.6 MPa over the season in a subtropical climate.

Stress responses to water deficits were detected after the trees were exposed to irrigation water reductions in May/June (pre-flowering stress) by stem water potential followed by stomatal conductance indicating that they were more sensitive stress indicators than photosynthesis. Since the trees needed 1-2 months to recover from severe water deficits during pre-flowering (May/June 2000) in the RDI treatment and reaching, therefore, in part into the growth phase of flower bud formation, it appeared to be advisable to reduce irrigation water application to some extent but not to completely withhold the water before flowering. Low photosynthetic rates and stomatal conductances as well as low stem water potentials during August, September, and October 2002, appeared to be associated rather with environmental factors than with irrigation management. Over-irrigation (Co-F) or even optimum irrigation (Co) did not improve photosynthesis at that time of the year, since the water uptake by the trees appeared to be limited by low stomatal conductances. The deficit irrigation treatment DI-2 followed by DI-1 displayed the lowest stem water potentials especially during the months August-November 2002 in contrast to the other treatments indicating that during this period of tree growth severe water reductions might affect tree productivity substantially.

Based on the physiological measurements, RDI and at some periods during the season the DI-1 treatment seemed to present possible irrigation scheduling practices that could be adopted by the growers. Furthermore, our studies showed that stem water potential can be used as a water status indicator in mango trees.

4. Effect of Irrigation Reductions on Vegetative and Fruit Growth, Yield, and Fruit Quality

4.1. Introduction

The annual vegetative and reproductive development of trees is for the grower useful in the planning of management procedures like spraying, fertilization, and irrigation. Vegetative growth of mango and other sub/tropical trees is not continuous but occurs as intermittent, short lasting flushes of terminal buds, before returning to a quiescent state (Schaffer et al., 1994). Three types of shoots can be produced: vegetative, reproductive, and mixed shoots. Depending on the cultivar, shoots can produce flushes up to four times a year (Davenport and Nuňez-Elisea, 1997). Initiation of flushes is usually influenced by pruning, irrigation, fertilization and temperature (Reece et al., 1949). Water deficit can lead to physiological stress in a plant and can be a natural effect or by irrigation management. To achieve high yields of a particular crop under deficit irrigation, a good understanding of the vegetative and reproductive crop responses under varying degrees of available soil water is essential. Most studies about the effects of irrigation on vegetative and reproductive growth have been done on temperate fruit crops. Reduced irrigation led to a decrease in trunk cross sectional area in most fruit tree crops (Ginestar and Castel, 1996; Mills et al., 1996; Boland et al., 2000). In apples, Ianca (1985) illustrated the sensitivity of trunk growth as a better parameter for water stress than fruit growth. The time of application of water stress is also very important. In apples, the later stress was applied in the season the less trunk growth was reduced in comparison with fully irrigated trees (Ianca, 1985). Ginestar and Castel (1996) indicated that there appeared to be an exponential relationship between water stress and trunk growth in citrus. Most authors perceived a decrease in shoot extension rate when reduced irrigation was initiated (Mitchell et al., 1989; Proebsting et al., 1989; Johnson et al., 1992; Boland et al., 1993; Caspari et al., 1993; Girona et al., 1993). Mitchell et al. (1986) showed that pear trees still kept some of their potential for shoot extension even after water stress began and that the decrease in growth only started when the parchedness of the soil profile started to influence root growth. The same pattern was observed by Steinberg et al. (1990) in peaches where water stress led to a decrease in the root:stem diameter ratio that was due to the roots being a stronger sink.

Mitchell et al. (1989) suggested that reduced irrigation led to a decrease in shoot growth while improving fruit growth for the specific period and that reduced irrigation is a good management tool for high density orchards to control vegetative growth.

Different organs on the same plant are known to have different sensitivities to deficit irrigation, with fruit growth being generally less sensitive to water deficit than vegetative growth (Higgs and Jones, 1991). However, Berman and DeJong (1996) found that fruit fresh weight was very sensitive to water deficit regardless of crop load level, while fruit dry weight was only reduced at heavy crop loads. It has been hypothesized that under deficit irrigation fruits can adjust osmotically thus enabling them to retain fruit turgor and grow actively (Mills et al., 1996). In most cases reduced irrigation had no negative effect on fruit growth and yield (Johnson et al., 1992; Torrecillas et al., 1993; Naor et al., 1999), and in some cases even led to an improvement in quality and yield in apples (Kilili et al., 1996). The time of application of stress is of great importance with almost no effect observed when pear trees were stressed during the fruit expansion phase (stage 3) (Mitchell et al., 1989; Caspari et al., 1993). Ginestar and Castel (1996) and Kilili et al. (1996) found that deficit irrigation early in the season and during stage 2 of fruit growth led to a decrease in fruit weight in apples and citrus and return bloom the next year, but had no effect during stage 3.

Fruit quality can be viewed as an absence of defects (Shewfelt, 1999), a degree of excellence or suitability for a particular use (Abbot, 1999). Because of the quality-conscious consumer, the production of fruits needs to shift from ‘quantity production’ to ‘quality production’. Most horticultural produce is sold by weight (Jones and Tardieu, 1998). Water as the major component of fruits (Kaufmann, 1972) contributes to a large extent to their weight. Water is, however, increasingly becoming very scarce and thus very expensive. There is therefore a great demand for irrigation scheduling methodologies that are precise in order to minimize the cost of production (Castel and Buj, 1990) while maintaining or even improving fruit quality. Some irrigation studies have been conducted to also evaluate internal quality besides of size in various fruit species (Crisosto et al., 1994; Ginestar and Castel, 1996; Irving and Drost, 1987; Li et al., 1989; Mills et al., 1996).

Although one irrigation study has been conducted in South Africa in mangoes (Mostert and Hoffman, 1996), little or no information is available on how and to what extent reduced irrigation strategies affect the vegetative and fruit growth as well as fruit quality. The objective of this study was to determine the effect of deficit irrigation on mango tree growth and crop production and to identify periods during the year to initiate water deficits that will reduce vegetative growth while not affecting fruit growth.

4.2. Materials and Methods

Details about the irrigation treatments and study site have been described in chapter 2.

Trunk diameter was measured (10-12 trees per replicate) in yearly intervals using a digital caliper (Mitutoyo, Japan). Measurements were taken 10 cm above the rootstock parallel and perpendicular to the tree row, and mean trunk cross-sectional area (TCA) was determined. Light interception was measured below the canopy at 30 cm above ground at an area of 1.50 m x 1.60 m at both sides of a tree (perpendicular to the row) on 4 trees per treatment and at full sunlight using a PAR ceptometer (PAR-80, Decagon, WA, USA). Relative light interception by the various treatments was calculated by subtracting measurements below the canopy from those of full sunlight.

The effect of irrigation treatments on fruit growth was evaluated in 2000/2001 by measuring the axial and perpendicular fruit diameter (5-10 fruits per tree, 2 trees per replicate) in weekly intervals starting 52 days after flowering until harvest with a digital caliper. For fruit dry weight estimations, 20-25 fruits were randomly collected from a separate set of trees on a weekly basis. Following measurements of fruit diameter, the fruits were oven-dried at 50-75ºC until they reached equilibrium in dry weight, and their dry weight was then determined. Dry weight of tagged fruits was estimated using regression analysis between fruit diameter and dry weight of the destructive fruit samples at each sampling date. Mean fruit dry weight accumulations over the season were used to calculate relative growth rates (RGR). Ambient air temperatures were monitored at a weather station located on the farm within 5 km of the study site. Degree-day accumulations were integrated into the RGR equations instead of daily time intervals, because fruit growth and development are dependent on temperature. Degree-days accumulations were calculated from daily minimum and maximum temperatures by the single-sine method (Zalom et al., 1983) with lower and upper thresholds at 13 and 35ºC.

Effects of irrigation treatments and crop load on fruit growth were evaluated in 2001/2002 by measuring the axial and perpendicular fruit diameter and the length (5 fruits per tree) with a caliper in weekly intervals starting 1-2 weeks after flowering until harvest in 2001/2002. Before the natural fruit drop in October, fruits of 2-3 trees of the control (Co) were tagged and measured. After the fruit drop, fruit number per tree was thinned down to two crop loads (19±2 and 43±3 fruits per tree) in three trees per treatment and crop load. Because of a fruit counting error, only the high crop load treatment was available in the farm control. Dry weight of tagged fruits was estimated using regression analysis between fruit diameter, length, and dry weight of the destructive fruit samples at each sampling date. Relative growth rates were calculated as described above.

The harvest of the experimental trees (10-12 trees per 4 replicates per treatment) followed normal farm procedures. Fresh weight of each individual fruit was measured at harvest for yield determinations. Fruits destined for quality evaluations (18 fruits per 4 replicates per treatment) were washed and waxed after harvest in the packing shed. Fruit quality parameters, such as total soluble solids (refractometer, N-1E, Atago, Japan), titratable acid (titrator, DL 50, Mettler Toledo, Switzerland) weight loss, firmness (penetrometer, FT 327, Southtrade, Italy), and flesh color (SAMGA color charts), were determined at harvest, six days after ripening at room temperature (24±0.3ºC), after storage under shipping conditions (11±0.1ºC for 28 days) and six days after ripening at room temperature.

Fruit samples (4 x 2 replicate fruit samples per replicate per treatment, 100 mg, freeze-dried, ground powder) were extracted three times with 80% ethanol; after centrifugation the supernatants were decanted and combined. The extracts were air-dried and stored at -40ºC. For the determination of soluble carbohydrates, the dried supernatants were dissolved with 10 mL of deionized water. The pH of the solution was adjusted to 7.0 with 0.2 M KOH or 0.2 M H_2PO_4. Organic acids were removed from the solution by adding 0.6 g of anion exchange resin (Amberlite IRA-67, Sigma Chemicals); and the sample was shaken for 30 minutes. The solution was then filtered and dried at 48ºC. The residue was then dissolved with 3-6 mL (depending on fruit maturity) deionized water and filtered with a 0.45 μm membrane filter. A 20-μl was injected into a high pressure liquid chromatograph (HPLC; model 1100, Agilent, Gemany) equipped with a Zorbax carbohydrate column (4.6 x 250 mm) and a refractive index detector (model 1100, Agilent, Germany) for nonstructural carbohydrate separation and quantification at a wavelength of 254 nm. The column was eluted with a solution of 75% acetonitrile and 25% deionized water at 1.4 mL min^{-1} at 30ºC. Standard solutions of fructose, glucose, and sucrose (Sigma Chemicals) in the range of 1-8 mg mL^{-1} were used as external standards for calibration. Peak area was used to quantify the nonstructural carbohydrates relative to the external standard solutions.

Data were analyzed with ANOVA (F-Test) with one and/or two factors (irrigation and/or crop load, storage conditions). Means were compared by using the Tukey-Test at P=0.05.

4.3. Results and Discussion

4.3.1. Vegetative Tree Growth

Trunk cross-sectional area (TCA) is linearly related to the aboveground weight and size of the tree (Westwood et al., 1970). TCA was significantly reduced in Co, DI-1, and DI-2, compared to the farm control (Co-F) in 2002 and 2003 (Fig. 4.1). TCA in the RDI treatment was significantly lower in 2001 and 2003 than Co-F but not in 2002. Low increases in TCA of the RDI treatment in 2001 were apparently attributed to the two periods of water withholding in spring and summer of the 2001/2002 growing season. The high increase in TCA during 2002 in the RDI treatment seemed to be associated to some extent to a relatively low yield during this year (Fig. 4.10). Reductions in vegetative growth in the four treatments (Co, DI-1, DI-2, RDI) affected tree productivity (yield) in 2001 (Fig. 4.10). In a manner similar to our results, Chalmers et al. (1981,1984), Mitchell et al. (1989), and Mills et al. (1996) observed a reduction in vegetative growth in trees exposed to reduced irrigation treatments in contrast to control trees in peach, Asian pear, and apple. Part of the larger amounts of irrigation water applied to the farm control trees might have been used for excessive vegetative growth.

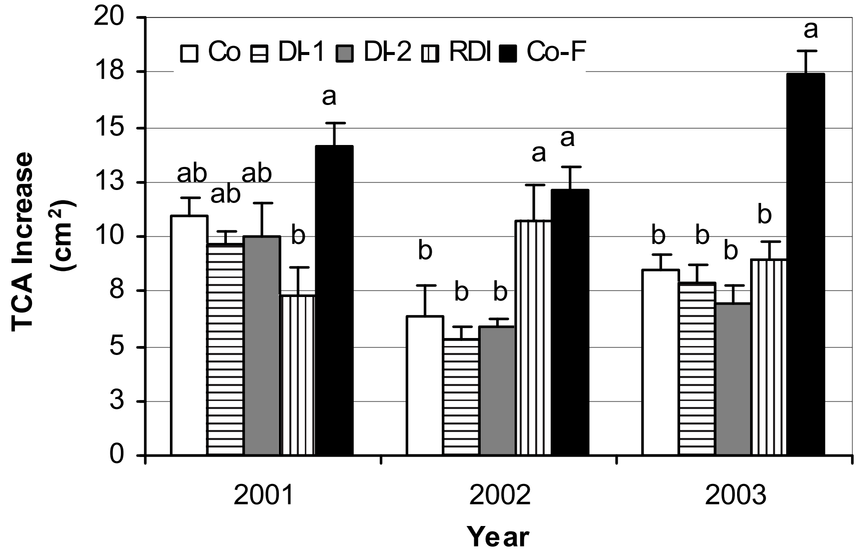

Fig. 4.1 Mean increases in trunk cross-sectional area (TCA) in the different irrigation treatments during January 2000 - February 2003 (each bar represents the mean ± SE of 4-8 replicate tree samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Shoot numbers per tree, after the vegetative flush had taken place after harvest (Fig. 4.2), confirmed the reduction in vegetative growth as observed in trunk cross-sectional area increases (Fig. 4.1). Shoot numbers per tree were significantly reduced in the Co, DI-1, DI-2, and RDI treatments in comparison to the farm control (Co-F) in 2003, while during 2002 differences between treatments were not significant. Differences between the Co and RDI treatments were minor. However, both DI treatments were significantly lower than the control (Co). Deficit irrigation affected most severely the DI-2 treatment indicating that this irrigation treatment might apparently lead to substantial yield reductions in the following years if continued.

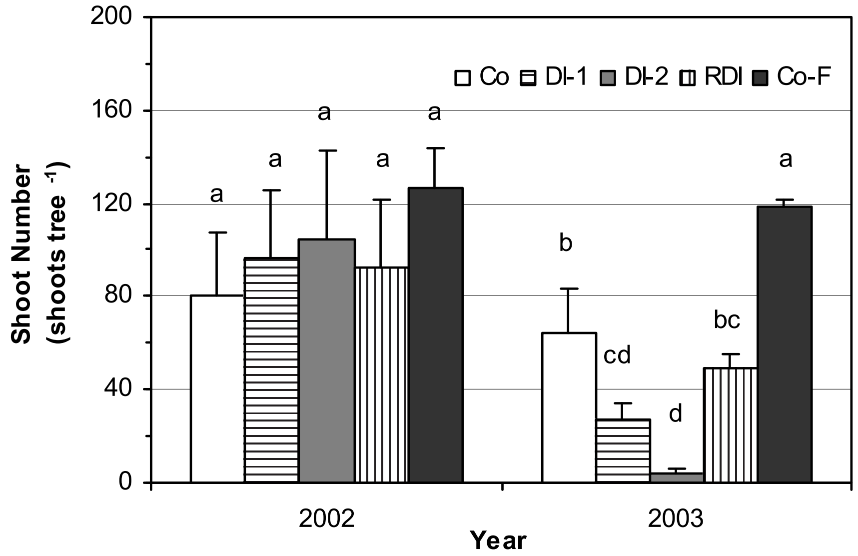

Fig. 4.2 Mean shoot number per tree in the different irrigation treatments during 2000-2003 (each bar represents the mean ± SE of 4 replicate tree samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Light interception studies confirmed the results of TCA and shoot numbers per tree in the different treatments with the farm control intercepting significantly the most light in comparison to the other treatments (Fig. 4.3). The control showed significantly more light interception than the DI-2 and RDI treatments, while differences in light interception between the DI-1, DI-2, and RDI treatments were minor. High increases in TCA (Fig. 4.1), shoot number per tree (Fig. 4.2), and light interception (Fig. 4.3) in Co-F apparently indicated that large amounts of irrigation water were used for vegetative growth leading to generally low irrigation water use efficiencies in Co-F over the years (Fig. 2.5, 2.11, 2.17) in comparison to the other treatments.

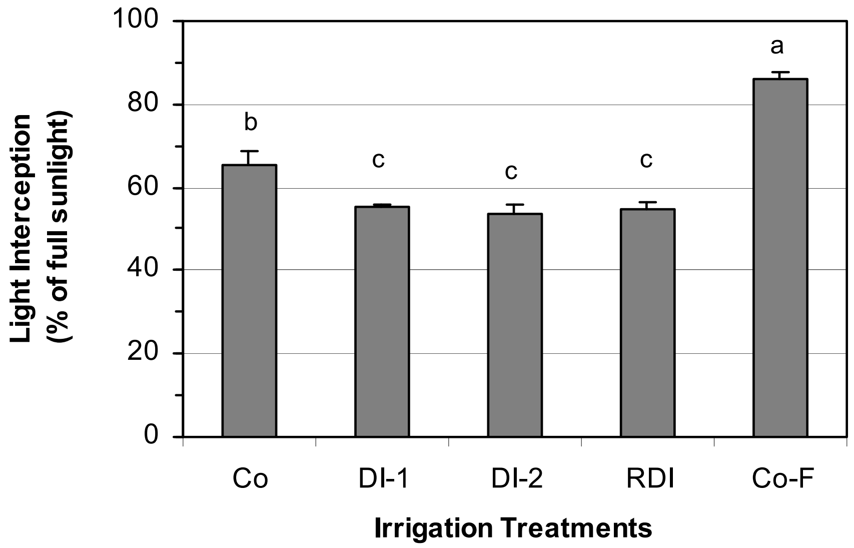

Fig. 4.3 Mean light interception per tree in the different irrigation treatments during September 2002 until March 2003 (each bar represents the mean ± SE of 4 replicate tree samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

4.3.2. Seasonal Pattern of Fruit Growth

The seasonal pattern of fruit diameter showed no significant differences between treatments during the 2000/2001 growing season (Fig. 4.4).

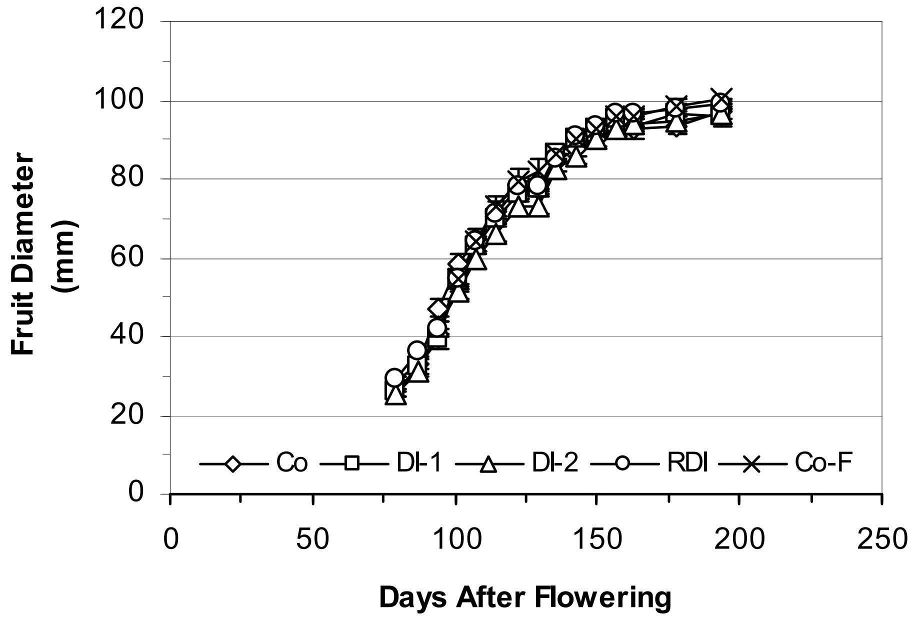

Fig. 4.4 Seasonal pattern of fruit diameter for the different irrigation treatments in 2000/2001 (each data point represents the mean ± SE of 8 replicate fruit samples; details of irrigation scheduling are outlined in Table 2.4).

The double-sigmoid growth curve of stone fruits is traditionally divided into three stages. The first and third stages are characterized by rapid growth interspaced by a stage of slow growth (Lilleland, 1932). Like many deciduous stone fruits, such as peach (Lilleland, 1932), apricot (Lilleland, 1930), and plum (Lilleland, 1933), seasonal dry weight accumulations of subtropical mango fruits exhibited a double-sigmoid growth curve (Fig. 4.5, 4.7, 4.8). There were no significant differences between irrigation treatments similar to results in pears exposed to RDI as reported by Jerie et al. (1989). Irving and Drost (1987) and Behboudian et al. (1994) also found no effect on fruit growth in apple and peach, respectively, when RDI was implemented late in the season. The RDI treatment followed by the farm control (Co-F) displayed the highest dry weight accumulations towards harvest. In contrast to the control (Co), reduced irrigation treatments tended to increase fruit dry weight accumulation towards harvest. A similar response to reduced irrigation treatments has been reported for citrus by Domingo and Ruiz-Sanchez (1996). However, Huang et al.

(2000) reported reduced growth rates of citrus fruits in response to deficit irrigation carried out during the last stage of fruit growth. The rapid recovery of citrus fruit growth rates after re-watering (Huang et al., 2000) might be attributed to the strong sink strength of fruits attracting, therefore, water more efficiently than other tree organs (Forshey and Elfving, 1989; Mills et al., 1996).

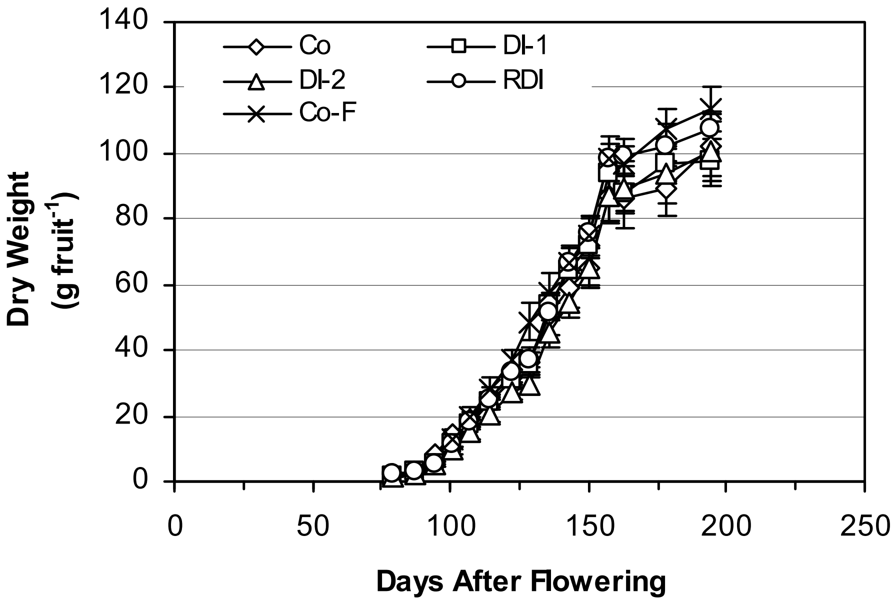

Fig. 4.5 Estimated fruit dry weight accumulation during the growing season of 2000/2001 (each data point represents the mean ± SE of 8 replicate fruit samples; details of irrigation scheduling are outlined in Table 2.4).

Fruit relative growth rates on a dry weight basis showed a similar pattern in mango over the season (Fig. 4.6) as has been described for peach displaying three phases of sink activity (DeJong and Goudriaan, 1989) and apple (Schechter et al., 1993). In apples, relative growth rates as well as percent cell division increased rapidly during phase I and by the end of phase I, 85% of the cell division had occurred (Schechter et al., 1993). In phase II, fruit relative growth rates decreased exponentially in peach (Pavel and DeJong, 1993a, b) and apple (Pavel and DeJong, 1995), while relative growth rates remained relatively constant in peach or took an asymptotic course in apple during the last growth phase (phase III). During the first phase (87-94 DAF) fruit relative growth rates increased quite rapidly in all irrigation treatments except for RDI reaching a peak at 101 DAF. In the RDI treatment, phase I of fruit relative growth rates was extended by one week showing the effect of pre-harvest water stress, i.e.

prolonging the period of dormancy before flowering. During phase II, relative growth rates in mango fruits decreased exponentially, while in phase III relative growth rates declined slightly taking an asymptotic course.

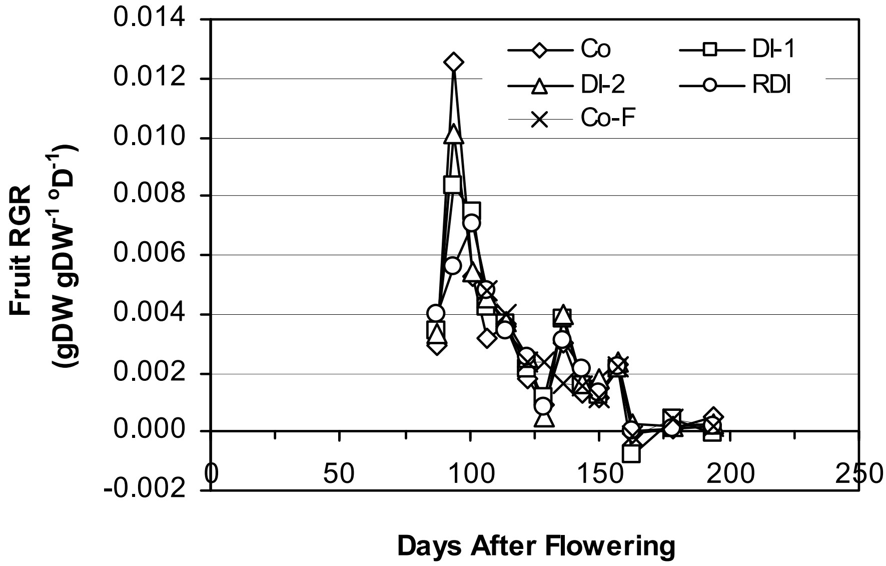

Fig. 4.6 Mean relative growth rates of mango fruits during the growing season of 2000/2001 subjected to different irrigation regimes (each data point represents the mean ± SE of 8 replicate fruit samples; details of irrigation scheduling are outlined in Table 2.4).

Irrigation treatments did not affect dry weight accumulations over the season of 2001/2002 within a crop load level (Fig. 4.7) indicating that the higher applications of irrigation water were used in part for vegetative growth (Fig. 4.1-4.2) and in part wasted (Fig. 2.6).

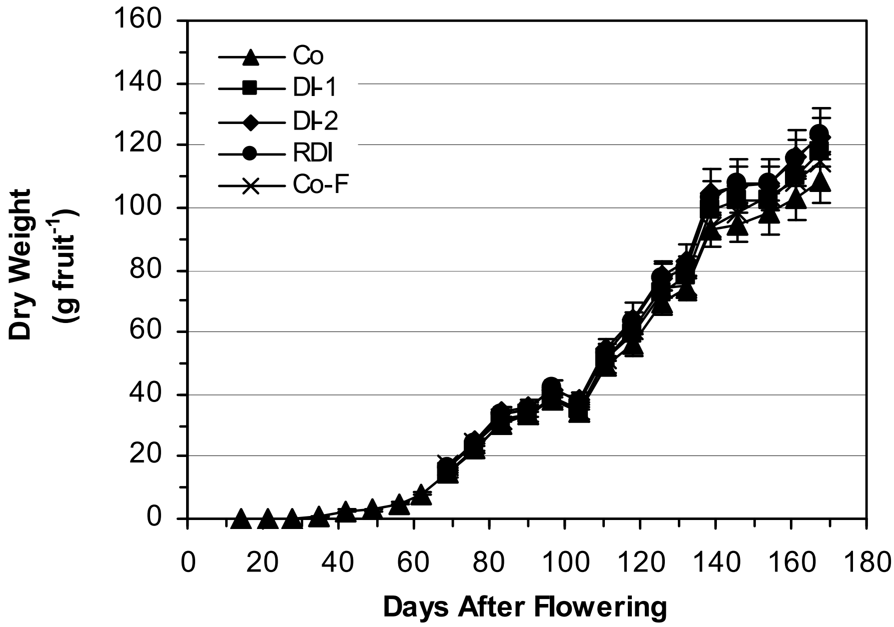

Fig. 4.7 Seasonal pattern of fruit dry weight for the different irrigation treatments in 2001/2002 (each data point represents the mean ± SE of 3-6 replicate fruit samples; details of irrigation scheduling are outlined in Table 2.4).

In contrast to irrigation treatments, crop load treatments did affect significantly dry weight accumulation in fruits after fruit drop in October 2001 (Fig. 4.8) in a manner similar to results reported in peach by Pavel and DeJong (1993b). There were no interactions between crop load and irrigation treatments.

Fruit dry weight data of the low crop level of the Co treatment were used for the adaptation of peach growth model to mangoes, since they represented the maximum fruit growth potential.

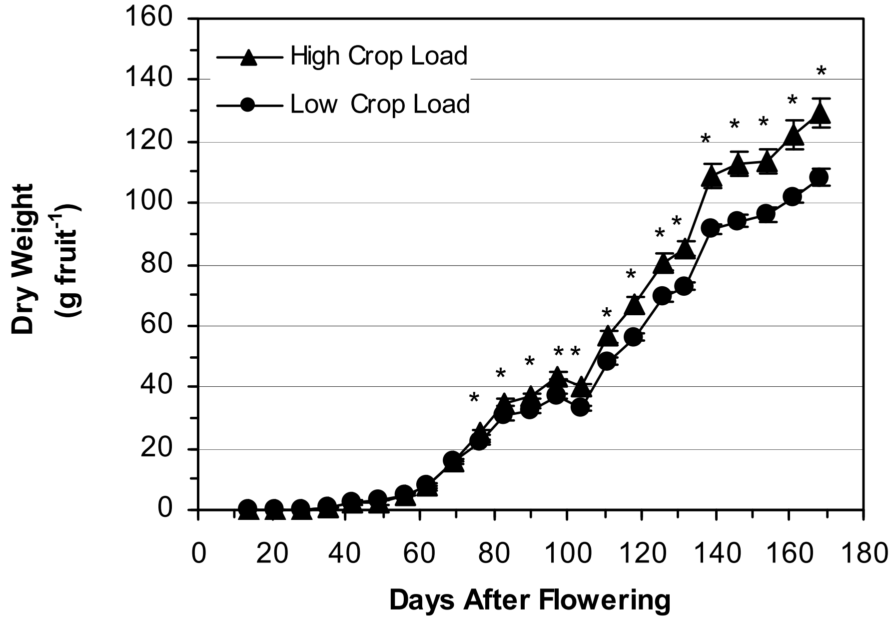

Fig. 4.8 Seasonal pattern of fruit dry weight for the high (43±3 fruits per tree) and low (19±2 fruits per tree) crop load treatments in 2001/2002 (each data point represents the mean ± SE of 12-15 replicate fruit samples; asterisks depict significant differences between treatments at P=0.05).

Significant differences in fructose (Fig. 4.9 A), glucose (Fig. 4.9 B), and sucrose (Fig. 4.9 C) concentrations between irrigation treatments were observed at some sampling dates during mango fruit development but they were not consistent. In apples, reduced irrigation regimes increased concentrations of nonstructural carbohydrates during fruit development (Mills et al. 1996). Concentrations of fructose and sucrose decreased over the growing season, while sucrose concentrations increased with increasing fruit development and maturity, respectively, in a manner similar as observed in peach (Pavel and DeJong, 1993a).

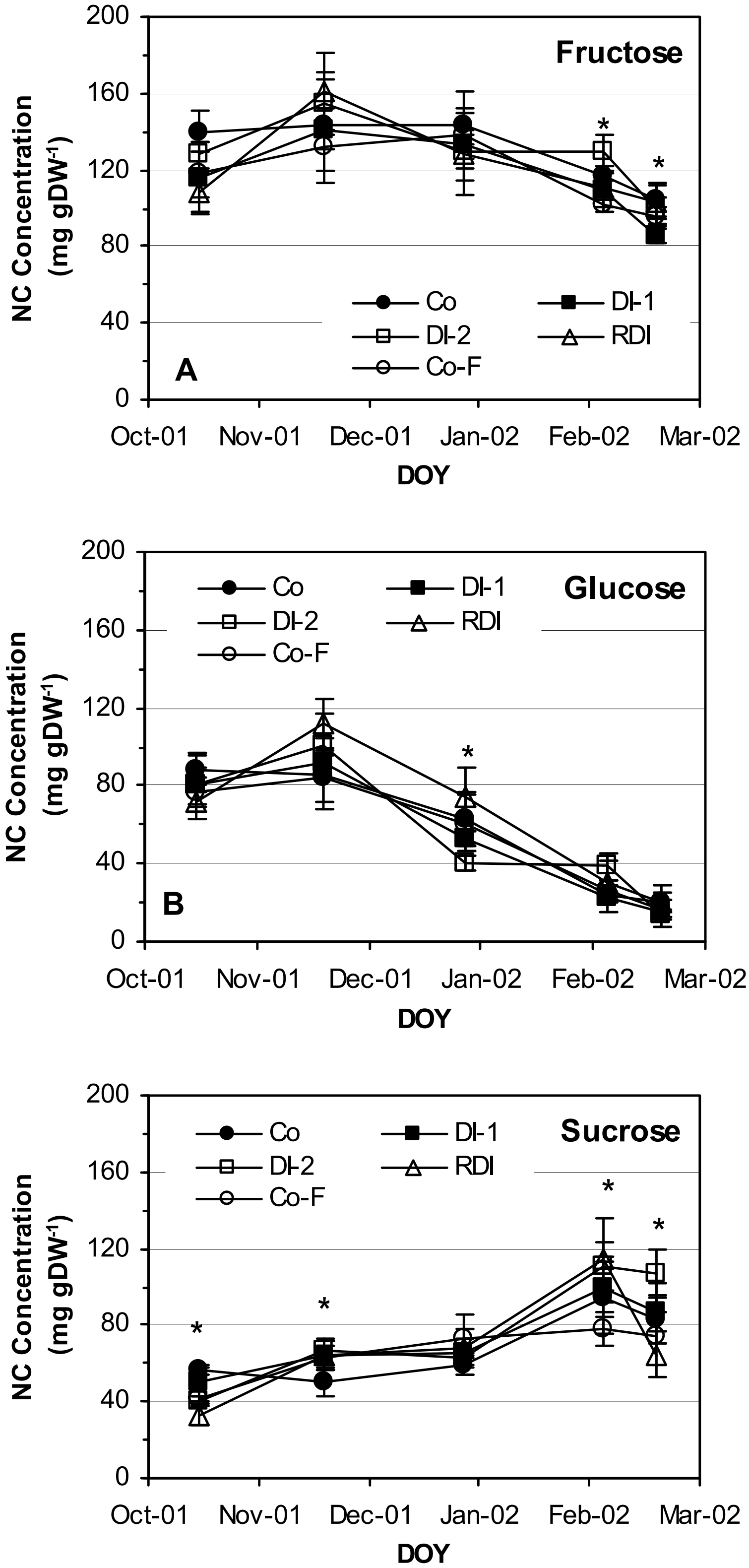

Fig. 4.9 Seasonal pattern of nonstructural carbohydrates concentrations (fructose, A; glucose, B; and sucrose, C) in 2001/2002 (each data point represents the mean ± SE of 4 replicate fruit samples; asterisks depict significant differences between treatments at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

4.3.3. Fruit Yield and Quality

Differences in yields were significant between irrigation treatments in the season of 2002 (Fig. 4.10) in comparison to 2001 and 2003. The yield of the farm control was significantly higher in 2002 than those of the DI-2 and RDI treatments. Similar effects of deficit irrigation on yield have been reported in several fruit crops by Irving and Drost (1987), Strabbioli (1992), Torrecillas et al. (1993), and Caspari et al. (1994). The relatively low yield of Co in 2002 apparently reflected that this treatment was only irrigated to 82 and 88% of the field capacity during 2000/01 and 2001/02. The low yield in the RDI treatment in 2001 might be attributed to carry-over effects of last year's stress periods (complete water withholding for 4 weeks before flowering and during the last stage of fruit growth). The farm control (Co-F) showed the highest yield across all irrigation treatments during the three years indicating that a part of the higher irrigation water applications was used by the trees for fruit growth. Low yields in 2001 and 2003 interspaced with high yields in 2002 displayed the alternative bearing habit of mangoes.

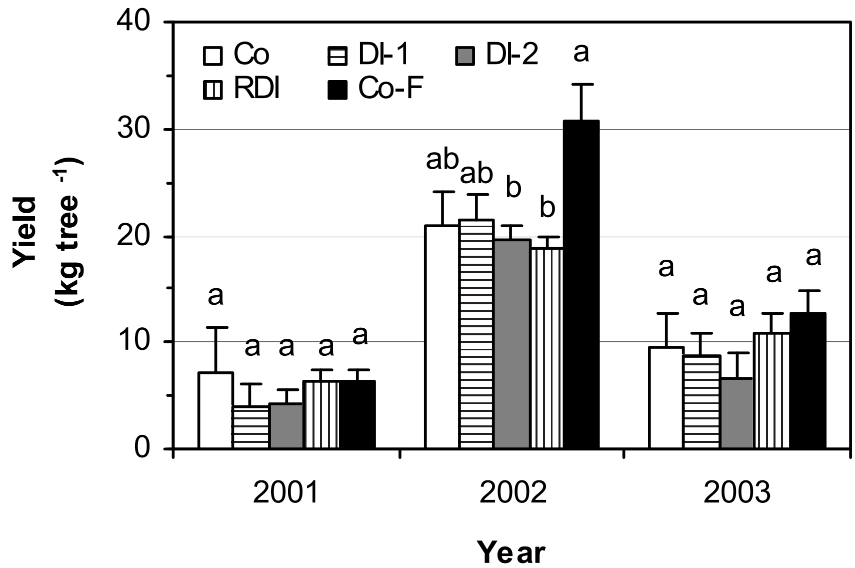

Fig. 4.10 Mean fruit yield of the different irrigation treatments for the seasons of 2001-2003 (each bar represents the mean ± SE of 4 replicate tree samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Flesh color at harvest, did not show any significant differences between treatments over the years (Fig. 4.11). In many cases the intensity of the flesh color was out of range of the color chart in 2003.

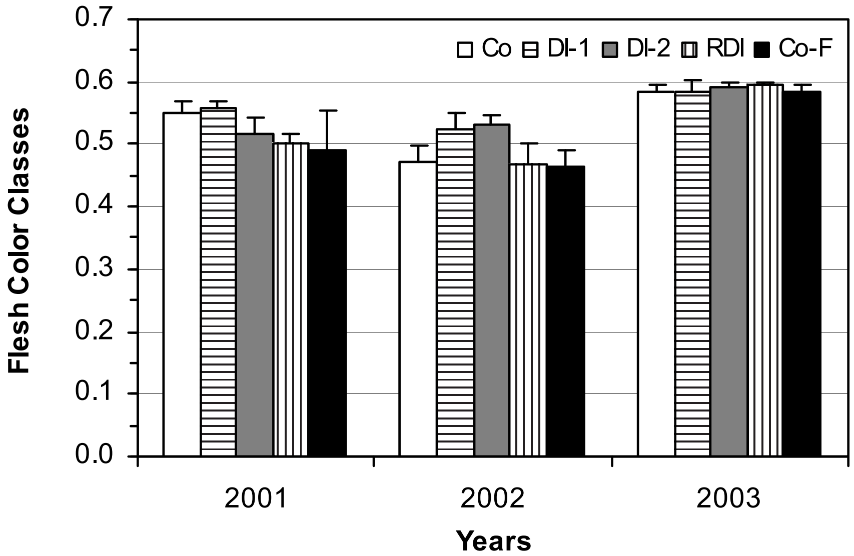

Fig. 4.11 Mean fruit flesh color classes (SAMGA color chart 1998) of the different irrigation treatments at harvest for the 2001-2003 seasons (each bar represents the mean ± SE of 4 replicate fruit samples, P=0.05; details of irrigation scheduling are outlined in Table 2.4).

Concentrations of total soluble solids (TSS) did not show any significant differences between irrigation treatments at harvest (Day 1 - Harvest/Local) (Fig. 4.12). Data from 2003 were chosen as a representative example, since the results were very similar for the three years. In contrast to our results, Crisosto et al. (1994) observed higher concentrations of TSS in fruits of trees that were deficit irrigated. Significant differences were observed between the DI-2 and Co-F treatments after the fruits ripened for 6 days at room temperature (Local) and after the shipping simulation (day 1, Export). The low concentrations of TSS in the DI-2 treatment might be attributed to a reduction in photosynthetic capacity induced by water deficit. However, after the fruits of the shipping simulation (Export) were ripened for 6 days at room temperature, differences between treatments had disappeared. It appears that pre-harvest irrigation management practices may not necessarily influence fruit quality at harvest but may rather affect post-harvest quality of fruits at least for a short period of time.

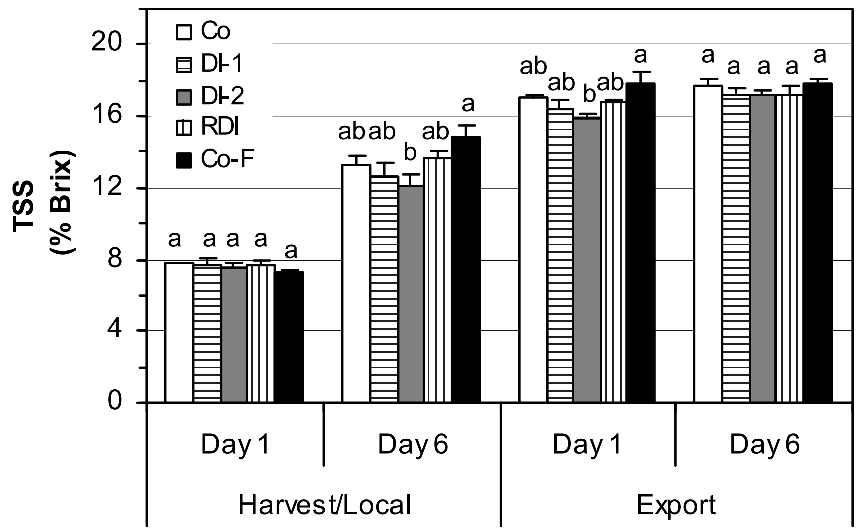

Fig. 4.12 Mean concentration of total soluble solids (TSS) in fruits of the different irrigation treatments at harvest (day 1), after ripening at room temperature (24±0.3 °C, Local, day 6) and after shipping simulation (Export, day 1) for 4 weeks at 11°±0.1 °C followed by ripening at room temperature (24±0.3 °C, Export, day 6), for the 2002/2003 season (each bar represents the mean ± SE of 4 replicate fruit samples; different letters depict significant differences at P=0.05; details of irrigation scheduling are outlined in Table 2.4).

In contrast to TSS concentrations, representing the total concentration of soluble solids, the analysis of individual nonstructural carbohydrates showed that only at harvest (day 1) significant differences of fructose occurred between treatments (Fig. 4.13). The RDI treatment displayed a significantly lower concentration of fructose than that of the farm control. Concentrations of glucose and sucrose were not significantly different between treatments at harvest and on day 1 after the shipping simulation (Export).

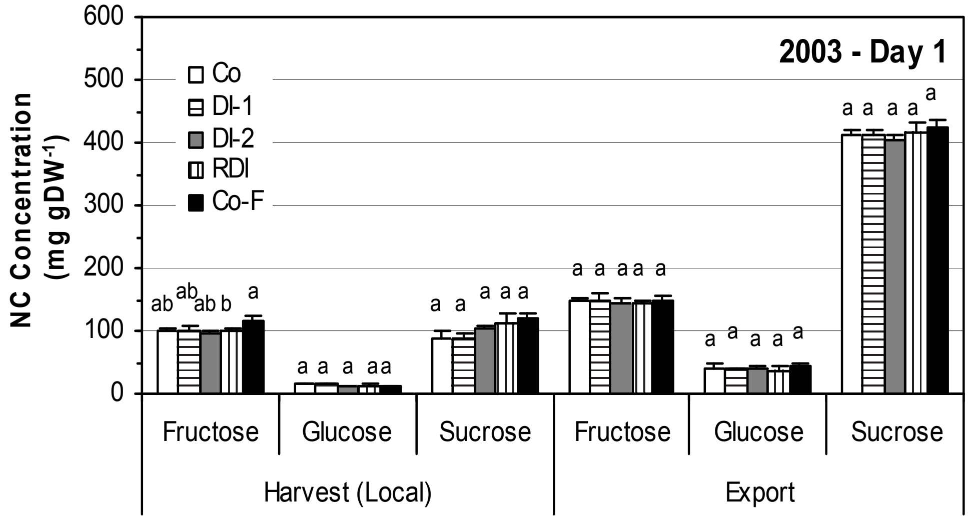

Fig. 4.13 Mean concentration of nonstructural carbohydrates in fruits of the different irrigation treatments on day 1 at harvest, after ripening at room temperature (Local), and after shipping simulation (Export), for the 2002/2003 season (each bar represents the mean ± SE of 4 replicate fruit samples; different letters depict significant differences at P=0.05, for details of storage conditions see legend of Fig. 4.12; details of irrigation scheduling are outlined in Table 2.4).

After the fruits were ripened for 5 days (day 6) at room temperatures after harvest and after the shipping simulation, differences between treatments in concentrations of fructose, glucose, and sucrose, were not significant (Fig. 4.14).

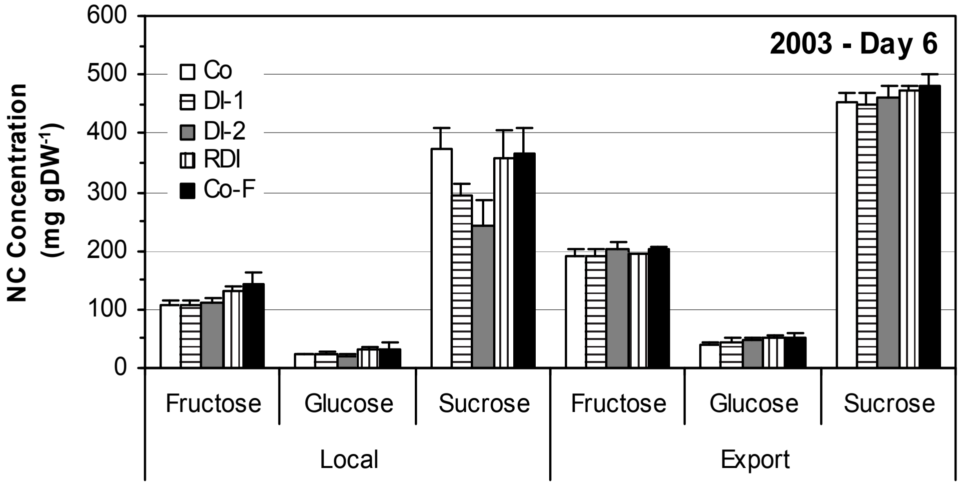

Fig. 4.14 Mean concentration of nonstructural carbohydrates in fruits of the different irrigation treatments on day 6 after ripening at room temperature (Local) and after shipping simulation (Export) for the 2002/2003 season (each bar represents the mean ± SE of 4 replicate fruit samples, P=0.05; for details of storage conditions see legend of Fig. 4.12; details of irrigation scheduling are outlined in Table 2.4).

Across all treatments, differences between ripening procedures for 6 days under local and export conditions were significant in fructose, glucose, and sucrose concentrations (Fig. 4.15). Sucrose was the dominating nonstructural carbohydrate followed by fructose and then glucose in 'Kent' mango fruits. The relatively low TSS (Fig. 4.12) but high TA concentrations (Fig. 4.17) at harvest, and higher TSS and lower TA concentrations after ripening indicated that part of the organic acids might have been converted to nonstructural carbohydrates.

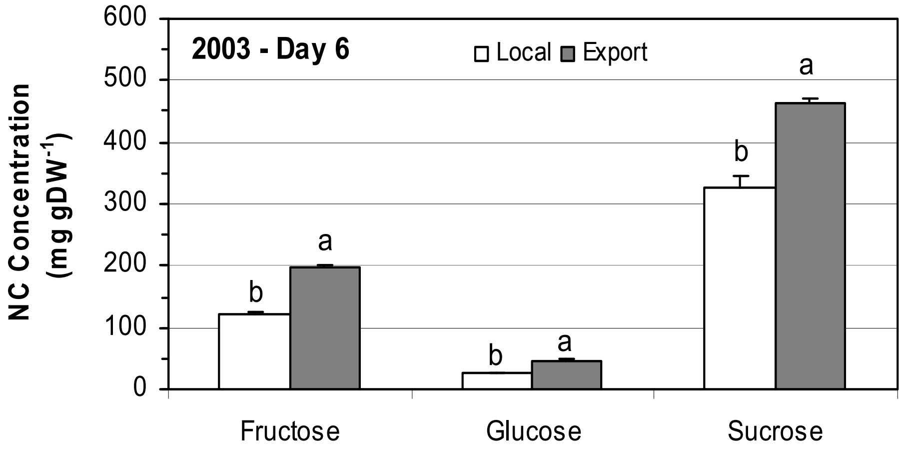

Fig. 4.15 Mean concentration of nonstructural carbohydrates in fruits of the different irrigation treatments on day 6 after ripening at room temperature after harvest (Local) and shipping simulation (Export) for the 2002/2003 season (each bar represents the mean ± SE of 4 replicate fruit samples; different letters depict significant differences at P=0.05, for details of storage conditions see legend of Fig. 4.12).

Flesh color is commonly used as maturity index by South African mango growers, while TSS concentration is generally applied by grape, citrus, and other fruit growers. A comparison between the two maturity indices showed that there was no relationship between flesh color and TSS concentration at harvest suggesting that flesh color might not be the best index for maturity determinations in mango (Fig. 4.16).

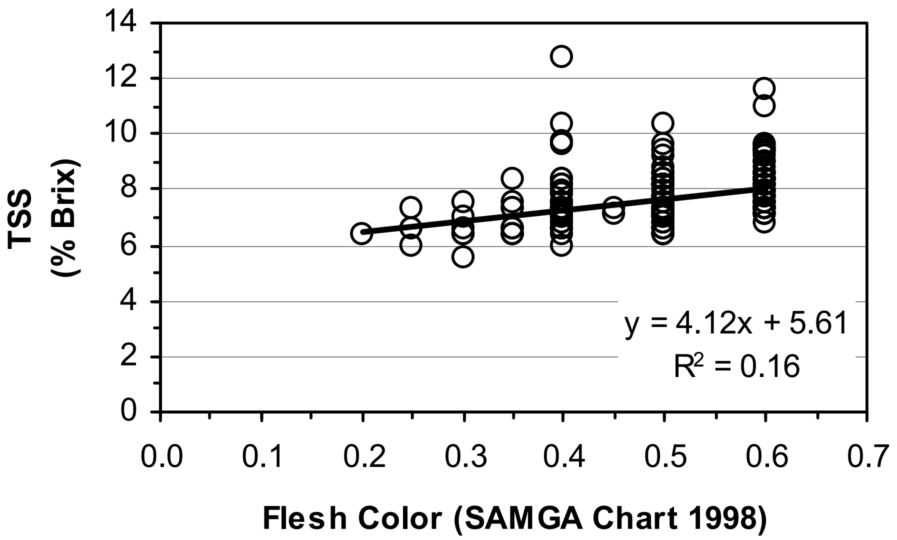

Fig. 4.16 Relationship between flesh color and total soluble solid (TSS) concentration in mangoes at harvest 2002 (n=214).

Concentrations of titratable acids (TA) showed significant differences between treatments at harvest (day 1) and after the shipping simulations (Export) (Fig. 4.17). Generally, fruits of the farm control showed the lowest TA concentrations, while differences between reduced irrigation treatments (DI-1, DI-2, RDI) were not significant.

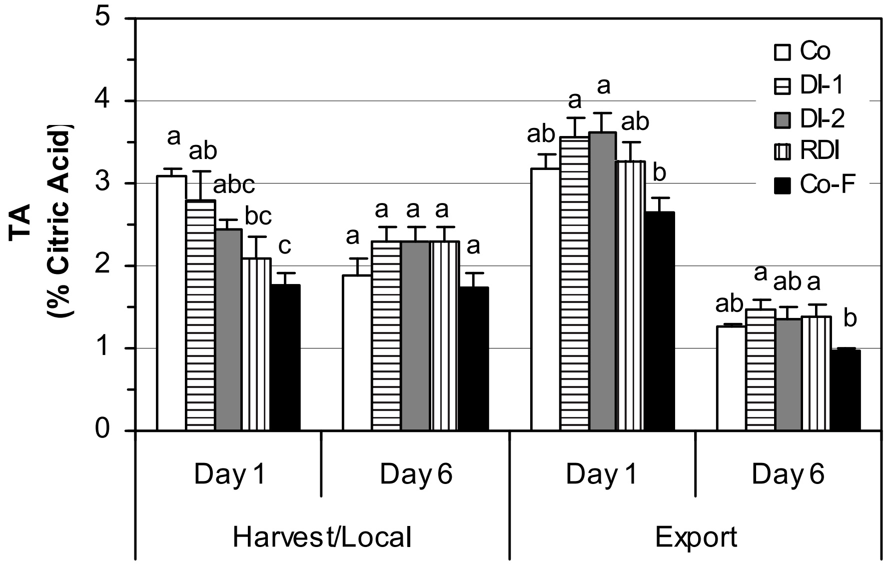

Fig. 4.19 Mean concentration of titratable acids (TA) in fruits of the different irrigation treatments at harvest (day 1), after ripening at room temperature (Local, day 6), after shipping simulation (Export, day 1) followed by ripening at room temperature (Export, day 6), for the 2002/2003 season (each bar represents the mean ± SE of 4 replicate fruit samples; different letters depict significant differences at P=0.05: for details of storage conditions see legend of Fig. 4.12; details of irrigation scheduling are outlined in Table 2.4).

Fruit firmness was not significantly affected by irrigation treatments (Fig. 4.18) and decreased with in the maturing fruits. The lack of firmness in fruits after shipping simulation and ripening for 6 days at room temperature in comparison to fruits that were ripened for six days at room temperature after harvest indicated that the length of the storage period after shipping was substantially reduced under room temperature conditions.

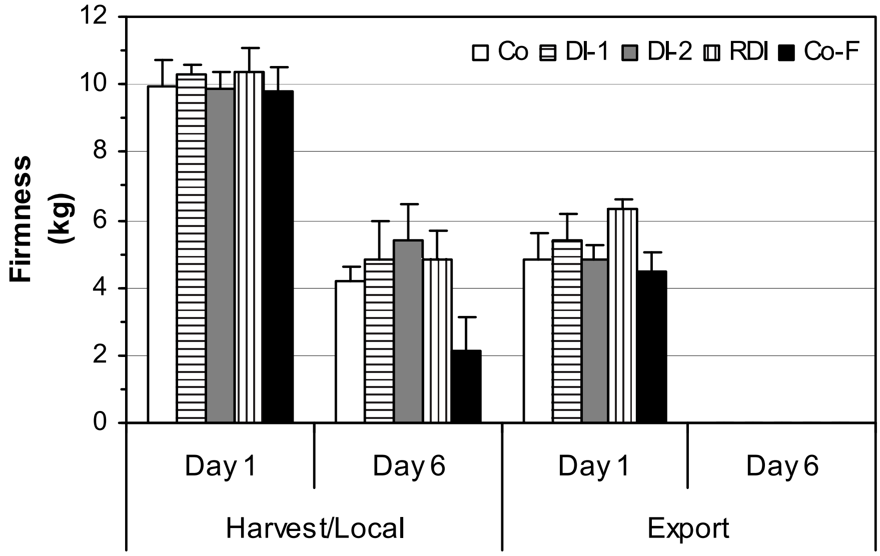

Fig. 4.18 Mean firmness in fruits of the different irrigation treatments at harvest (day 1), after ripening at room temperature (Local, day 6), and after shipping simulation (Export, day 1) followed by ripening at room temperature (export, day 6), for the 2002/2003 season (each bar represents the mean ± SE of 4 replicate fruit samples, P=0.05; for details of storage conditions see legend of Fig. 4.12; details of irrigation scheduling are outlined in Table 2.4).

Relative fruit fresh weight losses did not display significant differences between treatments after the various storage conditions (Fig. 4.19). However, relative fruit fresh weight losses were substantially increased after shipping and ripening at room temperature in comparison to the other two treatments (Local, day 6 and Export, day 1) indicating that the length of storage after shipping is limited at room temperatures of 24±0.3°C.

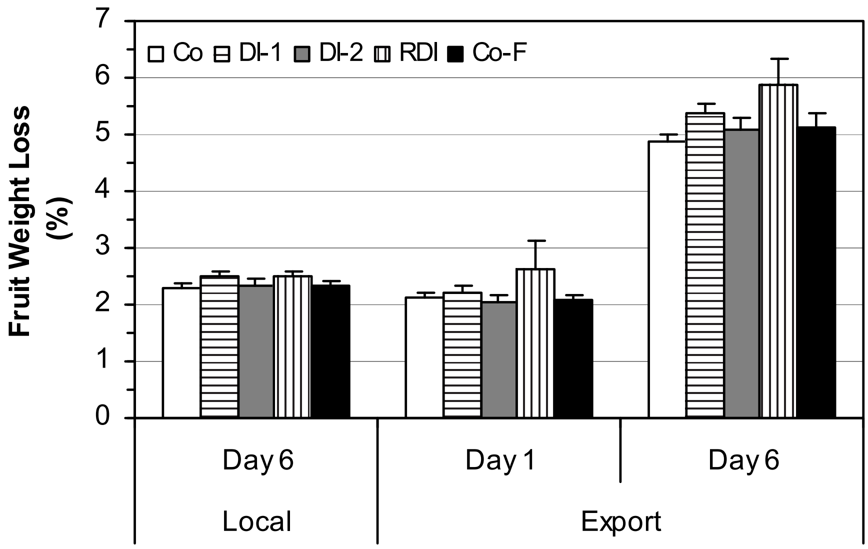

Fig. 4.19 Mean relative fruit fresh weight losses in fruits of the different irrigation treatments after ripening at room temperature for 6 days after harvest (Local) and after shipping simulation (Export, day 1) followed by ripening at room temperature (Export, day 6), for the 2002/2003 season (each bar represents the mean ± SE of 4 replicate fruit samples, P=0.05; for details of storage conditions see legend of Fig. 4.12; details of irrigation scheduling are outlined in Table 2.4).

4.4. Conclusions

The irrigation treatments Co, DI-1, DI-2, and RDI, did reduce vegetative growth as indicated by trunk cross-sectional area in comparison to the farm control (Co-F) over the years. High increases in TCA, shoot number per tree, and light interception in Co-F apparently indicated that large amounts of irrigation water were used for vegetative growth leading to generally low irrigation water use efficiencies in Co-F over the years in comparison to the other treatments. Fruit yield was significantly reduced in DI-2 and RDI compared to the other treatments in 2002 but not in the other years. In comparison to irrigation high crop loads had a larger effect on fruit growth. However, it cannot be excluded that with increasing tree age and crop load fruit growth might be affected in addition by irrigation. During fruit development, differences in irrigation scheduling were not well reflected in concentrations of nonstructural carbohydrates, since differences between the various treatments were inconsistent. Among the studied maturity indices (flesh color, firmness, total soluble solid concentration - TSS, titratable acid concentration - TA) TSS and TA provided the most sensitive indices to assess quality at harvest followed by firmness. Flesh color is commonly used as maturity index by South African mango grower. A comparison between TSS concentration and flesh color showed no relationship between them at harvest suggesting that flesh color might not be the most suitable index for maturity determinations in mango and might need to be re-evaluated. Differences between irrigation treatments were detected only in fructose concentrations at harvest but disappeared as soon as the fruits ripened. Comparing concentrations of fructose, glucose, and sucrose, 6 days after the fruits were harvested (local) or taken out of the shipping simulation (export) showed that the ripening process took its course much faster in export compared to local fruits as indicated by the higher concentrations of nonstructural carbohydrates in export fruits. Although the study was conducted over three years conclusive suggestions about the effect of the various irrigation treatments on vegetative and fruit growth and quality can only be made after a longer time period because of seasonal differences in climate and the alternating growth habit of mangoes.

5. Adaptation of the Peach Growth Model to Mango

5.1. Introduction

To facilitate integration of information about the carbon budget of mango trees, the PEACH model (Grossman and DeJong, 1994) was converted to a mango model. The results of the model will be used to examine factors that limit mango crop yield and to make recommendations to improve management of mango production.

The PEACH model simulates fruit and vegetative growth based on information about tree biomass, photosynthetic capacity, respiration by all organs, and weather data. The model uses the hypothesis that plants function as assemblies of semi-autonomous organs that compete with one another for carbohydrate resources (White, 1979; Harper, 1980; Watson and Caspar, 1984; Sprugel et al., 1991) as the basis for the simulation of carbon partitioning (Grossman and DeJong, 1994). Maintenance respiration requirements are given the highest priority for carbon based on studies that found that, under starvation conditions, growth respiration ceases before maintenance respiration ceases (Crapo and Ketellapper, 1981 Amthor, 1989) and the observation that well-managed fruit trees maintain their organs, with the exception of some leaves, throughout the growth period. The partitioning of carbon for growth is based upon each organ’s sink strength and its proximity to carbon sources. The sink strength of each organ type is based upon experimentally determined estimates of the maximum organ growth potential, the genetically determined growth achieved when the organ is grown under optimal environmental conditions in the presences of a non-limiting supply of carbon and other resources (Warren Wilson, 1967, 1972; Wareing and Patrick, 1975; Ho, 1984, 1988; Pavel and DeJong, 1993b; Grossman and DeJong, 1995). Leaves, current-year stems, and fruits are considered to be closest to the source and have highest priority for carbon after maintenance respiration, followed by branches and the trunk, and finally roots.

The PEACH model calculates carbon assimilation using a modified version of the carbon assimilation submodel of SUCROS ’86 (Simple and Universal Crop Growth Simulator) (van Keulen et al., 1982; van Kraalingen and Spitters, 1986), a model that simulates the growth of annual crops. SUCROS ’86 employs Gaussian integration of the instantaneous rate of leaf photosynthesis over canopy depth and diurnal light and temperature conditions (Goudriaan, 1986; Kropff et al., 1987) modified to account for the discontinuous canopy of a fruit tree orchard using empirical data on the seasonal pattern of light interception (Grossman and DeJong, 1994).

Conversion of the PEACH model to simulate mango growth required information on fruit and vegetative growth, tree biomass, photosynthetic capacity, respiration by all organs, and weather information. The PEACH model assumes optimal irrigation and fertilization and is not designed to simulate suboptimal and other environmental conditions directly.

5.2. Materials and Methods

Data that had been collected on mango photosynthesis, vegetative and fruit growth were used in the model. We developed a ‘hybrid peach-mango’ growth model, using mango parameters wherever possible and substituting peach parameters where mango parameters were not available.

Fruit growth potential (Fig. 5.1) was estimated from rapidly growing fruits in the experiment conducted during 2001 (Fig. 4.6 and 4.7). The timing and growth of vegetative flushes was determined from data collected during 2002 and 2003. The PEACH model was revised to permit multiple vegetative flushes in one year. Fruit and leaf respiration rates were obtained from data collected by A. González of CSIRO-Plant Industry in Darwin, Northern Territory, Australia. Temperature and solar radiation were monitored at a weather station located within 5 km of the study site on the farm.

The seasonal pattern of light saturated photosynthetic rate for mango leaves measured during the season of 2002/2003 (Fig. 3.8, 5.2) was incorporated into the photosynthetic module of PEACH.

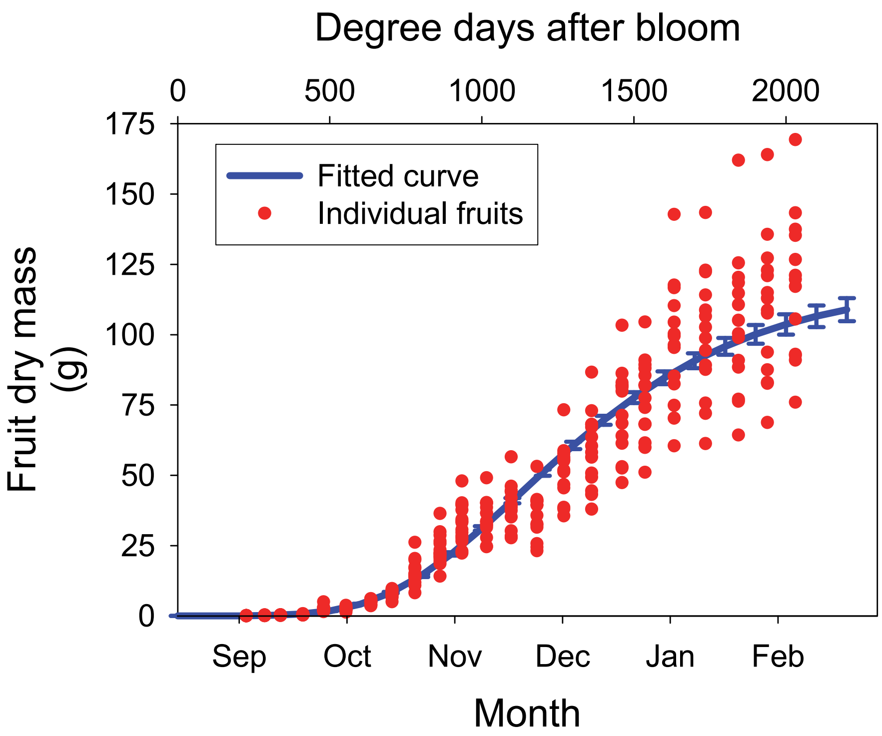

Fig. 5.1 Fruit growth potential of Kent mangoes growing in Hoedspruit, South Africa (points represent fruit dry mass estimated from length, width, and breadth measurements versus degree-days after bloom (upper axis) and month (lower axis); line is fitted curve;. bars represent standard error of the predicted values).

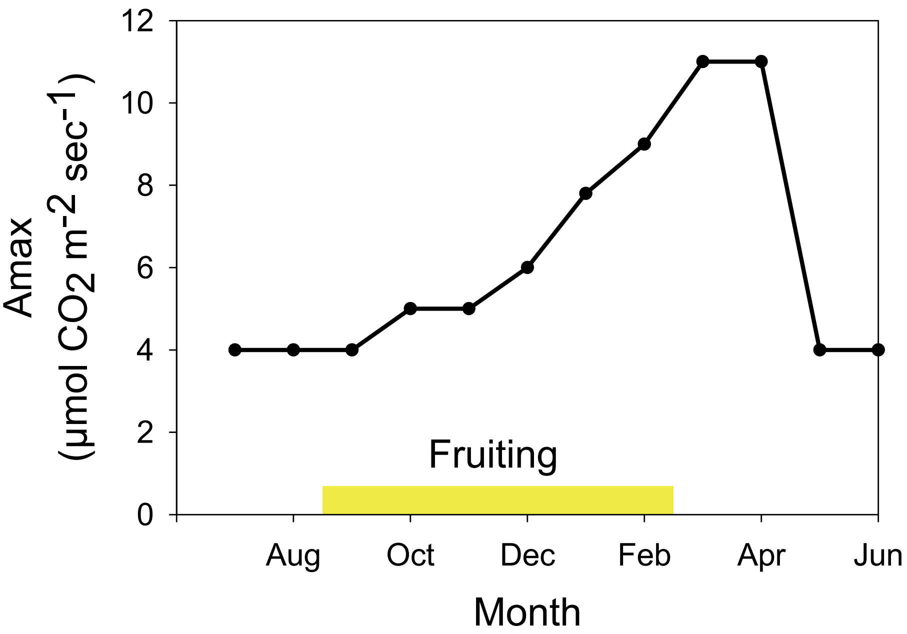

Fig. 5.2 Seasonal pattern of light saturated photosynthetic rate (A_{max}) of 'Kent' mangoes growing in Hoedspruit, South Africa.

5.3. Results and Discussion

Minimum temperature increased slightly through the fruit growth while maximum temperature was relatively constant throughout the year (Fig. 5.3).

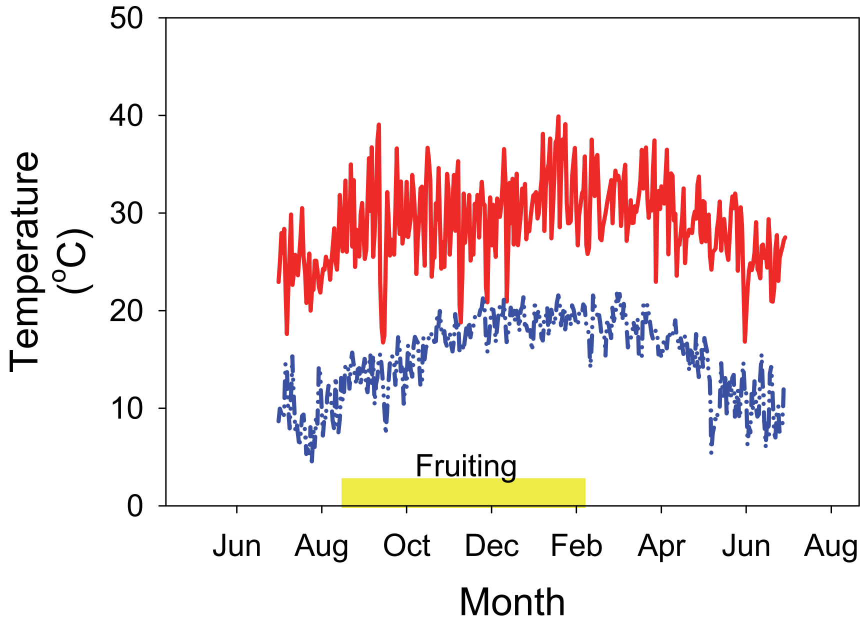

Fig. 5.3 Minimum and maximum temperature at Hoedspruit, South Africa, for the season 2001/2002.

Solar radiation had two peaks, during the middle of the fruit growth period and near the end of fruit growth (Fig. 5.4).

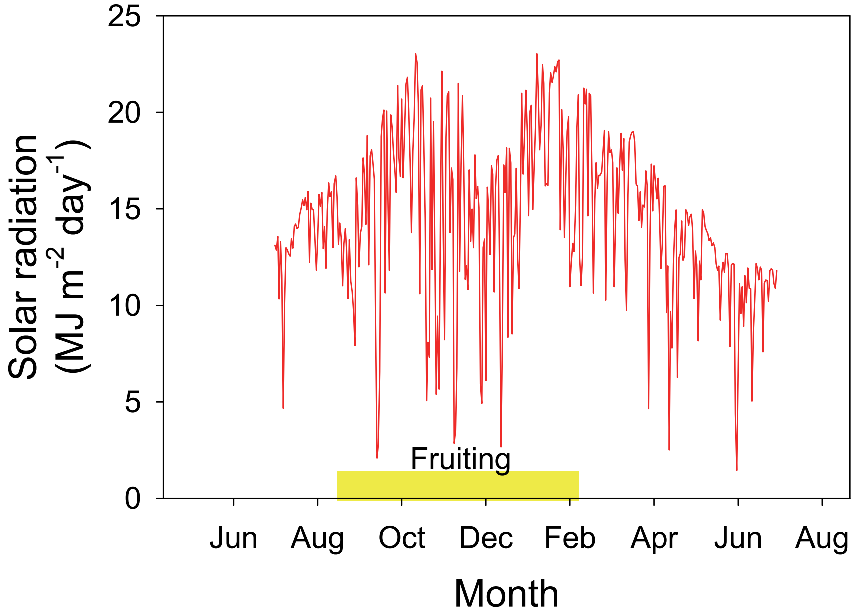

Fig. 5.4 Solar radiation at Hoedspruit, South Africa, for the season 2001/2002.

The photosynthetic rate was lower during the fruiting period (4-9 μmol m^{-2} s^{-1}) than during the period after fruit harvest (11 μmol m^{-2} s^{-1}) (Fig. 5.2). As expected from the photosynthetic rates, simulated carbon assimilation was lower during most of the fruit growth period than it was during the post harvest period (Fig. 5.5). Maintenance respiration increased during the fruit growth period, and remained relatively high after harvest.

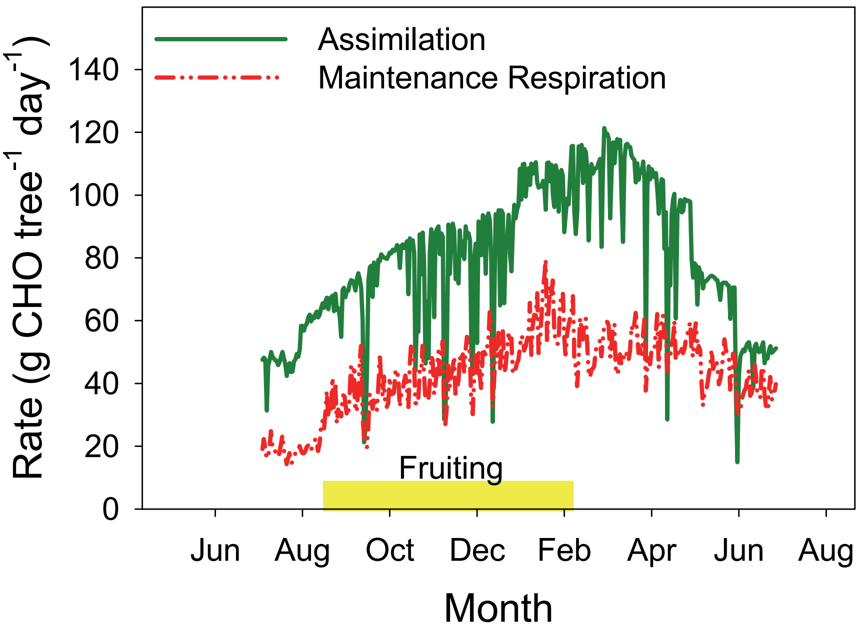

Fig. 5.5 Simulated carbon assimilation and maintenance respiration of a 'Kent' mango tree with a crop load of 30 fruits.

The difference between daily assimilation and maintenance respiration, representing the amount of currently-fixed carbon available to support growth, was somewhat higher during the initial post-harvest period than it was during the fruit growth period (Fig.5.6).

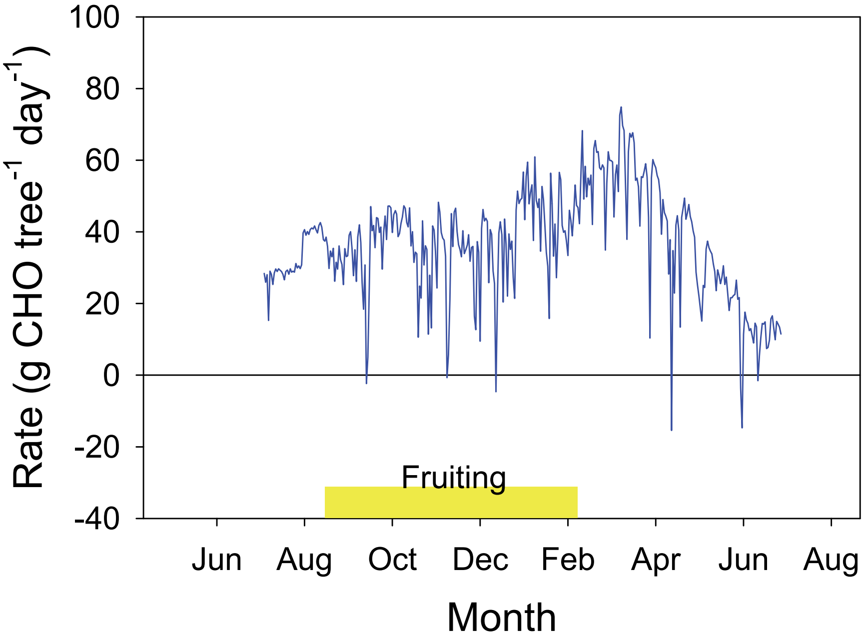

Fig. 5.6 Simulated difference between carbon assimilation and maintenance respiration of a Kent mango tree with 30 fruits.

Fruit growth was limited by carbon availability periodically during growth (Fig. 5.7). Most of the limitations occurred during the final period of fruit growth.

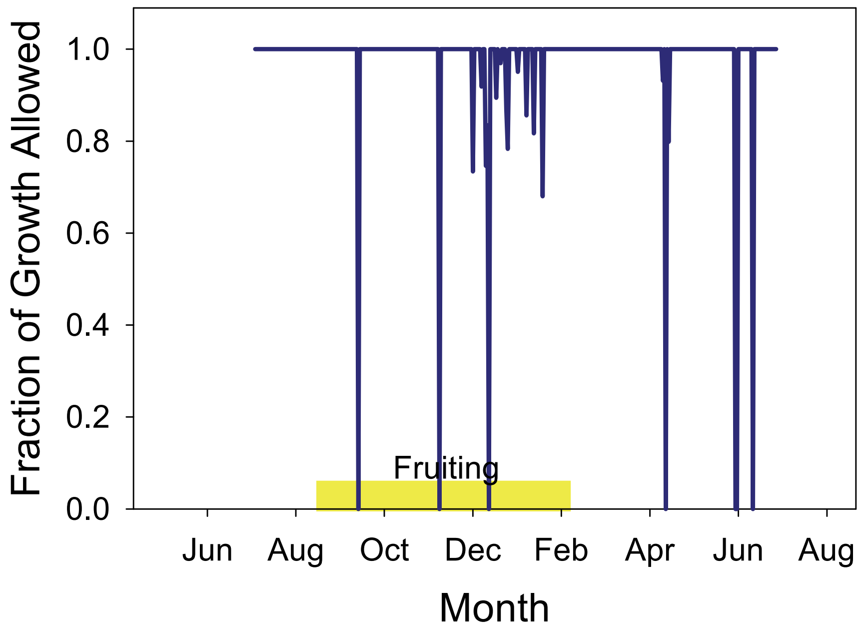

Fig. 5.7 Simulated fraction of growth allowed for fruits, leaves, and stems on a Kent mango tree with 30 fruits.

Final fruit size accounted for 100 g dry weight (Fig. 5.8) corresponding well to the results for heavily cropped trees in the irrigation experiment at Hoedspruit (Fig. 4.9).

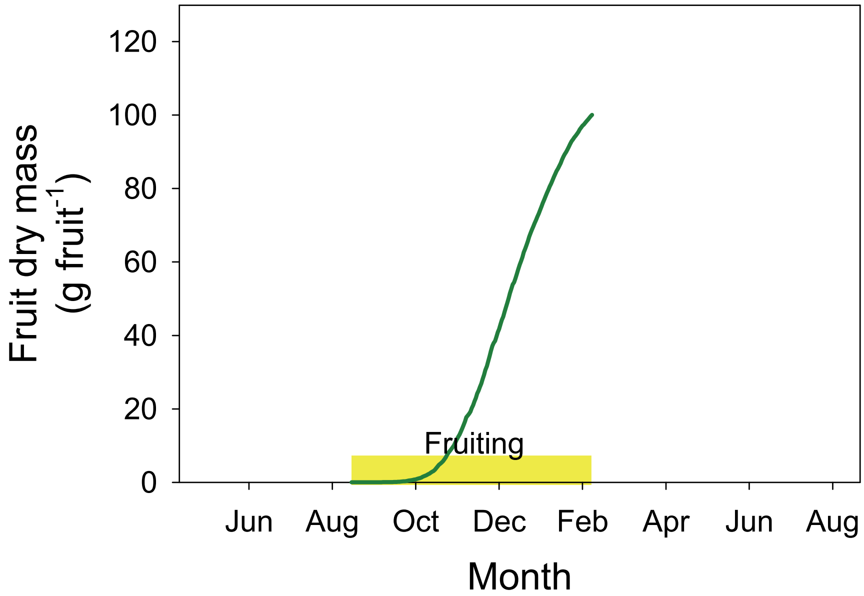

Fig. 5.8 Simulated individual fruit growth on a 'Kent' mango tree with 30 fruits.

The quantity of storage reserves varied from lows of 400-500 g at the beginning of the simulation and the time of fruit harvest (Fig. 5.9). Storage reserves grew during the first half of the fruit growth period and after fruit harvest. Reserves declined during the third vegetative flush. In the future, data on storage carbohydrate will be used to test whether the hypotheses about reserve accumulation used in the model can be supported.

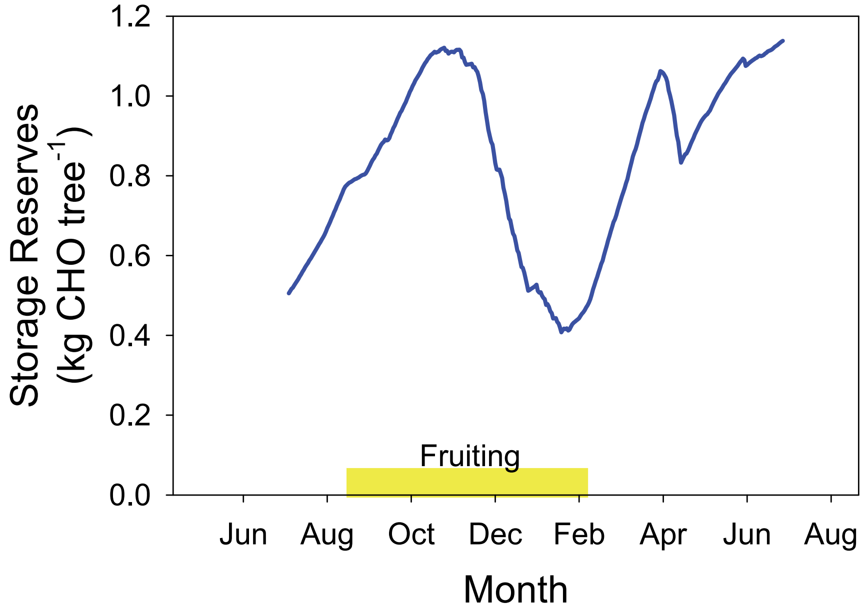

Fig. 5.9 Simulated storage reserves in a ‘Kent’ mango tree with 30 fruits.

Three vegetative flushes were simulated (Fig. 5.10). The potential growth was the same for all three flushes but the realized growth of the first and second flushes was less than the potential growth. The first flush began to grow on August 15, at the same time as bloom. Because this flush coincided with bloom, the number of shoots that were allowed to grow was limited by the number of fruits and the availability of carbon reserves. Growth of the second flush, which began on January 1, near the time of harvest, was limited by intermediate photosynthetic rates, high respiration rates (Fig. 5.5) and low reserves (Fig. 5.9) which reduced the fraction of potential growth allowed (Fig. 5.7). The third flush began growth on April 1 when there were high reserves (Fig. 5.9) and few limitations on growth (Fig. 5.7).

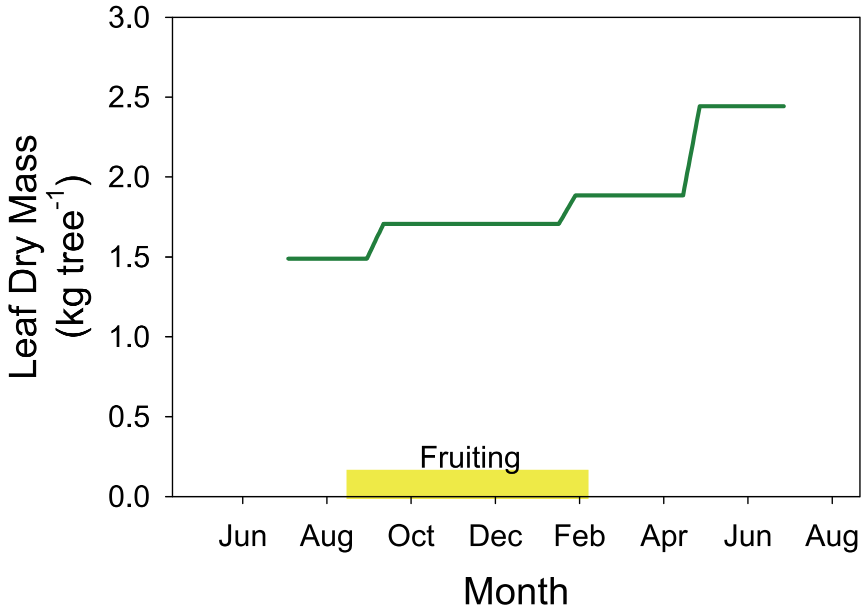

Fig. 5.10 Simulated leaf growth on a ‘Kent’ mango tree with 30 fruits.

5.4. Conclusions

The conversion of the PEACH model has produced a hybrid peach-mango model that simulates fruit growth accurately and provides testable hypotheses regarding changes in reserve carbohydrate and vegetative growth.

6. General Conclusions and Practical Implications

Deficit irrigation represented a suitable irrigation method to save water and to simultaneously achieve acceptable yields, especially under conditions of water shortages. However, the implementation of deficit irrigation scheduling would require a regular monitoring of soil water content on a frequent basis. Since low rainfall during the season of 2002/2003 might indicate the beginning of a drought period, many of the results obtained in this study might be quite useful for the near future. During a drought period and consequent water shortages, farmers might have to consider to either irrigating with lower water applications (deficit irrigation) or not irrigating for periods of time. The worst possible scenario would be to take out of production part of their orchards resulting in a loss of highly valuable orchards. Deficit irrigation practices might offer an acceptable solution before loosing orchards under conditions of severe water shortages.

With respect to water savings and irrigation water use efficiencies RDI followed by DI-1 appeared to be the most advantageous irrigation treatments among the ones evaluated. RDI and at some periods during the season DI-1 seemed to represent possible irrigation scheduling practices that could be adopted by the growers. The RDI treatment, receiving the same irrigation practice as Co except for one or two periods during the season when irrigation water was reduced or withheld, provided storage space for eventual rainfall, particularly in summer, leading to a saving of irrigation water of 12-24% as compared to the control. The period of water reduction before flowering could be further optimized by taking place slightly earlier (May) than in our studies in order to minimize or eliminate effects on flower bud development, flowering, fruit set, and consequently yield.

The current irrigation practice by the farm clearly showed that the trees were over-irrigated. Water and nutrient losses due to drainage as a result of over-irrigation on these coarse textured soils were very high primarily because of the use of drip emitters of high volume (8 L hr^{-1}) and only one long time application of irrigation water per day by the farm. Pulse irrigation (several applications of irrigation water per day) if technically feasible and using 2 emitters of a lower volume than 8 L hr^{-1} would be advisable when using a drip irrigation system to minimize water losses. The replacement of the drip with the microjet system drastically reduced the over-irrigation by the farm. Considering the technical infrastructure and soil properties on the farm, microjet irrigation appeared to be the more appropriate system in comparison to drip irrigation.

Stem water potential can be used as a water status indicator in mango trees. Stem water potential values for non-stressed mangoes fluctuated between -0.4 and -0.6 MPa over the season in a subtropical climate. Stress responses to water deficits were detected after the trees were exposed to irrigation water reductions in May/June 2002 (pre-flowering stress) by stem water potential followed by stomatal conductance indicating that they were more sensitive stress indicators than photosynthesis.

Flesh color of mangoes is commonly used as maturity index to determine the optimum time for harvest by South African mango growers. Among the studied maturity indices (flesh color, firmness, total soluble solid concentration - TSS, titratable acid concentration - TA) TSS and TA provided the most sensitive ones to assess quality at harvest followed by firmness. A comparison between TSS concentration and flesh color showed no relationship between them at harvest suggesting that flesh color might not be the most suitable index for maturity determinations in mango and might need to be re-evaluated.

The PEACH model is being converted to a mango model to facilitate integration of information about the carbon budget of mango trees. The results of the mango model will be used to examine factors that limit mango crop yield. Recommendations to the farmers can then be made to improve the management of mango production.

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8. Appendix

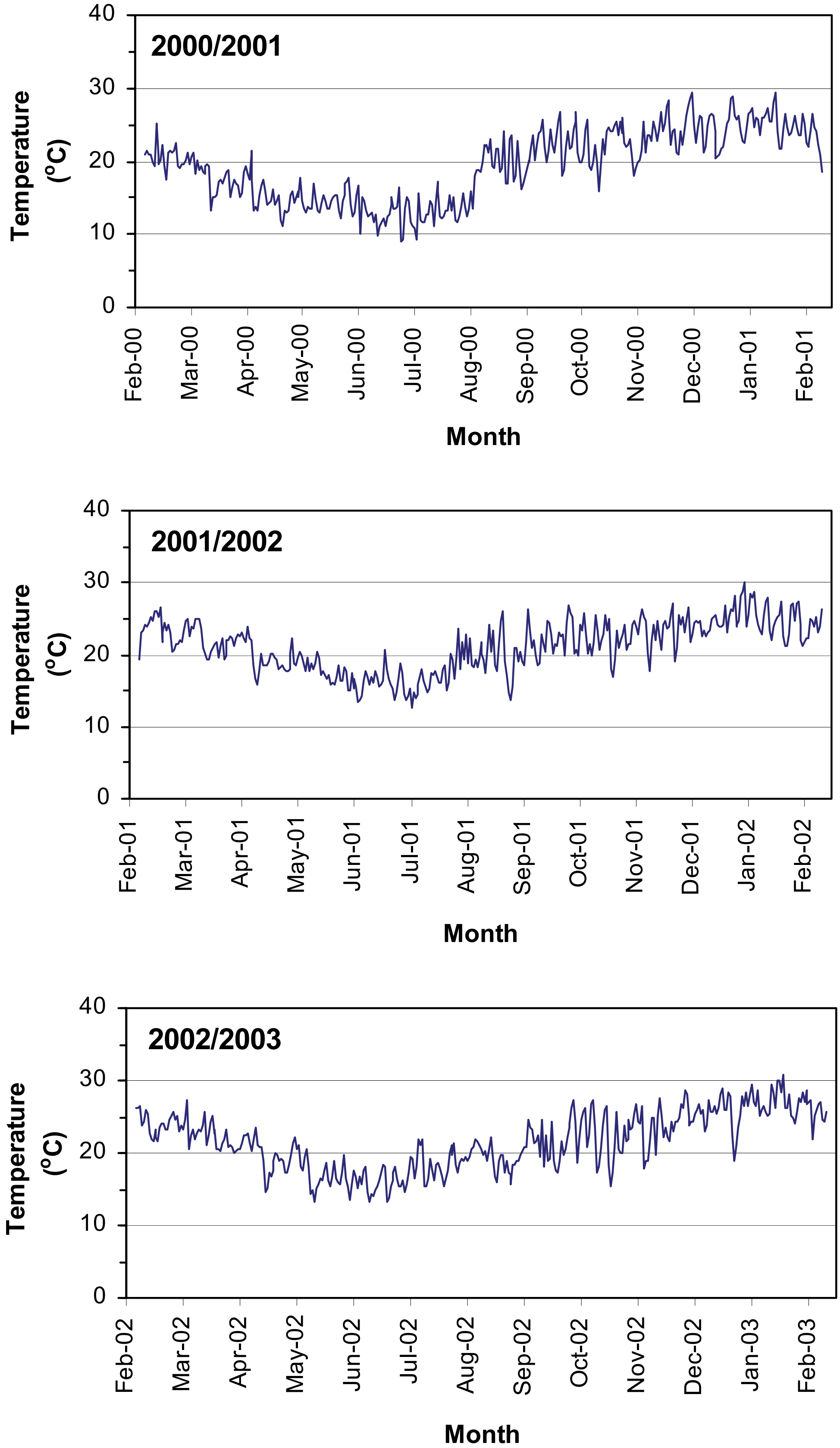
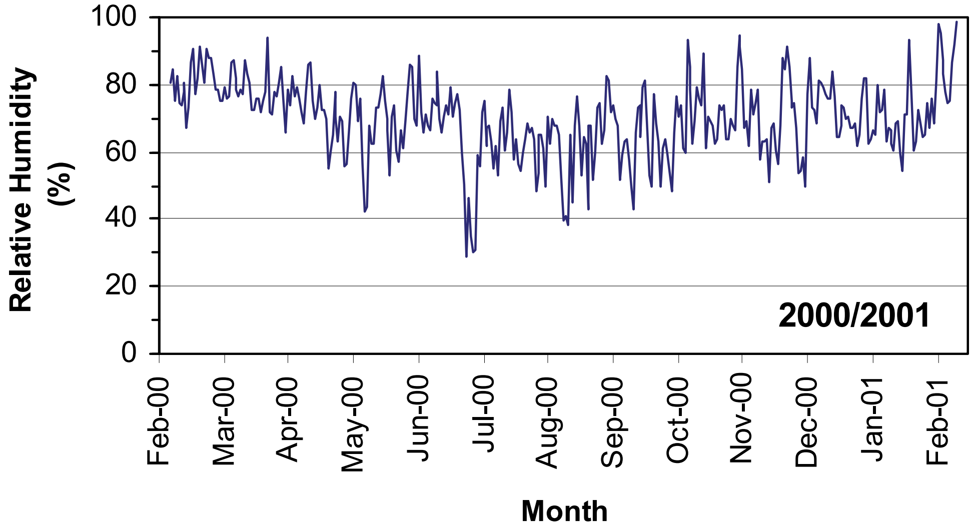
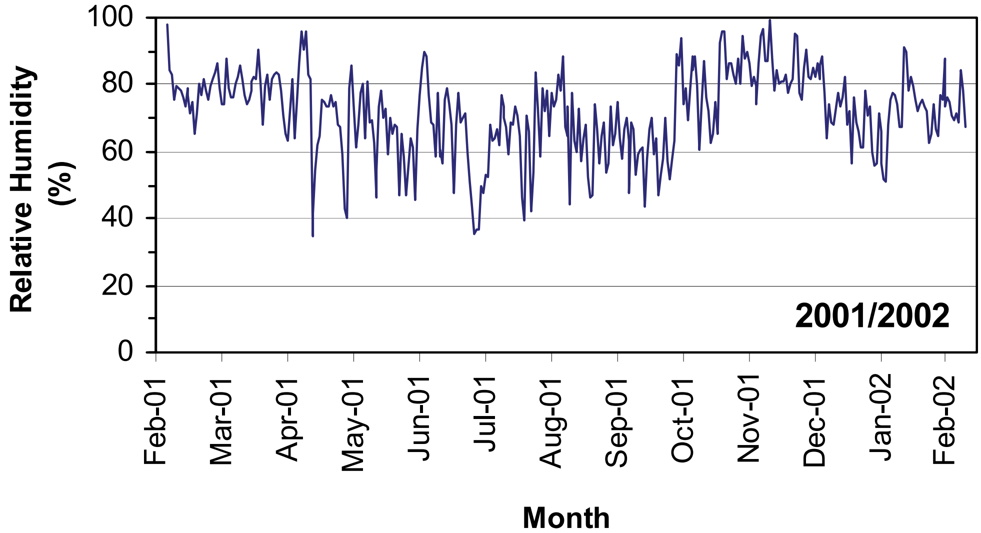


Fig. A.1 Daily mean air temperature during the seasons 2000-2003.





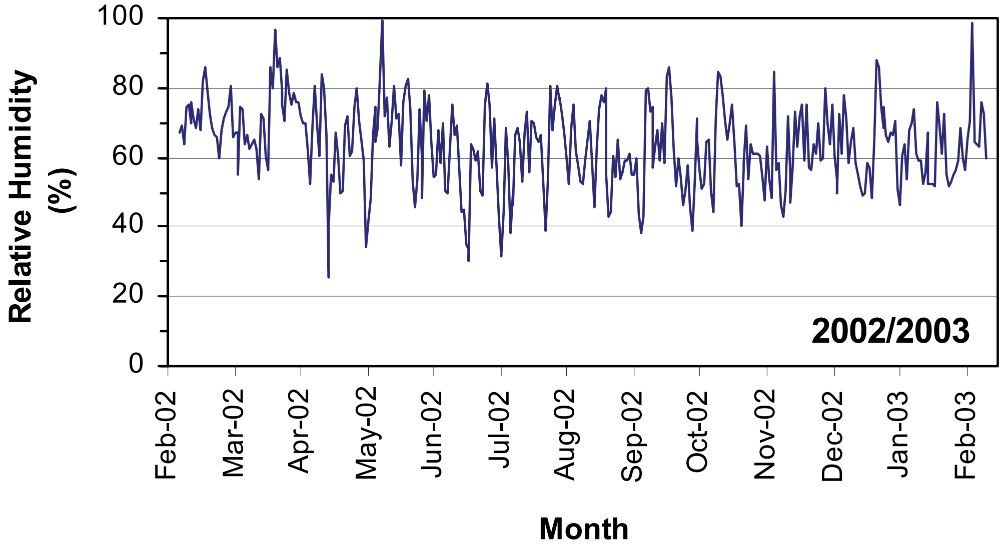


Fig. A.2 Daily mean relative humidity during the seasons 2000-2003.

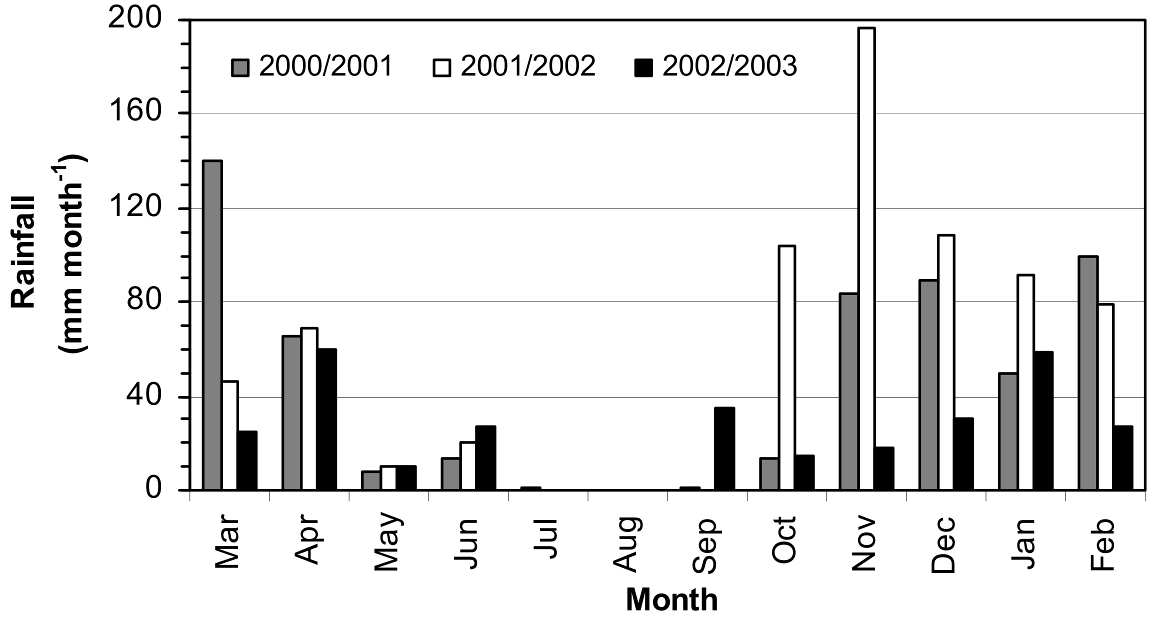
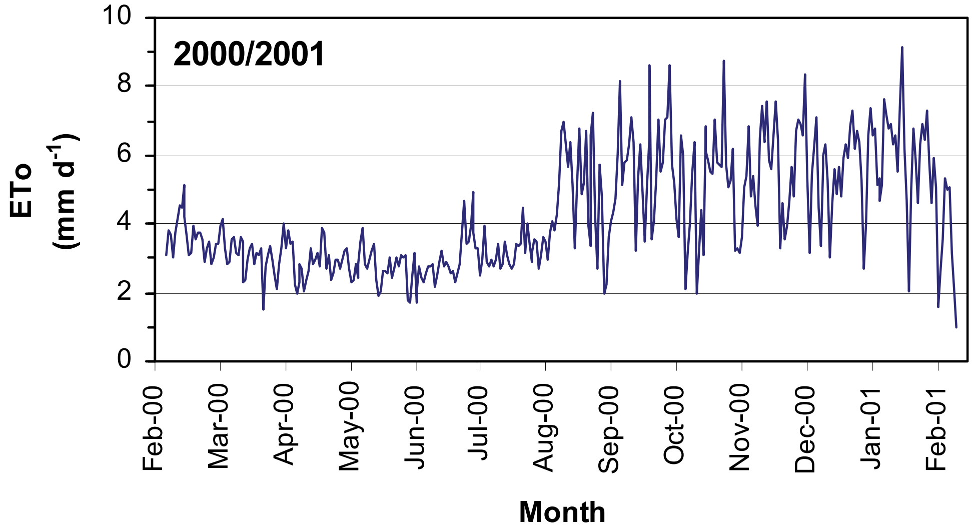
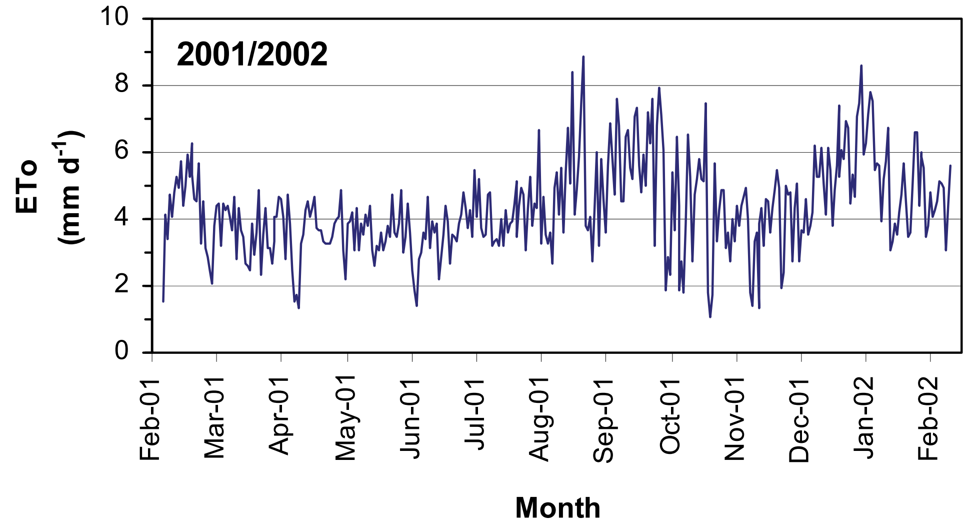


Fig. A.3 Monthly rainfall accumulations during the seasons 2000-2003.





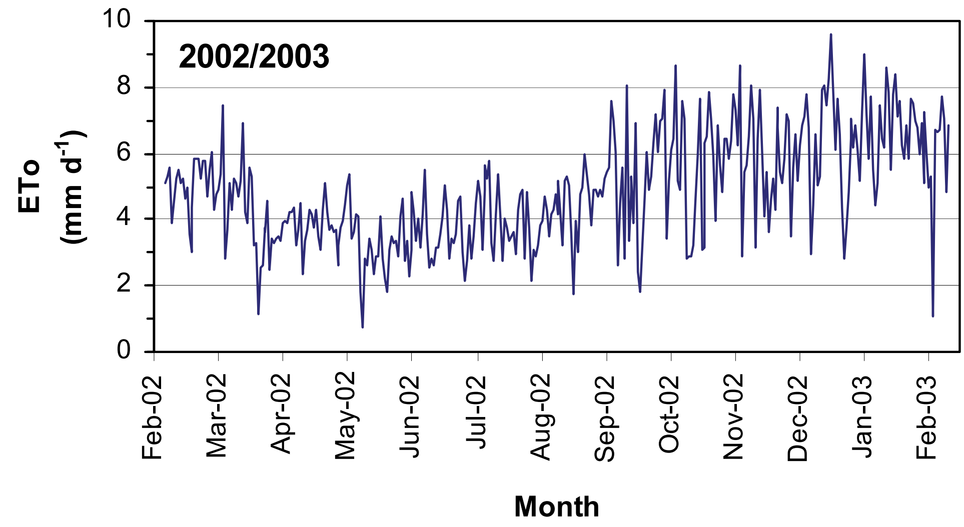


Fig. A.4 Daily mean evaporative demand (ETo) during the seasons 2000-2003.