Physiological studies of the influence of light and water stress on harvest and postharvest quality of deciduous fruit

By

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DECLARATION

I the undersigned hereby declare that the work contained in this thesis is my own original work and has not previously, in its entirety or in part, been submitted at any university for a degree.

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Summary

Successful export of South African fresh fruit requires fruit of a high quality. Variable fruit quality within a consignment is detrimental to effective marketing of the product. The light microclimate under which the fruit develops is one of the factors that affect within-tree and between-tree variation in quality, maturity and yield. Light exposure effects on fruit quality at harvest and after commercial storage and ripening periods, as well as the physiological mechanisms of these responses to light exposure were studied.

Increased exposure to light resulted in the development of typical sun leaf characteristics, with the associated increase in leaf nitrogen concentration and photosynthetic rates. Size and mass of 'Laetitia' plums and 'Cripps' Pink' apples increased with increasing exposure to light. Shade treatments were only started after the initial phase of cell division was complete. Increased size of the fruit was likely due to the improved carbon balance of the exposed foliage and fruit from the end of cell division until harvest. The transpiration stream was higher in the more exposed foliage compared to the shaded parts of the canopy. This was supported by increased transpiration rates and decreased midday water potentials of exposed leaves. 'Songold' plums and 'Rosemarie' pears were also investigated in the first season, but results were not conclusive.

Increased exposure to light was associated with advanced maturity of 'Laetitia' plums at harvest. Shaded fruit were able to attain a similar level of maturity as exposed fruit during storage and ripening periods. At harvest and after the storage and ripening periods, exposed fruit had a higher total soluble solid (TSS) content and therefore an improved eating quality. At harvest, blush colour of 'Laetitia' plums increased with increased exposure to irradiance. Blush colour continued to develop during storage and ripening, and after the ripening period it was evident that blush colour development was associated with a dosage effect i.e. exposure to a cumulative level of irradiance gives the fruit the potential to develop a certain amount of blush colour. Fruit exposed to more than 70% photosynthetic photon flux density (PPFD) were able to develop to a similar

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level of blush colour, whereas, fruit exposed to less than 50% PPFD were not able to attain the same level of blush colour.

Increased exposure to light did not result in advanced maturity of 'Cripps' Pink' apples at harvest, but it did lead to improved blush colour and increased TSS levels. Blush colour of 'Rosemarie' pears was also dependent on exposure to light from four weeks before harvest.

Exposed 'Laetitia' plums had a greater whole fruit content of Mn and B, but concentration on a dry mass basis of P, K, and B decreased with increasing light. Exposed 'Cripps' Pink' apples had increased whole fruit content of P, K, Ca, Mg, Mn, Fe, Cu and B, but concentration on a dry mass basis of K and Na decreased with increasing light. Nutrient content is often associated with the incidence of internal disorders of fruit after storage and further investigation of this effect is necessary as internal disorders were virtually absent in this study.

The termination of irrigation shortly before harvest in order to advance the maturity of all the fruit to a similar level, and the subsequent strip harvest of the fruit on a single harvest date, is a practice commonly used by South African plum producers to reduce cost and ostensibly to improve fruit quality. The effect of this practice on 'Songold' plum quality at harvest, after storage and after ripening was also studied.

Drip-irrigated plums and plums subjected to soil drying had a better eating quality and were more marketable than micro-irrigated and non-droughted fruit. Following commercial storage and ripening periods these fruit were firmer, had a higher TSS content and were of a similar size and mass to micro-irrigated and non-droughted fruit. The extended harvesting period, in contrast to a strip harvest, allowed the fruit that were smaller and less mature at the beginning of the period to attain a greater size and advanced maturity toward the end of the harvesting period.

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Opsomming

Suksesvolle uitvoer van Suid-Afrikaanse vars vrugte vereis volgehoue hoë gehalte. Wisselvallige vruggehalte binne 'n besending is nadelig vir die effektiewe bemarking van die produk. Die lig mikroklimaat waaronder die vrug ontwikkel is een van die faktore wat variasie in gehalte, rypheidsstadium en opbrengs binne die boom en tussen bome beïnvloed. Die effek van verhoogde ligblootstelling op vruggehalte by oes, na kommersiële opberging en na die rypwordingsperiode, sowel as die fisiologiese meganismes van die reaksie van verhoogde ligblootstelling is bestudeer.

Verhoogde blootstelling aan lig lei tot die ontwikkeling van tipiese son-blaar karaktertrekke, met die gepaardgaande verhoging in blaar stikstof konsentrasie en fotosintetiese tempo. Grote en massa van 'Laetitia' pruime en 'Cripps' Pink' appels het toegeneem met verhoogde blootstelling aan lig. Skadu behandelings is eers begin na die einde van die periode van selverdeling. Toenemende grootte van die vrugte is as gevolg van die verbeterde koolstof balans van die blootgestelde blare en vrugte vanaf fase II van vruggroei tot oestyd. Die transpirasie stroom is geallokeer na die blootgestelde blare. Dit word ondersteun deur die verhoogde transpirasie tempo en verminderde middag waterpotensiaal van die blootgestelde blare. 'Songold' pruime en 'Rosemarie' pere is ook bestudeer, maar die uitslae is nie so oortuigend nie.

Toenemende blootstelling aan lig is geassosieer met gevorderde rypheid van 'Laetitia' by oes. Dit was moontlik vir skadu vrugte om dieselfde rypheidsvlak as blootgestelde vrugte te bereik, tydens die opberging en rypwording periodes. Teen oestyd en na opberging en rypwording, het blootgestelde vrugte 'n hoër suiker inhoud gehad en dus 'n hoër eetgehalte. Teen oestyd, het die bloskleur van die pruime toegeneem met toenemende blootstelling aan lig. Ontwikkeling van bloskleur het aangehou gedurende opberging en rypwording, en na die die rypwordings periode was dit duidelik dat bloskleur ontwikkeling met 'n dosis-effek geassosieer word, m.a.w. blootstelling aan 'n sekere opgestapelde vlak van lig gee die vrug die potensiaal om 'n sekere hoeveelheid bloskleur te ontwikkel. Vrugte wat meer as 70% ligblootstelling gekry het, het dieselfde

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bloskleur ontwikkel, maar vrugte wat minder as 50% ligblootstelling gekry het, het minder bloskleur ontwikkel.

Toenemende blootstelling aan lig het nie gelei tot gevorderde rypheid van 'Cripps' Pink' appels teen oestyd nie, maar dit het wel gelei tot verbeterde bloskleur en verhoogde suiker inhoud. Bloskleur van 'Rosemarie' pere is afhanklik van blootstelling aan lig kort voor oestyd.

Blootgestelde 'Laetitia' pruime het 'n verhoogde vrug inhoud van Mn en B met verhoogde ligblootstelling gehad, maar die konsentrasie van P, K en B op 'n droë massa basis het afgeneem met verhoogde ligblootstelling. Blootgestelde 'Cripps' Pink' appels het 'n verhoogde vrug inhoud van P, K, Ca, Mg, Mn, Fe, Cu en B met verhoogde ligblootstelling gehad, maar die konsentrasie van K en Na op 'n droë massa basis het afgeneem met verhoogde ligblootstelling. Voedingstof inhoud is geassosieer met die voorkoms van interne probleme in vrugte na opberging en verdere navorsing oor hierdie effek is nodig.

Die terminering van besproeiing kort voor oestyd met die doel om die rypheid van al die vrugte op dieselfde vlak te kry sowel as die gepaardgaande oes van al die vrugte op een dag, is 'n algemene praktyke wat gebruik word deur Suid-Afrikaanse pruim produsente om kostes te beperk en oënskynlik, om vruggehalte te verbeter. Die effek van hierdie praktyke op 'Songold' pruim gehalte teen oestyd, na opberging en na rypwording is ook bestudeer.

Drup-besproeide pruime en pruime wat blootgestel is aan grond uitdroging het 'n beter eetgehalte en is meer bemarkbaar as mikro-besproeide en nie-droogte geïnduseerde vrugte. Na kommersiële opberging en rypwording periodes het hierdie vrugte 'n hoër fermheid en suiker inhoud gehad, en 'n gelyksoortige grootte en massa as mikro-besproeide en nie-droogte geïnduseerde vrugte. Die verlengde oesperiode het die kleiner en minder ryp vrugte aan die begin van die periode 'n kans gegee om toe te neem in grootte en 'n gevorderde vlak van rypheid te bereik aan die einde van die oesperiode.

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Introduction

Production of a uniform crop of apples (Robinson *et al.*, 1983; Seeley *et al.*, 1980), pears (Kappel and Neilsen, 1994) or stone fruit (Kruger *et al.*, 2001; Taylor *et al.*, 1993) is complicated by the considerable within-tree and between-tree variation in fruit size, quality and physiological maturity. These differences at harvest affect fruit quality poststorage, and this results in non-uniform quality within a consignment, which is detrimental with regard to effective marketing.

The light microclimate under which fruit develop contributes to the aforementioned variation. Variation in fruit quality after commercial storage periods can often be related to differences in maturity at harvest (Abdi *et al.*, 1997; Drake *et al.*, 2002; Taylor *et al.*, 1993). The variation in quality due to pre-harvest light exposure effects needs to be investigated further, as a uniform distribution of light within the orchard canopy could possibly result in greater uniformity of fruit quality poststorage. The physiological mechanism of light exposure effects on fruit quality also needs to be investigated further.

The effect of the light microclimate on leaf development, anatomy, and biochemistry, and the subsequent effect on photosynthesis, stomatal conductance and transpiration has been well documented (Salisbury and Ross, 1992). The mechanisms of physiological responses to light exposure are, however, still not fully understood. Previous research has suggested several possibilities that include an improved carbon balance due to direct light exposure effects, and partitioning of the transpiration stream towards more exposed foliage and fruits (Lakso, 1994).

The termination of irrigation shortly before harvest in order to advance the maturity of all the fruit to a similar level, and the subsequent strip harvest of the fruit on a single harvest date, is a practice commonly used by South African plum producers to reduce cost and ostensibly to improve fruit quality.

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Water stress or deficit irrigation has been found to affect stone fruit growth and yield differently during the different phenological periods of fruit growth (Lampinen *et al.*, 1995; Marsal and Girona, 1997; Naor *et al.*, 2001; Torrecillas *et al.*, 2000). Water stress in plants triggers the physiological response of osmoregulation. This leads to the accumulation of sugars and other solutes in order to withstand periods of water stress (Morgan, 1984).

It is necessary to determine which pre-harvest practices optimise fruit quality following commercial storage periods. The ability to produce high yields of high quality fruit is crucial in order to aid effective marketing.

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Chapter I:

Literature review

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1. Introduction

Solar radiation is the most important environmental factor that affects the production of fruit due to its primary role as the source of energy that drives the biological production of dry matter that ultimately limits fruit yield. An understanding of the effects of light exposure on leaf physiology, photosynthesis, stomatal mechanics and conductance, transpiration and the movement of mineral nutrients in the plant is essential to be able to interpret the effect of the environment, in particular the light microclimate, on these processes successfully. The subsequent effects of these physiological responses to light exposure on fruit growth, harvest maturity and postharvest quality are determining for the shelf quality and ultimately marketability of the fruit. In order to be able to interpret the effects of light exposure on fruit quality after storage it is imperative that we understand the response of fruit to cold storage, and the effect of harvest maturity on the response of fruit to prolonged storage.

Water relations of stone fruit during the entire season and particularly shortly before harvest is crucial in terms of final fruit size obtained. The effect of different irrigation systems and water relations on fruit growth and the effect of water stress on the accumulation of sugars will be discussed.

2. Characterisation of the light microclimate within an orchard system

The term 'light' or 'irradiance' refers to global solar radiation (downward direct and diffuse radiation), received on a horizontal surface from the sun and sky (Proctor *et al.*, 1974). The light microclimate in different parts of the tree varies over time and space, due to the discontinuous and heterogeneous nature of the canopy in an orchard system (Loreti *et al.,* 1994; Jackson, 1980). Various studies have been done on the changing light microclimate within an orchard system, as well as on the characterisation of these different light microclimates.

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Proctor *et al.* (1974) showed in a study of the penetration of global solar radiation into apple trees, that on cloudless days, global radiation varied considerably within the trees, and was dependent on solar zenith angle. Little absorption occurred on the outer perimeter, a zone of substantial absorption occurred between 1 and 2 m from the treetop and a zone of average absorption at 2 to 2.6 m. It was found that the changes in visible and infrared radiation with depth followed the same general trend as changes in total radiation. The region of greatest absorption was again between 1 and 2 m from the treetop. Similar studies on the microclimate within apple trees have shown that there are various light zones within the tree, and the distribution of radiation penetration was found to be symmetrical and dependent on depth within the canopy (Heinicke, 1963; Looney, 1968). Canopy orientation will, however, also affect the light microclimate in the different parts of the tree.

In order to deal with this problem, Jackson (1980) distinguished between two types of light penetration by categorising canopy structure into round-headed type trees (ie. horizontal, umbrella, cup-shaped) or hedgerow type trees (ie. central leader, palmette). The round-headed trees have a symmetrical pattern of light penetration into the tree, dependent upon depth within the canopy. The distribution of radiation penetration within hedgerow trees follows an asymmetrical pattern, and is dependent on the height:spacing relationships in the orchard and on whether the trees consisted of vertical cropping surfaces only, or had a large interior cropping volume also. The important difference between the round-headed and hedgerow type trees is that the most important surface for receiving solar radiation is the vertical or sloping sides rather than the upper surface as is the case in the round-headed trees.

Wagenmakers and Callesen (1995) observed that light penetration within the crown decreased rapidly from top to bottom and from outer to inner side. The penetration of solar radiation was also shown to vary within peach trees due to spatial considerations. Shoot height, orientation and position within the tree canopy were the important factors causing the variation in light microclimate (Génard and Baret, 1994).

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Light microclimate is also affected by many other factors and/or orchard practices. It is affected by planting system (Barrit, 1989; Elfving *et al.*, 1990; Ferree *et al.*, 1993; Grossman and DeJong, 1995; Loreti *et al.*, 1994), summer pruning (Dussi and Huysamer, 1995; Morgan *et al.*, 1984; Palmer *et al.*, 1992), choice of rootstock, row orientation and between- and within-row spacing (Jackson, 1980).

3. Light effects on leaf physiology

Although the roles of light quality and photomorphogenesis are certainly significant in the long-term growth and development of the tree, the discussion in this review will emphasise the quantitative aspects of radiation on the regulation of photosynthesis. For ease of discussion of photosynthetic responses to radiation, the term 'light' will refer to photosynthetic photon flux density (PPFD), 400-700 nm, which directly drives photosynthesis (Lambers *et al*, 1998).

The level of light is an important ecological factor on which all photoautotrophic plants depend. Low light intensities pose stresses on plants because light limits photosynthesis and thus net carbon gain and plant growth. Responses of the photosynthetic apparatus to lower light levels can occur at two levels: the structural level or at the level of the biochemistry. High light intensities may also be a stress for plants, particularly if other factors are not optimal. Damage to the photosynthetic apparatus may be the result (Lambers *et al*, 1998).

3.1. Photosynthetic response to light

Investigation of how varying light levels affect photosynthetic rates can be achieved by using the short-term asymptotic photosynthetic light response curve. The curve can also be used effectively as it is similar for fruit trees since most fruit trees are C_3 crops. There are three noteworthy points on the light response curve: the maximum light-saturated rate, the light saturation level, and the light compensation point (Flore and Lakso, 1989).

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In the dark, the plant gives off CO_2, because of respiration, and by convention, net CO_2 exchange is negative. As PPFD increases, photosynthetic CO_2 uptake increases until it equals CO_2 release by mitochondrial and photorespiration. The light level at which CO_2 uptake exactly balances CO_2 release is called the light compensation point (Flore and Lakso, 1989; Lambers *et al*, 1998).

Increasing PPFD above the light compensation point results in a proportional increase in photosynthetic rate, yielding a linear relationship between light and photosynthetic rate. Photosynthesis is thus light limited in this range. In this portion of the curve, another useful term is derived from the slope of the initial linear response, the apparent quantum efficiency (AQE) or quantum yield (mol CO_2 mol photons^{-1}). Maximum quantum yield is defined as the number of absorbed photons required to fix one molecule of CO_2, to evolve one molecule of O_2, or to initiate a photochemical event (Lambers *et al*, 1998). At higher levels of irradiance, the photosynthetic response to light starts to level off and reaches saturation. Once the point of saturation is reached, further increases in irradiance have no effect on photosynthetic rates. This is an indication that factors such as Rubisco activity, or the metabolism of triose phosphates have become limiting. At this point, photosynthesis is CO_2 limited; here carbon metabolism enzymes cannot keep pace with the absorbed light energy (Flore and Lakso, 1989).

3.2. Sun and shade leaves

Sun and shade leaves are commonly used terms that refer to leaves that have developed at high and low light levels, respectively.

3.2.1. Anatomical differences between sun and shade leaves

Sun leaves are thicker than shade leaves due to the formation of taller palisade cells and/or an increase in the number of layers of palisade cells in sun leaves. Certain sun leaves have palisade parenchyma on both sides of the leaf, and thus when they are oriented vertically both sides of the leaf can receive a high level of irradiance (Nobel,

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1999). Spongy mesophyll cells increase the pathlength of light in leaves by reflection at the gas-liquid interface, thereby enhancing leaf absorptance due to the greater internal light scattering. Shade leaves have a higher proportion of spongy mesophyll cells than sun leaves do, and this partially explains how shade leaves are able to utilise weak light more effectively than sun leaves (Nobel, 1999; Pearcy and Pfitsch, 1994). Shade leaves also have fewer chloroplasts per unit area when compared with sun leaves due to the reduced thickness of the mesophyll. There are also differences in the ultrastructure of the chloroplasts of sun and shade leaves. Shade leaf chloroplasts have a smaller volume of stroma, where the Calvin-cycle enzymes are located, but have larger grana and thylakoid membranes, which contain most of the chlorophyll and are responsible for light capture (Nobel, 1999; Pearcy and Pfitsch, 1994).

Numerous studies have shown that shading reduces specific leaf weight (SLW), i.e., grams per cm^2 leaf (Barden, 1977; Barrit *et al.*, 1987; Doud and Ferree, 1980; Kappel and Flore, 1983; Kappel and Neilsen, 1994; Klein *et al.*, 1991; Dussi and Huysamer, 1995). Shading also causes a reduction in leaf dry weight (Palmer *et al.*, 1992). Barden (1974) showed that the SLW of apple leaves differed markedly depending not only upon the light regime under which they unfolded and expanded but also upon subsequent light conditions. Jackson and Beakbane (1970) reported that the thickness of apple leaves and the thickness of their palisade layers are positively correlated to increased light exposure. Klein *et al.* (1991) found that SLW of individual spur leaves of walnut trees were correlated with the total daily light exposures measured immediately above the spur. Tustin *et al.* (1992) confirmed the general trend that SLW is reduced with increasing shade. It was shown that SLW is highly responsive to changing light conditions in the canopy, but in addition, is influenced by the origin of the leaves within the spur and by both the previous and current season's light environments.

3.2.2. Biochemical differences between sun and shade leaves

Shade leaves minimise light limitation by increasing their capacity for light capture at the expense of assimilatory capacity (Larcher, 1995). Shade leaves have a lower chlorophyll

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a to b ratio, and these leaves have more chlorophyll associated with the light-harvesting complex (LHC) than with the photosystems. This lower ratio is therefore a reflection of the greater investment in the LHC (Pearcy and Pfitsch, 1994). This also explains the larger grana of shade leaf chloroplasts, as this is where the major proportion of the LHC is located. Shade leaves also have higher chlorophyll content per chloroplast (Larcher, 1995; Pearcy and Pfitsch, 1994). Sun leaves, however, have more of the components that determine photosynthetic capacity per unit leaf area. They have larger amounts of Calvin-cycle enzymes per unit leaf area, due to more cell layers, larger number of chloroplasts per cell, and a larger volume of stroma (Larcher, 1995; Pearcy and Pfitsch, 1994). Sun leaves also have more stroma-exposed thylakoid membranes, which contain the b_6f cytochromes and ATPase (Larcher, 1995). The high photosynthetic capacity of sun leaves is achieved at the expense of high rates of dark respiration, and a large investment of resources such as nitrogen (Lambers *et al*, 1998).

3.3. Light exposure effects on leaf nitrogen content

In C_3 plants, generally more than half of leaf nitrogen is associated with the leaf photosynthetic apparatus (Le Roux *et al.*, 1999). Due to this, leaf photosynthetic capacity is strongly correlated with leaf nitrogen concentration expressed on either an area or a weight basis. One of the reasons that sun leaves have a higher photosynthetic capacity is due to a large investment in resources such as nitrogen. A number of studies have been done that show a positive correlation between leaf nitrogen content and exposure to higher light intensity.

Leaf nitrogen expressed on a leaf unit area basis has shown a good relationship with light within peach (DeJong and Doyle, 1985), and nectarine canopies (Rosati *et al.*, 1999). DeJong and Doyle (1985) further reported that leaf photosynthetic rates and nitrogen content were highly correlated. They suggested that leaf nitrogen content was not uniformly distributed over a tree canopy and that this distribution was related to variation in natural light microclimate. Kappel and Neilsen (1994) found that the total nitrogen concentration per spur leaf ($\mu g\ cm^{-2}$) of 'Anjou' and 'Bartlett' pears decreased from the

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periphery to the interior of the canopy (presumably from a region of high light to low light). There is also a suggestion that the export of N was more influenced by light exposure than by the nutritional status of the tree. SLW and N content per unit leaf area of individual spurs were also highly correlated with light exposure within the canopy of walnut trees (Klein *et al.*, 1991).

The leaf N concentration on an area basis [N]a was found to be strongly correlated to daily leaf irradiance in the tree crown of an isolated 20-year old walnut tree. The leaf N concentration on a weight basis [N]w was however, weakly correlated to daily leaf irradiance. There was a suggestion that variability in [N]a could largely be the result of variability in leaf anatomy. Most of the difference in [N]a between sun and shade leaves was found to reflect a change in leaf dry weight per area rather than nitrogen concentration (Le Roux *et al.*, 1999).

3.4. Light response curve revisited

The level of irradiance at which different leaves reach their compensation point varies with species and prevailing conditions. Light compensation points for sun leaves range from 10 to 60 μmol m^{-2} s^{-1} PPFD, whereas the corresponding values for shade leaves are 1 to 5 μmol m^{-2} s^{-1}. The chief reason for the difference between these values is that shade leaves have very low respiration rates, so little net photosynthesis suffices to bring the rates of CO_2 evolution to zero. These low respiratory rates together with the higher efficiency of light capture at low irradiance allow shade plants to survive in light-limited environments (Flore and Lakso, 1989; Lambers *et al*, 1998). Despite the differences in microenvironment, sun and shade leaves have very similar maximum quantum yields. Shade leaves have substantially lower light saturation levels than sun leaves (Flore and Lakso, 1989). The light saturation levels usually indicate the maximum PPFD to which the leaf was exposed during its growth. Maximum photosynthetic rates are also considerably higher for sun leaves compared to shade leaves (Larcher, 1995).

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Apple leaf photosynthesis is a C_3 type with a hyperbolic light response that saturates at 25-50% of full sunlight, with a light compensation point typically between 20 to 60 μmol m^{-2} s^{-1} PPFD. Maximum rates of photosynthesis are approximately 15 μmol m^{-2} s^{-1} or higher in apple leaves (Lakso, 1994). Plum trees are also a C_3 type plant with a hyperbolic photosynthetic response that saturates at 25-45% of full sunlight, with a light compensation point typically between 15 to 30 μmol m^{-2} s^{-1} PPFD. Maximum rates of photosynthesis are approximately 20 μmol m^{-2} s^{-1} in plum trees (Flore, 1994).

3.5. Further studies on the effect of light on photosynthesis

As with most plants, apple leaves that develop in exposed areas develop into the 'sun' leaves that have already been described. Later in the season, the decline of light-saturated photosynthetic rates appears to be remarkably slow compared to many other crops, with exposed leaves maintaining relatively constant rates until harvest in cropping trees (Lakso, 1994). Leaves that are shaded, however, show more rapid declines in light-saturated photosynthetic rates, apparently related to the time-shade integral, with little recovery if re-exposed by summer pruning (Lakso, 1994). Thus, in order to adapt to long growing seasons with high productivity, it would be advantageous to have as many exposed leaves as possible, especially because most new leaf production stops in midsummer, and productivity depends on the existing leaves (Lakso, 1994).

There have been numerous studies on the effects of light intensity on the ability of leaves to photosynthesise. Heinicke (1965) studied the photosynthetic rates of leaves in two light zones. Photosynthetic rates corresponded to these light zones, with the average net assimilation rate in the high intensity zone being three times higher than that found in the low intensity zone. Barden (1974) reported that the effect of light regime on the development of 1-year-old 'Red Yorking' apple trees increased photosynthetic and respiration rates in sun leaves when compared to shade leaves. Adaptations occurred in both parameters because of changing light conditions, even after leaf expansion had ceased. It was found that at two weeks after unfolding, leaves under full sunlight had

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photosynthetic rates about 65% higher than shade leaves, and the respiration rates of shade leaves were less than 60% of that of sun leaves.

Barden (1977) found, however, that at low levels of irradiance, sun and shade leaves have similar levels of photosynthesis. It was found that the effects of shade on young apple trees were similar whether from continual low illumination or alternating periods of full sun and dense shade. The results showed that sun leaves have a far higher light saturation point than shade leaves. Net photosynthesis of shade leaves was about 70% of that of sun leaves at light saturation. Dark respiration rates were higher in sun than shade leaves. Respiration rates also declined in leaves grown in full sun and that were subsequently shaded. Thus, although shade leaves have a lower photosynthetic potential, this reduced productivity is partially compensated for by lower respiration rates. Subsequently, Barden (1978) found a positive linear relationship between SLW and rate of net photosynthesis of apple leaves. Thus, leaves growing in full sunlight have a tendency to take advantage of this and maximise their net assimilation rate.

Ferree *et al.* (1993) also reported that more exposed leaves have a higher net photosynthetic potential than shaded leaves. However, shade leaves even in heavily shaded positions, make a positive contribution to photosynthesis. Similar studies have confirmed that as light exposure increases so does the rate of photosynthesis, and that the rate of photosynthesis for heavily shaded leaves can be higher than expected (Corelli and Sansavini, 1989). Avery (1975a) found the compensation point of apple shade leaves to occur at less than 2% of full sunlight. These shade leaves could attain 80% of full photosynthesis with between 10% and 40% of full sunlight, and reached light saturated photosynthesis at from 44% to 75% of full sunlight.

4. Leaf stomatal conductance and transpiration

Leaf stomata regulate two essential processes: CO_2 uptake necessary for photosynthesis and water loss due to transpiration. Plants have to balance their need to take up CO_2 from the atmosphere while limiting water loss (Nobel, 1999). The cuticle that covers exposed

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plant surfaces serves as an effective barrier to water loss and thus protects the plant from desiccation. Nevertheless, the plant cannot prevent the outward diffusion of water without simultaneously excluding CO_2 from the leaf (Nobel, 1999). The fact that the concentration gradient for CO_2 uptake is considerably smaller than the concentration gradient driving water loss worsens the problem (Taiz and Zeiger, 1998).

The solution to this problem is the regulation of stomatal conductance. At night, there is no need for CO_2 as no photosynthesis occurs, and water loss is minimised as stomatal apertures are kept very small. In the morning, when light levels are high, the water status of the plant is favourable, and the incident radiation on the leaf favours high photosynthetic activity. The leaf has a great demand for CO_2 and the stomatal apertures are wide open (Taiz and Zeiger, 1998). Accompanying these conditions is the increased water loss due to transpiration, but as water supply is not yet deficient, the plant will rather attain higher photosynthetic rates, which are essential for growth and reproduction. If the same conditions prevail but water is in short supply, the stomata will open less or even remain closed, thereby preventing dessication (Taiz and Zeiger, 1998).

4.1. Regulation of stomatal conductance

4.1.1. Stomatal anatomy and mechanics

The basic stomatal anatomy consists of two guard cells above a stomatal cavity. The cell walls of these adjacent cells are only linked at their distal ends, and therefore they form a pore whose aperture can vary due to the swelling or shrinking of the guard cells. In addition to the guard cells there are often a number of lateral and distal subsidiary cells (Lambers *et al*, 1998; Losch and Schulze, 1994). The stomata open because water and solutes are transported apoplastically into the guard cells and they swell. Stomatal closure occurs when these solutes and water are transported in the opposite direction, out of the guard cells and into the subsidiary cells. This is due to the submicroscopic wall anatomy of the guard cells (Nobel, 1999). The rigid cellulose microfibrils have a radial orientation, therefore only allowing the cells to increase their volume in a longitudinal

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direction. The guard cells, therefore, increase in length, especially along their outside walls, and as they do so they swell outwardly. The microfibrils then pull the inner wall with them, which opens the stomata (Nobel, 1999).

The opening or closing of the stomata requires rapid and massive transport of solutes across the plasma membrane of the guard cells. The major ion that is transported is K^+, which may be accompanied by Cl^-. Another possibility is that the charge is balanced by negative charges produced in the guard cell, normally through malate produced from carbohydrates in the guard cell (Taiz and Zeiger, 1998). The transport of K^+ and Cl^- in both the opening and closing reactions takes place through ion selective channels. The channels responsible for the entry of K^+ are open only when the membrane potential is very negative. A very negative membrane potential results from the activation of an H^+-pumping ATPase in the plasma membrane of the guard cells (Taiz and Zeiger, 1998). Abscisic acid (ABA) affects some of these channels by both the inhibition of the opening response and a stimulation of the closing reaction. The inward channel is inhibited by the ABA-induced increase in calcium concentration in the cytosol of the guard cells. Calcium concentration does not affect the outward channel (Losch and Schulze, 1994; Taiz and Zeiger, 1998).

4.1.2. Light induced stomata effects

Irradiance, CO_2 concentration, relative humidity, and water stress affect the activation of the channels that regulate the transport of solutes, and thus the opening and closing of stomata. The response of stomata to light ensures that stomata are only open when there is a possibility to assimilate CO_2. In this way water loss through transpiration is minimised (Lambers *et al*, 1998; Nobel, 1999). There are two mechanisms by which stomata respond to light. The first mechanism involves the stimulation by blue light, mediated by flavin-containing photoreceptors in the guard cells. The blue light activates the ion channels creating the electrochemical potential gradient that provides a driving force for ion uptake. Blue light stimulates starch degradation and malate biosynthesis. Guard cells utilise sucrose as a major osmotically active solute, and light quality can

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change the activity of different osmoregulatory pathways that modulate stomatal movement. The second mechanism is more indirect and involves the response of the guard cells to intercellular CO_2 concentration, which is reduced by an increased rate of photosynthesis (Taiz and Zeiger, 1998).

Stomata also open in response to red light that is perceived by chlorophyll. It is not certain if the red light effects are mediated by photosynthesis because many guard cells lack the ability to photophosphorylate and have little or no Calvin-cycle activity, due to the virtual absence of Rubisco and other Calvin-cycle enzymes (Taiz and Zeiger, 1998). Other studies have shown that guard cells do photophosphorylate and also have some Rubisco activity, possibly enough to have a regulatory role (Lambers *et al*, 1998).

4.1.3. Effects of transpiration rate on leaf stomatal conductance

The driving force of transpiration is the vapour pressure deficit (VPD) between the leaf and the atmosphere (Taiz and Zeiger, 1998). This driving force acts in conjunction with leaf stomatal conductance in order to determine the transpiration rate (Taiz and Zeiger, 1998). Exposure of a single leaf to dry air is expected to increase transpiration because of the greater VPD between the leaf and the air compared to a more humid environment. These conditions, however, will also lead to decreased stomatal conductance and hence affect transpiration (Taiz and Zeiger, 1998).

Water potential is an essential concept that is used when discussing the process of transpiration and the movement of water in the soil-plant-atmosphere continuum. The definition of water potential is the chemical potential of water in a system or part of a system, expressed in units of pressure and compared with the chemical potential of pure water at atmospheric pressure, and at the same temperature and height. The chemical potential of the pure reference water is set at zero (Salisbury and Ross, 1992). Using this definition we can see that as the relative humidity of air decreases, its water potential will become more negative. This negative water potential of the air is the driving force for transpiration. When the discussion involves leaf gas exchange, however, the driving

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force for transpiration must be expressed in terms of vapour pressure difference between the leaf and the air (Nobel, 1999).

Changes in the leaf temperature have a marked effect on the vapour pressure inside the leaf. As temperature rises, the air can contain more water vapour, and evaporation from the wet surfaces of the leaf cells raises the vapour pressure to saturation. This is true for all leaves regardless of the water status of the plant (Larcher, 1995). The outside air can also contain more water vapour as the temperature increases, but vapour content of the air typically rises less rapidly than that of the leaf (Larcher, 1995). Thus, if the vapour pressure in the outside air remains the same, then the VPD between the leaf and the air increases, and the expected response would be for the leaf transpiration to increase in proportion to the increased VPD. This would be the case, unless the stomatal conductance declines (Lambers *et al*, 1998; Larcher, 1995).

Further studies have been done to elucidate the mechanism of the stomatal response to humidity. These studies suggest that stomata do not directly sense or respond to either the water vapour concentration at the leaf surface or the VPD between the leaf interior and the leaf surface. The mechanism that causes the stomatal response to humidity of the air or transpiration rate is still largely unknown. The stomatal response, however, is not universal, and may even vary for one plant throughout the day. There is apparently a feedforward response that enables a plant to restrict excessive water loss before it develops severe water deficits and may enhance the ability of plants to use soil water supplies efficiently (Cowan, 1977).

4.1.4. Other environmental effects on stomatal conductance

The water potential within a leaf can also have a strong effect on stomatal opening and closure. As water potential decreases the stomata close. The water potential effect can override the effects of low CO_2 levels and bright light. Its protective value during drought is obvious (Salisbury and Ross, 1992).

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High temperatures (30-35°C) usually cause stomatal closure. This response to temperature might be indirect in nature due to water stress, or a rise in respiration rate might cause an increase in CO_2 within the leaf and there is usually a concomitant rise in VPD. High CO_2 is probably the correct explanation as it has been noted that continuous flushing of the leaf with CO_2 free air can prevent stomatal closure. In certain plants high temperatures cause stomatal opening instead of closure, which leads to increased transpiration and the removal of heat from the leaf (Salisbury and Ross, 1992).

Wind is also a cause of stomatal closure, there can be two reasons for this. The first reason for stomatal closure could be because more CO_2 is brought close to the stomata, increasing its diffusion into the leaf. The second reason is that wind also increases transpiration, by reducing boundary layer thickness, leading to water stress and stomatal closure (Salisbury and Ross, 1992).

Stomatal responses are often related to CO_2 concentrations, but this response varies greatly among species and is dependent on environmental conditions. Stomatal responses to CO_2 concentrations are found in both light and dark conditions. The mechanism of this response remains unclear, but it does play a major role in plant response to elevated atmospheric CO_2 concentrations. Under these conditions, stomatal conductance is less than it is under normal ambient conditions, enhancing the photosynthetic water use efficiency (Lambers *et al*, 1998; Nobel, 1999).

5. Potential physiological mechanisms of light exposure effects

The potential mechanisms of physiological responses to increased light exposure include an improved carbon balance, or increased transpiration resulting in greater partitioning of the transpiration stream and nutrient supply to more exposed sites in the canopy.

The importance of good light exposure during leaf expansion for the development of high photosynthetic capacity has been reviewed. However, the physiological mechanisms behind the apparent transduction of incident light to morphological and physiological

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changes are not clear. Since, in general, sun leaves transpire more than shade leaves, they would be expected to receive a greater proportion of the hormones and nutrients moving in the xylem (Flore and Lakso, 1989). Thus, a hypothesis that requires further examination is that the partitioning of the transpiration stream hormones and nutrients is in part a regulatory mechanism by which the plant allocates greater resources in the leaves that transpire the most (Neumann and Stein, 1983). This mechanism is not directly related to visible or photosynthetically active light, but to radiation-induced differences in foliage temperature, E, and the resultant allocation patterns of root supplied hormones and/or nutrients (Lakso, 1994).

Light exposure effects could also be directly due to light striking the organ of interest and the associated effects on temperature, photosynthesis, and carbon balance (Lakso, 1994). Direct exposure of fruit increases fruit temperatures, and this would possibly increase fruit transpirational flux and the translocation of nutrients and hormones to the fruit sink, thus increasing sink strength (Thorpe, 1974).

6. Mineral nutrition of fruit

The mineral status of fruit can often be a determining factor of the storage quality of the fruit. Mineral nutrients known to affect the development of internal breakdown in plums during storage are N, P, K, Ca and Mg (Kotzé *et al.*, 1987). Increased nitrogen, potassium and magnesium levels and low calcium and phosphate levels are associated with a high incidence of internal breakdown of plums. Calcium is the nutrient most commonly associated with postharvest disorders. In bitter pit in apple fruit, almost all pre-harvest factors which affect incidence of the disorder can be directly or indirectly related to calcium nutrition of the fruit (Ferguson *et al.*, 1999).

6.1. Transport of nutrients

Fruits accumulate nutrients via the phloem as well as via the xylem in the transpiration stream. The most important pathway for the transport of soluble carbohydrates from the

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leaves is the phloem. The translocation of mineral nutrients, however, occurs via both the xylem vessels and the phloem. Mineral elements are taken up by the roots and distributed by the water flow in the xylem. Following this the elements can be redistributed to other parts of the plant via the phloem (Tromp, 1975; Salisbury and Ross, 1992). This redistribution of the minerals via the phloem is the most important transport of certain elements into fruit. Studies have shown that this is probably the case for K, P, and Mg (Salisbury and Ross, 1992).

Calcium is taken up by the roots near the root tip and is then transported in the xylem as opposed to the phloem (Biddulph *et al*, 1959; Raven, 1977). The xylem transports calcium effectively due to the large volume of water involved and the lack of restrictions on the concentration of calcium in the xylem. Calcium is transported in the xylem due to ion exchange that is aided by the transpiration stream (Clarkson, 1984). Calcium concentration has been shown to increase with increasing rates of transpiration (Stebbins and Dewey, 1972). The rate of transpiration, calcium supply in the xylem and the age of the fruit mainly influence calcium transport into the fruit. The supply of water via the phloem is positively related to the amount of assimilates translocated, therefore the contribution of the xylem is only dominant in the early stages of development, when fruit growth is slow and the xylem is the main supplier of water and solutes. Thus, the concentration and rate of the xylem sap, mobility in the phloem and the rate of fruit growth determine the nutritional status of the fruit (Tromp, 1975; Salisbury and Ross, 1992).

6.2. Environmental effects

As temperature increases, it favours the translocation of all mineral nutrients in the phloem. Increased temperature also increases the rate of fruit growth, therefore, in terms of the transport of calcium, it indirectly affects the relative importance of xylem and phloem movement.

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There seems to be a strong link between the movement of K and Mg into fruit and the movement of assimilates in the phloem. This supports the theory that the main movement of these elements into the fruits occurs via the phloem. Studies have shown that there is a linear relationship between the dry weight increase of fruit and the increase in K and Mg levels in the fruit (Tromp, 1975). Relative humidity (RH) has almost no effect on fruit growth and therefore has almost no effect on the levels of K and Mg in the fruit, but air temperature has the main affect on the levels of these elements in the fruit.

The xylem sap flow increases at higher transpiration rates, therefore the Ca supply to the fruits should be increased. Various studies done on the effect of RH on the Ca status of the fruit have been contradictory in their findings. This is because the movement of Ca in the plant is very complex and is related to the general base status of the plant, and in particular to the ratio between K, Mg and Ca. Even if the base status is low, provided the ratio is adequate, Ca will be well distributed throughout the plant. Nevertheless, if for example, the amount of K is very high, Ca will be fixed in the roots and at sites in the xylem. Therefore, to relate environmental effects to the movement of Ca is difficult (Tromp, 1975; Salisbury and Ross, 1992).

7. Effect of the light microclimate on growth and cropping

7.1. Effects on vegetative growth and yield

Shading reduces growth but growth continues even at low light levels. Barden (1977) used either green saran cloth or wooden slats in order to reduce irradiance to 20%, and found that this reduced the dry weight increase of young 'Delicious' apple trees to about 50% of those grown in full sun. Yield has been shown to be linearly correlated to light exposure (Barrit, 1989; Palmer *et al.*, 1992; Wünsche and Lakso, 2000).

Mature cropping trees of 'Cox/M26 were shaded using plastic netting with different mesh sizes, and it was found that there was a greater effect on fruit bud formation and yield than on vegetative growth, when increment in girth was used as a measure of vegetative

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growth (Jackson and Palmer, 1977a, b; Jackson *et al.*, 1977). As this study was conducted over two years it was possible to see that the previous years shading had a pronounced effect on the fruit bud numbers of the following year. Barden (1974) found that there were no effects of shade treatments on shoot length, leaf number, or total leaf area as the number of shade periods increased.

7.2. Effects on fruit growth and size

Numerous studies have found that increasing light exposure leads to improved fruit growth and increased final fruit size (Barrit *et al.*, 1987; Jackson *et al.*, 1977; Kappel and Neilsen, 1994; Khemira *et al.*, 1993; Morgan *et al.*, 1984; Robinson *et al.*, 1983; Seeley *et al.*, 1980; Tustin *et al.*, 1988; Wagenmakers and Callesen, 1989; Wagenmakers and Callesen, 1995).

Shade reduces individual fruit size, as long as the number of fruits have not been so greatly reduced that the lack of competition makes up for the low photosynthetic productivity in the neighbouring leaves. The majority of the photosynthates from the leaves of any spur are utilised by the fruits on that spur (Hansen, 1969, 1970). When the products of photosynthesis are in ample supply they are mobile within the tree, but the sinks (fruits or shoots) adjacent to the sources are at a competitive advantage. Therefore fruits near well-illuminated leaves have the greatest chance to realise their growth potential (Jackson, 1980). Since many aspects of apple tree growth and physiology are affected by the photosynthetic rates, there will be many indirect, thus somewhat delayed, effects related to carbohydrate availability. One effect is that growth rates of young apple fruit during the fruit drop period have been found to decline with shading of the canopy, but increase with short-term CO_2 enrichment, implicating carbon supply limitations. Similarly, short-term shading has been shown to reduce cell division rates in young fruits as well as to cause significant abscission if imposed during the cell division period prior to the final fruit drop (Lakso, 1994).

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The most important stage of fruit growth is the initial phase of cell division. A lack of sufficient photoassimilates during this period will result in smaller fruit and a lower yield. At the onset of new growth in the spring, the stored reserves are primarily used to produce energy for respiration, while subsequent growth seems to depend on current photosynthate production (Hansen and Grauslund, 1973). If fruit development essentially depends on current photosynthesis, two important components need to be evaluated. The first concerns the partitioning patterns of the photosynthates between vegetative development (the extension shoots and the bourse shoots on fruiting and non-fruiting spurs) and reproductive development (fruit set and growth). The second pertains to the effects of light exposure on leaf photosynthetic characteristics and partitioning patterns.

Bepete and Lakso (1998) reported that early in the season the growing shoot tip is the priority sink for carbon so that, when light is a limiting factor, carbon is disproportionately allocated to shoot growth vs. fruit growth. Accordingly, as light levels decrease and total photoassimilate production is reduced on heavily cropping branches, shoot growth is maintained while fruit growth is reduced. Their results confirmed their hypothesis, as growing shoot tip was shown to be a stronger sink than fruit growth, especially under limiting light conditions. As this occurs early in the season, it has a pronounced effect on the essential fruit cell division stage, that is a determining factor in establishing crop potential.

The first five weeks after full bloom are crucial with respect to fruit growth rates and cell division. It is during this period that patterns of C fixation and partitioning can influence fruit set and final fruit size. Work done on individual spurs showed that 2 weeks after full bloom, 30% to 40% of the C fixed by the primary spur leaves are partitioned to the developing fruit, while the bourse shoot contributes less than 1% of its fixed C. Three weeks later the primary spur leaves contribute from 50% to 80% of their fixed C to the fruit, while bourse shoot contributions range from 20% to 50% (Tustin *et al.*, 1992).

A major influence on the photosynthetic potential of apple leaves and, therefore, on their capacity to contribute carbohydrates toward plant growth, is light in the previous and

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current season. Shade has been found to delay carbohydrate partitioning to fruit. Correlli Grappadelli *et al.* (1994) found that between one and three weeks after bloom seems to be the period for the beginning of photosynthate export from exposed extension shoots to the fruit, but this only occurs later for shaded shoots. The export of labelled carbohydrates from shaded shoots at five weeks was similar to that of exposed shoots at three weeks. Thus, it seemed that shading to 35% of full light was equal to the loss of about five to six leaves in terms of shoot C balance. Shaded spurs require significant import of photosynthates to maintain fruit development during the first three weeks after bloom. Lakso and Corelli Grappadelli (1992) reported that exposed growing extension shoots begin carbon export after about 10 to 12 leaves have unfolded. Shading delays the onset of export from extension shoots. The early cessation of shoot growth allows more rapid export from extension shoots, but fruit growth during the critical cell division period is supported primarily by spur leaves and terminated extension shoots.

Fruit growth of apples occurs predominantly by cell division for four to five weeks after full bloom. Thereafter, fruit growth is a result of cell enlargement. For apple, it has been found that cell division rates were higher in exposed fruit compared with shaded fruit (Blanpied and Wilde, 1968). Lakso *et al.* (1989) found that within the range of natural light in the canopy of apple trees, the growth rate of apple fruit during the first five weeks after bloom was correlated with the exposure of spurs during that period. They further stated that the effect of canopy shade on final fruit size occurred primarily in this first five-week period after bloom and that little additional effect could be attributed to changes in light availability the rest of the season. Tustin *et al.* (1988) confirmed these findings when it was found that fruit size and fruit set were positively correlated to photosynthetic photon flux. Kappel and Neilsen (1994) found a positive correlation between rate of fruit growth and final fruit size with increased exposure to light in 'Anjou' pears. There was however, a lack of such a relationship for 'Bartlett' pears, which may be ascribed to other factors besides light microclimate.

It is also possible that the effect of sunlight on apple fruit size could be largely due to a heating effect. The speeding up of metabolic processes, and the resultant increased

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growth of such fruits, should cause them to become more efficient sinks for assimilates. This could further stimulate photosynthesis by the adjacent well-illuminated leaves, as 'sink strength' is a determining factor in the photosynthesis rate of apple (Avery, 1975b; Thorpe, 1974).

In stone fruit there is a final stage of rapid fruit growth, which is a determining factor in the final fruit size and yield that is obtained. In a study done on peach and nectarine trees, it was found that by covering individual fruit with plastic modified the microenvironment around the fruit by increasing the humidity. Higher humidity limits fruit transpiration and consequently fruit water status is improved, particularly during the day. Since peach growth is very sensitive to the water status during the final stage of fruit development, the improvement of fruit water status by reducing transpiration results in a more rapid increase in fruit volume (Li *et al.*, 2001). Similar results were obtained in a study done on nectarine fruit by Muleo *et al.* (1994) who found that covering individual fruit with aluminium foil during the final swell of fruit growth resulted in an increase in fruit size and fresh weight. Studies done on peach fruit confirm the above mentioned findings (Marini *et al.*, 1991; Li *et al.*, 2001).

Fruit which are more exposed to light have higher transpiration rates, and thus the previous discussion of light as being an essential factor in attaining good fruit size in pome fruit might not be as applicable to stone fruit. Water status could be equally or more important than light in attaining higher yields of stone fruit.

8. Light microclimate effects on fruit quality

8.1. Fruit skin colour

Fruit red colour formation, due to anthocyanin, is controlled by a high-energy photoreaction, with an action maximum at 650 nm and a subsidiary one at 430-480 nm, followed by a subsequent photoreaction with an action maximum near 655nm (Jackson, 1980). Proctor and Creasy (1971) found that a minimum of 5 Wm^{-2} irradiation for 48

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hours was needed to initiate anthocyanin synthesis in green apples. It seems from their results that anthocyanin production increases linearly with light intensity up to at least 100 Wm^{-2}. It has also been suggested that the direct heating effect of sunlight on the apple skin speeds up anthocyanin production and red colour formation (Thorpe, 1974).

In red apple cultivars the outer canopy fruit have the highest development of red coloured skin or red blush (Barrit *et al.*, 1987; Campbell and Marini, 1992; Doud and Ferree, 1980; Jackson *et al.*, 1977; Khemira *et al.*, 1993; Myers and Ferree, 1983; Wagenmakers and Callesen, 1989; Wagenmakers and Callesen, 1995). While there is a general acceptance that an increase in red blush results from improved light penetration, the relationship between blush development and light penetration within canopies has not been well defined.

Heinicke (1966) found that the best blush developed on apples that received a cumulative radiation exposure of over 70% of the full exposure values. Inadequate blush developed where values were less than 40%. Seeley *et al.* (1980) reported that the threshold photosynthetic irradiance for red blush to develop in 'Miller Studeespur Delicious' was 5 Wm^{-2}, but large increases in photosynthetic irradiance were needed to induce visibly detectable differences in the amount of blush. Jackson (1970) showed a similar correlation between anthocyanin content and irradiation level for individual apples on a tree of 'Laxton's Superb'. Increased levels of radiation penetration, about 20%, were required before anthocyanin began to accumulate. Robinson *et al.* (1983) found that the visual colouring of 'Miller Studeespur Delicious' was not affected by increased shading. Due to the high-colouring nature of the cultivar the minimum amount of radiation required for anthocyanin accumulation to begin was probably easily attained within the tree canopy. Hue angle and chroma, two components of fruit colour, were negatively correlated with light exposure for 'Bartlett' and 'Anjou' pear cultivars, i.e. they were less green than the fruit which were more shaded (Kappel and Neilsen, 1994).

Dussi and Huysamer (1995) confirmed that good light distribution within the orchard canopy is critical in the development of sufficient red skin colour in 'Forelle' pears, by

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demonstrating the effect that summer pruning had on colour development. In their study fruit skin colour variables presented a highly significant negative correlation with light intensity in the canopy i.e. with increasing exposure to light, fruit were redder, darker, and less intense. In a study done on the affects of summer pruning on the quality of 'Gala' apples Morgan *et.al.* (1984) found a significant correlation between increased light exposure and red blush colour development. Red blush development was improved by both early and late summer pruning treatments. It is generally accepted that this increase in red blush, due to summer pruning, results from improved light penetration.

The development of red colour was significantly affected by light deprival at different times of fruit growth of nectarines (Muleo *et al.*, 1994). Anthocyanin synthesis was prevented by shade shortly before harvest. It was found that fruits that were previously covered and then exposed to sunlight the last two weeks before harvest had greater anthocyanin synthesis. Marini *et al.* (1991) found very similar results for peach fruit. They confirmed that fruit redness and ground colour depended on photosynthetic photon flux density (PPFD) in the vicinity of the fruit. Fruit exposed to 45% PPFD had 14% less red colour than non-shaded fruit, whilst ground colour was better in the shaded fruit. Corelli-Grappadelli and Coston (1991) found that red colour was positively correlated and ground colour negatively correlated with PPFD in peach fruit. In a study done on 'Bing' sweet cherry, artificial shading treatments reduced red colour development (Patten and Proebsting, 1986). In the same study, using natural shade, the relationship of fruit colour to percentage of full sun was logarithmic, with colour being dramatically reduced at light levels below 10-15% of full sun.

Tustin *et al.* (1988) evaluated the ground colour of 'Granny Smith' apples and found that it was negatively correlated to increased PPFD transmission. Fruit from lower, inner canopy regions were the greenest, and the fruit became less green or paler green as the PPFD transmission increased. Morgan *et al.* (1984) in their studies of 'Gala' apple, suggested that ground colour was not related to percentage transmission of PPFD. However, the ground colour of 'Gala' does change significantly as maturity approaches, to the extent that it is used as a maturity indicator.

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8.2. Total soluble solids (TSS)

Taylor *et al.* (1993) found that 'Songold' plums sampled from the top of trees had higher TSS levels than those sampled from the bottom. This variation in TSS due to position of the fruit in the canopy was found to be due to a shading effect, as increased shading results in decreased photosynthesis. In both peach and nectarine fruit, TSS was found to be lower in shaded than non-shaded fruit (Marini *et al.*, 1991; Muleo *et al.*, 1994). In both cases, TSS was found to be dependent on PPFD in the vicinity of the fruit. 'Bing' sweet cherry shows a highly positive relationship between TSS and exposure to light. A study using natural shade showed a logarithmic relationship between TSS and percentage full sun (Patten and Proebsting, 1986).

Tustin *et al.* (1988) found a highly positive correlation between TSS concentration and percentage transmission of PPFD for 'Granny Smith' apples. Barrit *et al.* (1987) also found TSS concentration to be positively correlated to light exposure in 'Oregon Spur Delicious' apples. Doud and Ferree (1980) confirmed the above findings in a study done on 'Delicious' apples. Contradictory to these findings there was no positive correlation between PPFD transmission and TSS concentration for 'Gala' apples (Morgan *et al.*, 1984). Seeley *et al.* (1980) found that TSS was highly correlated with irradiance in the immediate growing environment of 'Delicious' apples. After 105 days of cold storage the TSS had increased and was highly correlated with irradiance. This study suggested that a positive relationship existed between TSS and irradiance. Robinson *et al.* (1983) confirmed this finding in a study conducted on the same cultivar.

Concentration of TSS at harvest was positively correlated to increased light exposure during the season for both 'Bartlett' and 'Anjou' pear cultivars (Kappel and Neilsen, 1994). These results confirmed the findings of Kappel (1989) for 'Bartlett' pear. Another study conducted on 'Anjou' pears found no significant differences in TSS under differing light microclimatic conditions (Khemira *et. al.*, 1993).

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8.3. Other quality parameters

Flesh firmness was negatively correlated to increased light exposure during the season for 'Bartlett' pears at harvest (Kappel and Neilsen, 1994). By contrast, 'Anjou' flesh firmness at harvest showed no correlation to light exposure during the growing season. 'Bartlett' pears were also found to be firmer under more shaded conditions by Kappel (1989). Khemira *et al.* (1993) found that the fruit were larger, but also softer, under more exposed conditions in a study done on 'Anjou' pears. Barrit *et al.* (1987) found that 'Oregon Spur Delicious' apples in the more shaded positions in the canopy had higher firmness and levels of starch, N, P, K, Zn, Ca, Fe, B, and Mg. In a different study, shading was also found to increase levels of P, K, B, and Zn, whilst reducing levels of Ca and Mg in 'Delicious' apple trees (Doud and Ferree, 1980).

Jackson *et al.* (1977) in their study on the effect of shade on fruit quality had several interesting findings. It was found that fruit grown under shade generally had a better skin finish with less russet and cracking than the more exposed fruits. Fruits grown under shaded conditions also developed less bitter pit, senescent breakdown, and soft rots, but more core flush and shrivel than the more exposed fruit. There was no evidence that the concentrations of N, P, K, Ca, or Mg differed in fruits of the same size produced under shaded or exposed conditions, but smaller fruits had higher concentrations of Ca, N, and P than did larger ones. The greater part of the direct and residual influence of exposure on bitter pit incidence could be statistically accounted for by the regression of bitter pit on fruit size and leaf Ca concentration. Shaded fruits did not seem to be simply physiologically retarded versions of exposed fruit, as shaded fruit had consistently less starch when harvested, both in absolute terms and as a percentage of dry matter, than the exposed controls at the same date. Thus, this study found that fruits on the outer parts of apple trees are generally larger, redder, more prone to bitter pit and rotting and less prone to shrivel and core flush than fruits from the inner zones.

Seeley *et al.* (1980) found that starch content was positively correlated to irradiance in the immediate growing environment of 'Delicious' apples. There was, however, no

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relationship between fruit firmness and irradiance. A significant finding of this study was that, even though as little as 9% of full sunlight was sufficient to allow red colour development, it was not sufficient to produce the highest quality in terms of size, starch content, and TSS. Robinson *et al.* (1983) found, while doing a study on the same cultivar, that as shade increased starch content and total solids were reduced, but fruit firmness and total acidity increased. Campbell and Marini (1992) found that flesh firmness, length:diameter ratio, and starch index of 'Delicious' apple were not consistently affected by any measure of canopy light microclimate. They further suggested that factors other than light were responsible for nearly two-thirds of the variation in fruit quality measurements.

In a study done on 'Bing' sweet cherry, fruit from unshaded limbs were firmer than those from shaded limbs, when compared at equal colour maturities (Patten and Proebsting, 1986). When the same study was done using natural shade there was no relationship between firmness and percentage exposure to full sun.

Perring and Clijsters (1974) enclosed 'Jonathan' apples in black cloth bags 50 days after full bloom and harvested them 84 days later. The treated apples had slightly higher concentrations of P, and N, but their Ca concentration was reduced by 12%. No breakdown developed in storage, although individual control apples that broke down were found to have very low Ca concentrations. The appearance of lenticel blotch pit on treated apples during storage was consistent with a 40% reduction of Ca concentration in the peel.

Taylor *et al.* (1993) found that mineral element levels of 'Songold' plums sampled from the top of trees was lower than in those sampled from the bottom. They attributed this to lower concentrations of elements in the translocation stream at the top of the trees due to sink effects lower down. Shading in the lower canopy resulted in lower photosynthesis, and this resulted in fruit sampled from the top of the tree having a greater dry mass. The observed differences could have been due to this as results were expressed on a concentration basis.

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9. Harvest maturity and fruit quality response to postharvest storage

9.1. Stone fruit

Mitchell (1986) stated that the maturity of stone fruit at harvest determines its ultimate quality. This has been found for plums (Abdi *et al.*, 1997; Hartmann *et al.*, 1988; Kotzé *et al.*, 1989; Kruger *et al.*, 2001; Taylor *et al.*, 1993; Visagie and Eksteen, 1981) apricots (Salunkhe *et al.*, 1968; Taylor and De Kok, 1992), peaches (Marini, 1985; Rood, 1957), nectarines (Visagie and Eksteen, 1981) and prunes (Proebsting *et al.*, 1974). Harvest maturity affects postharvest quality of the fruit in terms of the physiological condition of the fruit, susceptibility to mechanical injury, susceptibility to decay, shrivelling, flavour, skin ground and blush colour, fruit appearance and aroma (De Swardt and Redelinghuys, 1968; Kruger *et al.*, 2001; Mitchell, 1986; Taylor *et al.*, 1993).

Plums harvested too ripe are susceptible to bruising, decay, overripeness and bladderiness. If harvested too green, plums have an acid taste and poor aroma (De Swardt and Redelinghuys, 1968). Mitchell (1986) reported that fruit harvested too green are prone to shrivel due to the inability of a poorly developed surface cuticle to prevent water loss. Advanced maturity at harvest of apricots are associated with increased incidence of internal breakdown (Visagie, 1985), and gel breakdown (Taylor and De Kok, 1992). Increased incidence of internal breakdown in plums has been associated with immature fruit (Eksteen, 1982), and with fruit harvested too ripe (De Swardt and Redelinghuys, 1968). Kotzé *et al.* (1987) found that when subjected to a dual temperature storage regime, harvest maturity has little effect on the incidence of internal breakdown of 'Songold' plums. Taylor *et al.* (1993) reported that incidence of gel breakdown in 'Songold' plums increased with advanced maturity at harvest.

Characteristics that change with advancing maturity are valuable as indicators of harvest maturity (Lill *et al.*, 1989). Advanced maturity of plums at harvest is associated with an increase in skin ground colour, TSS and TSS:acid ratio, and a decrease in firmness and

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malic acid levels (Taylor *et al.*, 1993). It has therefore been noted, as could be expected, that the later the harvest, the more advanced the maturity of the fruit (Taylor *et al.*, 1993). TSS level in the fruit is not an accurate indicator of fruit maturity at harvest as differences in TSS at harvest are probably due to shading effects, as previously discussed. This is consistent with findings on plums (Taylor *et al.*, 1993), peaches (Rood, 1957), and apples (Tvergyak, 1991), where it was found that variability between years and within the canopy lead to the unsuitability of using TSS to establish harvest maturity. Taylor *et al.* (1993) found that flesh firmness and malic acid concentration provided the most useful means of establishing the harvest maturity of 'Songold' plums.

Harvest maturity of stone fruit affects the response of fruit quality parameters to postharvest storage. Taylor *et al.* (1993) found that differences in firmness and malic acid concentration of 'Songold' plums when measured after 35 days of dual temperature storage were comparable to differences present at harvest, but absolute differences were too small to affect fruit quality. The differences in maturity present at harvest were therefore negated during postharvest storage. They also found that fruit with an advanced maturity at harvest developed a more yellow ground colour during storage due to a decline in chlorophyll and increase in carotenoids. Abdi *et al.* (1997) reported that hue angle of fruit sampled at an advanced maturity was lower, and that the hue angle continued to become smaller during storage representing a change from green to red skin colour. Kruger *et al.* (2001) also reported an improvement in skin colour development during storage.

Response of TSS to storage is contradictory. TSS of plums decreases during storage (Abdi *et al.*, 1997; Taylor *et al.*, 1993) but this is in contrast to the situation in peaches and nectarines (Aly *et al.*, 1981) and apricots (Salunkhe *et al.*, 1968) where levels increase or remain constant, respectively. It has been noted that increased TSS:acid ratios are indicative of better flavour in apricots and therefore fruit harvested at an advanced stage of maturity are expected to provide the best flavour (Salunkhe *et al.*, 1968; Taylor *et al.*, 1993).

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Abdi *et al.* (1997) found that fruit harvested at an earlier maturity withstand postharvest storage better than fruit harvested at a more advanced maturity, but less mature fruit have a lower quality when ripened than mature fruit.

9.2. Pome fruit

Fruit maturity at harvest affects both storability and post storage quality of apples (Drake *et al.*, 2002). Presently, skin colour, firmness, TSS, starch content and ethylene production are or have been used as indices of apple fruit maturity for scheduling harvest. Starch content in the fruit flesh has often been used as a measure of maturity for scheduling the harvest of apples (Beaudry *et al.*, 1993; Drake and Kupferman, 2000; Fan *et al.*, 1995; Lau, 1988; Smith *et al.*, 1979). Other studies have shown that starch may not be a reliable indicator of apple maturity (Blanpied, 1974; Knee *et al.*, 1989). Regardless of these contradictory findings, starch content is used extensively in the commercial apple industry as an indicator of apple maturity.

Advanced maturity of apples at harvest is associated with a decrease in firmness and malic acid concentration and an increase in TSS and skin colour (Drake *et al.*, 2002; Drake and Eisele, 1997; Drake and Kupferman, 2000; Lau and Looney, 1982; Meheriuk and Pruitt, 1973). Previous studies have found similar results for pears (Chen and Mielke, 2000; Drake and Eisele, 1997). Consumer preference for apples is reported to improve with increased soluble solids content to titratable acidity ratios (Boylston *et al.*, 1994). Therefore, the increase in TSS and decrease in TA associated with advanced maturity of apples at harvest will lead to improved eating quality and flavour.

Harvest maturity affects the response of fruit quality parameters to postharvest storage. After storage, differences in firmness, TSS, TA and the TSS to TA ratio between fruit harvested at different maturity levels are similar to differences in those parameters at harvest. Apple blush colour has been noted to increase during storage. This increase in blush colour has been reported to be due to a loss of chlorophyll during the storage period (Drake *et al.*, 2002; Drake and Eisele, 1997; Drake and Kupferman, 2000; Lau and

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Looney, 1982; Meheriuk and Pruitt, 1973). Harvest time has been found to influence fruit texture after storage, but results varied for different apple cultivars (Zerbini *et al.*, 1999). Previous studies have found similar results for pears (Chen and Mielke, 2000; Drake and Eisele, 1997).

Increased incidence of internal breakdown after storage has been noted for apples harvested at an advanced maturity (Drake *et al.*, 2002; Drake and Eisele, 1997; Drake and Kupferman, 2000; Lau and Looney, 1982; Meheriuk and Pruitt, 1973). Calcium is the nutrient most commonly associated with postharvest disorders. In bitter pit in apple fruit, almost all pre-harvest factors which affect incidence of the disorder can be directly or indirectly related to calcium nutrition of the fruit (Ferguson *et al.*, 1999). The only exception may be maturity, but the reason for the higher incidence of bitter pit in less mature fruit is, however, not clear, but is possibly related to subsequent rates of ripening (Ferguson and Watkins, 1989).

Drake *et al.* (2002) reported that acceptable fruit quality of 'Cripps' Pink' apples could be achieved following long-term storage when fruit were harvested at different levels of maturity. Fruit were harvested at a starch index between two and four and stored under either RA or CA. This created a harvest window of between 10 and 15 days, and allowed harvest scheduling to be based on other factors such as the desire for higher TSS levels or an improved blush colour, should either represent a marketing concern. Firmness and acid levels remain at acceptable levels in 'Cripps' Pink' apples during long-term storage.

10. Water relations

10.1. Differences between micro- and drip-irrigation systems

Irrigation technique affects root spread, growth, productivity and overall water status of the tree. Comparison of micro- and drip-irrigation systems indicates that roots spread less and trees grew more slowly under drip-irrigation of a peach orchard (Mitchell and Chalmers, 1983). A decrease in tree vigour under drip-irrigation has also been found in

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apple trees (Proebsting *et al.*, 1977). Peach and apple trees under drip-irrigation do, however, crop earlier (Mitchell and Chalmers, 1983; Proebsting *et al.*, 1977).

10.2. Effect of pre-harvest water stress on stone fruit growth and final yield

The sensitivity of stone fruit to water stress over the different stages of fruit growth has been reported in several previous studies (Lampinen *et al.*, 1995; Marsal and Girona, 1997; Naor *et al.*, 2001; Torrecillas *et al.*, 2000). Stone fruit growth and final diameter respond differently to water stress or deficit irrigation during different phenological periods of fruit growth. Tree response to deficit irrigation depends on the fruit growth stage (Behboudian and Mills, 1997). Deficit irrigation in stages I and II of fruit growth has been reported to have no affect on yield (Li *et al.*, 1989), but deficit irrigation in stage III decreased yield (Berman and De Jong, 1996; Lampinen *et al.*, 1995; Li *et al.*, 1989; Marsal and Girona, 1997; Naor *et al.*, 1999; Naor *et al.*, 2001; Torrecillas *et al.*, 2000).

Irrigation deficit treatments applied to apricot trees during the initial exponential phase, the lag phase of the double sigmoidal curve, and during the second exponential phase of fruit growth shortly before harvest, illustrated these different responses (Torrecillas *et al.*, 2000). Fruit growth was retarded during water stress in the first two stages of fruit growth, but these fruit showed a compensatory increase in growth rate in the final stage of growth and attained a similar size to control fruit at harvest. Fruit subjected to water stress during the final rapid stage of fruit growth were smaller and this resulted in a reduced yield at harvest.

In previous studies, covering individual peach and nectarine fruit in stage III of fruit growth with plastic or aluminium foil modified the microenvironment around the fruit by increasing humidity (Li *et al.*, 2001; Muleo *et al.*, 1994). Higher humidity limited fruit transpiration and consequently fruit water status was improved, which resulted in a more rapid increase in fruit volume.

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Besset *et al.* (2001) reported that when compared with optimum irrigation, light water stress induced a slight decrease in water potential and photosynthesis was light saturated at a lower level of irradiance, but this did not have an effect on final yield. Source limitation with light water stress was not enough to reduce fruit growth. Fruit growth is dependent on the accumulation of osmotically active solutes in the fruit (Berman and DeJong, 1996) and this is not affected by light water stress. Severe irrigation stress, on the other hand, induces a reduction in yield due to a limitation of assimilates supplied to the fruit. This is possibly related to limitations in leaf photosynthesis caused by the severe stress (Besset *et al.*, 2001; Berman and DeJong, 1996; Grossman and DeJong, 1995).

10.3. Effect of pre-harvest water stress on sugar accumulation in fruit

Water stress triggers the physiological function of osmoregulation (Meyer and Boyer, 1981). Osmoregulation is the accumulation of solutes in cells, sufficient to decrease the osmotic potential of cells, so that water can be absorbed from the water source by cells without losing cell turgor or decreasing cell volume. Many plants, to tolerate water stress, are largely dependent on their capacity for osmoregulation for maintaining cell turgor through the accumulation of solutes (Morgan, 1984). Previous investigations have observed osmoregulation in stems (Meyer and Boyer, 1981), roots, and leaves (Ranney *et al.*, 1991). Water-stressed plants have been found to accumulate more sugars than unstressed plants (Meyer and Boyer, 1981).

In a study conducted on 'Satsuma' mandarin fruit, osmotic potential of juice vesicles in water stressed fruit decreased, and sugars accumulated in vesicle cells (Yakushiji *et al.*, 1996). Concentrations of sucrose, fructose, and glucose increased in fruit sap under water stress, and the acidity in the fruit juice increased. Total sugar content per fruit of water stressed trees was significantly higher than in fruit of well-watered trees. The results suggested that sugar accumulation in 'Satsuma' mandarin fruit was due to active osmoregulation in response to water stress, and not due to dehydration under water stress. Other studies on citrus fruit have also shown that irrigation stress causes an increase in

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TSS content (Peng and Rabe, 1998; Verreynne *et al.*, 2001; Yakushiji *et al.*, 1998). It has also been noted that water stressed fruit are smaller but have higher levels of total soluble solids (Besset *et al.*, 2001; Crisosto *et al.*, 1994). It is not known how these fruit respond to cold storage and ripening periods.

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Chapter II:

Effect of shading on harvest maturity and postharvest quality of 'Laetitia' and 'Songold' plums

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ABSTRACT

In 2000-2001 and 2001-2002 entire branches of 'Laetitia' and 'Songold' plums were bagged with different densities of shade netting after the end of cell division, giving 100% visible light transmission (no bags), 80%, 50% and 20% light transmission. Increased exposure to irradiance led to increased leaf nitrogen content, photosynthesis, stomatal conductance, and transpiration in 'Laetitia' trees. Fruit quality, in terms of diameter, mass, skin ground and blush colour, firmness, total soluble solids and titratable acidity, was assessed at harvest, after storage and after ripening. 'Laetitia' and 'Songold' plums were stored at –0.5°C for 10 days followed by 8 days at 7.5°C and a ripening period of 5 to 7 days at 15°C. Fruit diameter, mass, and proportion of dry mass of 'Laetitia' plums at harvest increased as exposure to irradiance increased. Increased exposure to irradiance was associated with advanced maturity. The delayed maturity and maturity associated quality parameters of the shaded fruit were able to attain similar levels as the control fruit after storage and ripening. Differences in fruit blush colour and total soluble solid content were due to light exposure effects and the differences were still significant after storage. After ripening, blush colour and TSS content were increased with increased exposure to irradiance. As exposure to irradiance increased so did whole fruit content of Mn and B. On a dry mass basis the concentration of P and K (2001-2002) and B (2000-2001) decreased with increasing light.

INTRODUCTION

The importance of the canopy microclimate to fruit production and particularly to fruit quality in many fruit species has been recognised for many years. Increased exposure to irradiance shows a positive correlation with fruit size in apples (Barrit *et al.*, 1987; Jackson *et al.*, 1977) and stone fruit (Marini *et al.*, 1991; Muleo *et al.*, 1994; Patten and Proebsting, 1986; Taylor, 1993). Final size of stone fruit is also affected by fruit water status during the final stage of rapid fruit growth. In previous studies, covering individual peach and nectarine fruit with plastic or aluminum foil modified the microenvironment around the fruit by increasing humidity. Higher humidity limited fruit

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transpiration and consequently fruit water status was improved, which resulted in a more rapid increase in fruit volume (Li *et al.*, 2001; Muleo *et al.*, 1994).

Mineral nutrient concentrations of fruit have been found to decrease with increased exposure to irradiance in apple, but results show that this is probably due to the smaller size of shaded fruit (Barrit *et al.*, 1987; Doud and Ferree, 1980). Taylor *et al.* (1993) found that mineral element levels in 'Songold' plums harvested from the top of trees were lower than in those sampled from the bottom. This was possibly due to partitioning of the translocation stream or differences in dry mass between top and bottom fruit.

Pre-harvest exposure of fruit to different levels of irradiance also results in unequal maturity at harvest and thus differences in fruit quality in the same consignment. At harvest, advanced maturity is associated with an increase in the development of skin colour and total soluble solids, whilst firmness and titratable acidity decrease (Abdi *et al.*, 1997; Kruger *et al.*, 2001). Postharvest storage of plums results in a decline in firmness, TSS, and TA, but an increase in skin colour development (Abdi *et al.*, 1997; Kruger *et al.*, 2001; Taylor *et al.*, 1993). Taylor *et al.* (1993) found that advanced maturity at harvest is associated with an increased incidence of internal disorders after postharvest storage.

The potential mechanisms of physiological responses to increased light exposure include an improved carbon balance directly due to light striking the organ of interest and the associated effects on temperature and photosynthesis (Lakso, 1994). Alternatively, increased transpiration resulting in greater partitioning of the transpiration stream and nutrient supply to more exposed sites in the canopy. Light-induced differences in leaf and fruit temperature, transpiration rate, and the resultant partitioning of xylem-derived solutes may provide a better nutrient supply to exposed foliage and fruits (Neumann and Stein, 1983 as reported by Lakso, 1994). Direct exposure of fruit increases fruit temperatures, and this would possibly increase fruit transpirational flux and the

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translocation of nutrients and hormones to the fruit sink, thus increasing sink strength (Thorpe, 1974).

This study aims to investigate the effects of pre-harvest light exposure on harvest maturity and fruit quality, possible mechanisms underlying these responses, and the response of fruit quality to storage and ripening in 'Laetitia' and 'Songold' plums. Development of fruit under different light microclimates leads to variability in fruit quality and is detrimental to effective marketing of the product. An improved carbon balance, partitioning of the transpiration stream or the indirect effect of variable fruit maturity at harvest are potentially mechanisms underlying the physiological responses to light exposure.

MATERIALS AND METHODS

Plant material

'Laetitia' and 'Songold' plum trees on Mariana rootstock were planted in 1992 on Welgevallen Experimental Farm in Stellenbosch, Republic of South Africa (33°55'S 18°53'E). The trees were planted at 4.5m x 1.25m spacing and trained as central leaders on a three-wire system. The row orientation was roughly north-east by south-west. Micro-jet sprinklers were used for the irrigation system and the irrigation scheduling was based on neutron moisture probe measurements. All cultural and physical orchard practices were in agreement with commercial norms for the region.

2000-2001.

Treatments and experimental design: Artificial shade treatments were created by using bags of black polypropylene shade netting of varying densities, fastened around entire branches. Four treatments were used: 80%, 50%, and 20% density shade netting, and a control treatment. Two or three branches per tree were bagged and a total of 20 fruit on those branches tagged. In the case of the control trees two or three branches were selected and 20 fruit tagged, but branches remained unbagged. All branches selected were on the north-west side of the tree, of similar size, and exposed to a similar light

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microenvironment. Both the 'Laetitia' and 'Songold' experiments were designed as complete randomised blocks, with 10 blocks of four treatments. The treatments were applied to the 'Laetitia' trees on 6 December 2000 and to the 'Songold' trees on 13 December 2000. Full bloom of 'Laetitia' was on 2 October 2000 and for 'Songold' on 7 October 2000.

Photosynthetic light response: The response of leaf net CO_2 assimilation rate (A) to photosynthetic photon flux density (PPFD) (the photosynthetic light response curve) was determined on one leaf from five 'Laetitia' trees of each treatment selected randomly from different blocks. A portable photosynthesis system (LI-6400, Li-Cor, Lincoln, Nebraska, USA) was used for this purpose. Irradiance levels of 1500, 600, 400, 200, 100, and 0 μmol m^{-2} s^{-1} PPFD were provided by an internal red/blue LED light source (LI-6400-02B, Li-Cor, Lincoln, Nebraska, USA). Cuvette carbon dioxide (CO_2) concentration was controlled at 380 μmol mol^{-1} using the LI-6400 CO_2 injection system and compressed CO_2-cylinders. Leaf temperatures were regulated at 25°C. The measurements were taken on 26 January 2001.

Response curves were fitted individually using non-linear regression (Statistica 5.5) and the monomolecular function $y = a\ (1- e^{b-cx})$ given by Causton and Dale (1990). The fitted curve coefficient 'a' gave the light-saturated rate of net CO_2 assimilation (A_{max}), 'ace^b' gave the apparent quantum efficiency (AQE) (gradient at x=0), and the daytime dark respiration rate (R_D) was calculated from the light response using '$a\ (1- e^b)$' (Causton and Dale, 1990).

Leaf transpiration rate (E) and stomatal conductance (g_S) were measured simultaneously during the determination of the photosynthetic light response. Values at light saturation (1500 μmol m^{-2} s^{-1}) were analysed. The photosynthetic light response measurements were determined for the 'Laetitia' trial only.

Harvest and postharvest quality determination: The 'Laetitia' plums were harvested on 31 January 2001 and the 'Songold' plums on 21 February 2001. The 20

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tagged fruit per replicate were harvested and five fruit evaluated for quality. The remaining fruit were immediately placed in storage at –0.5°C. These fruit were subjected to a dual temperature storage regime with 10 days at –0.5°C followed by eight days at 7.5°C and a seven-day ripening period at 15°C. Five fruit per replicate were evaluated after 18 days of dual temperature storage and five fruit after seven days of ripening. The following quality parameters were measured on each date:

Fruit diameter was measured around the equator using electronic callipers and individual fruit mass was determined. Ground and blush colour were evaluated using the respective colour charts for 'Laetitia' and 'Songold' plums provided by Hortec, Stellenbosch (Unifruco Research Services ground colour chart for apples and pears; Laetitia blush colour DFB PL. 25; Songold colour DFB PL. 19). A colorimeter (NR-3000, Nippon Denshoku, Tokyo, Japan) was used to measure the hue angle (°) of the blushed side of 'Laetitia' fruit only, at a point on the fruit where colour was most uniform. Fruit firmness was determined on peeled, opposite cheeks of the fruit using a penetrometer (Southtrade fruit pressure tester, FT 327, Alphonsine, Italy) fitted with an 11 mm tip. Slices cut from each side of each of the five fruit were juiced together and a total soluble solids (TSS) reading taken using a hand held refractometer (Atago PR-100 9501, Japan). Juice obtained for TSS was also analysed for titratable acidity (TA) by titration with 0.1 M NaOH to a pH of 8.2 using an automated titrator (Tritino 719S and Sample Changer 674, Metrolum Ltd., Herisau, Switzerland). Results were expressed as percent malic acid. Internal browning, gel breakdown, aerated flesh (air-filled cells in mesocarp giving fruit a dull appearance) and over-ripeness, as described by Taylor (1996), as well as incidence of decay were rated. These ratings were done as a percentage of the five fruit evaluated per replicate, both after storage and again after ripening. Slices cut from each side of each of the five fruit per replicate were freeze-dried and milled together. The samples were analysed for phosphorus, potassium, calcium, magnesium, sodium, manganese, iron, copper, zinc and boron concentration, expressed as a percentage of dry mass. Mineral analysis was done at a commercial laboratory (Bemlab, Stellenbosch) according to standard methods, and was only done for the 'Laetitia' plums at harvest.

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2001-2002.

Treatments and experimental design: The experiment was repeated on the 'Laetitia' plum trees, using the same orchard and rows, but not the same trees and branches, as in the previous season. The artificial shade treatments were applied in the same manner as in the first season, but the 80% density shade netting treatment was not repeated. A complete randomised block experimental design was again used, but the number of blocks was increased to 12. The treatments were applied to the trees on 28 October 2001. Full bloom of 'Laetitia' was on 13 September 2001.

Microclimate around branch: The PPFD levels under the shade netting and around the control branches were determined using a quantum sensor (LI-189, Li-Cor, Lincoln, Nebraska, USA) to determine relative reduction in light due to the shade treatments. The PPFD measurements were taken on 21 January 2002 which was a cloudless day. Measurements were taken during the midday period (11h30 to 13h00), block by block. 10 measurements were taken at random positions under the shade net or around the control branch.

Microclimatic data loggers (Watchdog Model 450, Spectrum Technologies Inc., Plainfield, Illinois, USA) were used to measure the relative change in air temperature and relative humidity under the shade treatments as compared with the control treatment for a 36-hour period on 30, 31 January and 1 February 2002. The control and 20% shade treatment each had one data logger in one of the blocks, and the 50% shade treatment had two data loggers in two different blocks. The loggers were placed under the shade nets or next to the control tree branch in an exposed portion, and were shielded from direct sunlight by radiation shields.

Leaf and fruit skin temperatures were determined on three dates using an infrared thermometer (Raynger MX4, Raytek, Berlin, Germany). The temperature of three leaves and fruit were determined per tree, on cloudless days, and measurements were taken during the midday period (11h00 - 13h00), block by block.

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Pre-harvest physiological responses: At harvest, 20 leaves per tree were harvested from underneath the shade treatments or from the tagged control tree branches for analyses of fresh mass, dry mass, leaf area and percentage nitrogen concentration. Fresh leaf mass was determined directly after harvest. Leaf area was measured by scanning the leaves with a Hewlett-Packard C Scanjet 4c Scanner (Program Desk Scan II, Version 2.3). Data analysis was performed with a computer program (Delta-T Scan Version 2.04nc of Delta-T Devices Ltd, Cambridge, England). Dry mass was determined after the leaves were oven-dried at 90°C to constant mass. Specific leaf mass (SLM) was calculated as follows: SLM = dry mass/leaf area (g m^{-2}). The oven-dried leaves were milled and the percentage nitrogen concentration determined according to standard methods by a commercial laboratory (Bemlab, Stellenbosch). The nitrogen concentration on a mass basis was converted to an area basis using the following calculation: g(nitrogen)cm^{-2} = (% nitrogen x SLM)/10000.

Leaf water potential under the different shade treatments was determined using a pressure chamber (PMS 600, PMS Instruments, Corvallis, Oregon, USA). Three leaves per tree were measured on five different dates during the season. Measurements were taken during the midday period (10h00 to 14h00), block by block.

The response of leaf net CO_2 assimilation rate (A) to PPFD was determined as previously described in one leaf from four 'Laetitia' trees of each treatment selected randomly from different blocks, using the LI-6400 (Li-Cor, Lincoln, Nebraska, USA). Irradiance levels of 1500, 1300, 1000, 700, 400, 200, 100, 50, and 0 µmol m^{-2} s^{-1} PPFD were used during this year. Measurements were performed on 25 January 2002.

Fruit growth was determined by measuring fruit diameter of tagged fruits on four different dates during the growing season using electronic callipers.

Harvest and postharvest quality determination: The 'Laetitia' plums were harvested on 22 January 2002. The fruit were subjected to the same dual temperature

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storage regime as for the previous year, but the ripening period was reduced to five days at 15°C. Fruit were again evaluated at harvest, after storage, and after ripening, using the same set of quality parameters as described for 2000-2001. The following additional measurements were performed in 2001-2002. The combined fresh mass of slices from each side of the five fruit per replicate was determined at harvest, and the dry mass after freeze-drying to constant mass. These measurements were used to calculate the percentage water in the fruit as follows: %water = (fresh mass-dry mass)/fresh mass x 100. Mineral analysis of 'Laetitia' fruit at harvest was done in the same manner as in 2000-2001, on the fruit sample that had been used to determine fresh and dry mass. The mineral percentages on a dry mass basis were converted to a fresh whole fruit basis as follows: grams fruit $^{-1}$ = {(mineral % x dry mass) x (dry mass/fresh mass)} x (fruit mass/fresh mass).

Statistical analysis: The data were analysed with the General Linear Models (GLM) procedure of SAS (SAS release 6.12P; SAS Institute, 1996, Cary, NC). Linear and quadratic orthogonal polynomial contrasts were used to analyse the responses to decreasing light interception. The Statistica software system (Version 6; Statsoft Inc., Tulsa, OK) was used to fit non-linear photosynthetic response curves.

RESULTS

Microclimate around branch

There was a substantial decrease in photosynthetic photon flux density (PPFD) transmission under the shade treatments of the 'Laetitia' trees in 2001-2002 (Table I). The PPFD level under the 20% shade net was approximately 70%, and under the 50% shade net approximately 45% of the PPFD around the control branch. The 80% shade net was estimated to have a PPFD level of approximately 25% of the control. This assumption is based on irradiance measurements obtained from a similar experiment on 'Cripps' Pink' apple trees at the same experimental site during 2000-2001. The PPFD level around the 'Songold' branches was assumed to be similar to the levels observed in

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the 'Laetitia' trial, as the trees were planted in the same orchard and the physical and cultural practices were the same for both 'Songold' and 'Laetitia'.

Relative humidity was slightly lower at 45% PPFD compared to the other treatments between 08h00 and 11h30 (Figure 1). Air temperature during the midday period differed between the treatments (Figure 2). Maximum air temperature was recorded between 15h00 and 18h00 on 31 January, and was 41.6°C at 45% PPFD, which was 8°C higher than the 33.6°C recorded at 70% PPFD. This difference was probably due to reduced air movement through the 50% shade net. The control treatment obtained the highest maximum of 44.4°C. Nocturnal air temperature was similar around control and shaded branches.

Leaf temperature increased quadratically as PPFD decreased on the first measurement date (Table II). There were no differences on the second date. On the third date, which was a warmer day, leaf temperature followed a quadratic trend over irradiance, as it decreased from 100% to 70% PPFD and then increased again to 45% PPFD. Absolute differences between treatments were, however, small. A similar quadratic trend was found for fruit skin temperature on this day, but no differences in fruit temperature were found on the first two dates.

Pre-harvest physiological responses

Leaf nitrogen concentration expressed as a percentage of dry mass was highest in the control treatment and decreased linearly as PPFD decreased (Table III). There were no significant trends over irradiance with regard to nitrogen concentration on an area basis or SLM.

On 13 November, 16 days after the shading treatments were started, the midday leaf water potential was lowest at 100% PPFD, but increased at 70% and 45% PPFD to similar levels (Table IV). After the shading treatments had been in place for a longer period of time the midday leaf water potential continued to be higher as PPFD decreased, and was also higher at 45% PPFD relative to 70% PPFD.

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The light saturated rate of net CO_2 assimilation (A_{max}) decreased linearly as PPFD decreased in 2000-2001 (Figure 3 (a), Table V). Measured rates were unusually low, as were stomatal conductance measurements, but in contrast to this transpiration measurements were within a normal range and comparable to measurements in the second season. These results were due to an unusually high vapour pressure deficit (VPD) which was the driving force of transpiration despite the low stomatal conductance measurements. VPD measurements ranged between 2.4 and 5.5 in 2000-2001, and between 1.2 and 1.4 in 2001-2002. In 2001-2002 A_{max} was again highest at 100% PPFD and then followed a quadratic trend over irradiance as A_{max} was higher at 45% than at 70% PPFD (Figure 3 (b), Table V). The increase in A_{max} at 45% PPFD may have been due to the increase in air temperature under this shade treatment. In both seasons, photosynthesis reached light saturation at different PPFD levels with respect to the different treatments (Figure 3 (a), (b)). Increased exposure to irradiance was associated with light saturation at increased PPFD levels. There were no statistically significant trends in apparent quantum efficiency (AQE) over irradiance in either of the seasons (Table V). Leaf stomatal conductance (g_S), transpiration rate (E) and daytime dark respiration rate (R_D) followed the same trend as A_{max} in both seasons, with a linear decrease as PPFD decreased in 2000-2001, and a quadratic response over irradiance in 2001-2002 (Table V).

The diameters of tagged fruit were first measured 18 days after the shade treatments were started. Control fruit already had the largest diameter, and fruit at 70% and 45% PPFD had similar, lower mean fruit diameters, giving a quadratic trend over irradiance (Table VI). This pattern was maintained throughout the season.

Harvest and postharvest fruit quality

The percentage fruit water content increased linearly as PPFD decreased (data not shown). During both seasons and at each of the evaluation dates there were linear decreases in 'Laetitia' fruit diameter as PPFD decreased (Table VII). The main difference occurred between 100% PPFD and shading treatments, but not between

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shading treatments. There was no significant effect on 'Songold' plum diameter (Table VII).

In 2000-2001, 'Laetitia' fruit mass decreased linearly as PPFD decreased, but only significantly when measured after 18 days of storage (Table VIII). In 2001-2002, a quadratic trend over irradiance was found for 'Laetitia' fruit mass at harvest due to the lowest value being measured at 70% PPFD. After storage and ripening, however, fruit mass decreased linearly as PPFD decreased. There was no statistically significant effect on the mass of 'Songold' plums (Table VIII). Differences in size and mass between the three evaluation dates could be an artefact of sample variability as different samples were measured on each date.

In 2000-2001, 'Laetitia' ground colour at harvest decreased quadratically as PPFD decreased (Table IX). Ground colour development was similar for the fruit under shade treatments, but they were greener than the control fruit. After storage there was no significant trend over irradiance. In 2001-2002, at harvest and after storage, there was a linear decrease in ground colour as PPFD decreased (Table IX). Ground colour is not visible after the ripening period as fruit turns fully red. At harvest, 'Songold' ground colour decreased linearly as PPFD decreased, but the differences were small (Table IX). There was no significant trend after storage and ripening. Blush colour of 'Songold' plums only developed after the ripening period and decreased linearly, but not significantly, as pre-harvest PPFD decreased (Table IX).

At harvest in both seasons there was a quadratic decrease in 'Laetitia' blush colour as PPFD decreased (results not shown). At harvest in both seasons the hue angle of 'Laetitia' plums increased as PPFD decreased (Figure 4). A linear trend over irradiance was found for blush colour after storage and ripening in both seasons (results not shown). The trend over irradiance changed from quadratic to linear as the differences between the control and shading treatments narrowed during storage. Blush colour of shaded fruit improved to a greater extent than control fruit during storage and ripening.

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In both seasons a linear trend over irradiance was found for hue angle after storage and ripening (Figure 4).

At harvest in both seasons 'Laetitia' fruit flesh firmness decreased linearly as PPFD increased (Figure 5). The same linear trend over irradiance remained after storage and ripening in both seasons, but the absolute differences between the treatments after ripening were small (Figure 5). 'Songold' fruit firmness tended to increase as PPFD decreased at each of the evaluation dates, but a statistically significant linear trend over irradiance was found only after storage (Table X).

In 2000-2001, total soluble solids (TSS) of 'Laetitia' fruit decreased as PPFD decreased. At harvest, a linear trend over irradiance was significant, and after storage and ripening a quadratic trend over irradiance was found, with the biggest decrease occurring from 100% to 70% PPFD (Table XI). In 2001-2002, TSS decreased linearly as PPFD decreased after storage and ripening, but there were no effects at harvest (Table XI). TSS of 'Songold' plums decreased linearly as PPFD decreased at each evaluation date, but only significantly at harvest and after storage (Table XI). In 2000-2001, there was no effect on titratable acidity (TA) in 'Laetitia' (Table XII). In 2001-2002, however, TA increased linearly as PPFD decreased at each of the evaluation dates. At harvest, TA of 'Songold' plums decreased linearly as PPFD decreased, but after the ripening period TA increased as PPFD decreased (Table XII).

Mineral nutrient analysis

In 2000-2001 the shade treatments resulted in no significant trends over irradiance with regard to macronutrient concentration in 'Laetitia', but the concentrations did tend to increase as PPFD decreased (Table XIII). In 2001-2002 the concentrations of phosphorus, potassium, and magnesium increased linearly as PPFD decreased, but the concentration of calcium was similar for control and shaded fruit (Table XIII). In 2000-2001, boron concentration increased linearly as PPFD decreased, but this was the only micronutrient concentration affected in either of the seasons (Table XIV). The 'Laetitia'

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total fruit content of potassium, magnesium, manganese, iron, and boron decreased linearly as PPFD decreased, although only significantly for manganese (Table XV).

The results concerning internal disorders were inconclusive due to the virtual absence of any disorders in both 'Laetitia' and 'Songold' plums in both seasons.

DISCUSSION

The pre-harvest exposure of 'Laetitia' and 'Songold' plums to different light microclimates had an effect on harvest maturity, postharvest storage and ripening, and on final shelf quality. These results and their mechanisms have clear implications for orchard and harvest management.

An improved carbon balance is a potential mechanism underlying the physiological responses of foliage and fruit to direct light exposure. As with apples (Jackson *et al.*, 1977) and pears (Kappel and Nielsen, 1994), final 'Laetitia' plum diameter and mass decreased as exposure to light decreased. This could result from reduced resources for growth, and allocation of the available resources to the strongest sinks. The effect on the leaves of reduced exposure to light was the development of typical shade leaf characteristics. Leaf nitrogen content and photosynthetic capacity of leaves is positively correlated in peach (DeJong and Doyle, 1985) and nectarine canopies (Rosati *et al.*, 1999). Photosynthetic rates declined with decreasing exposure to irradiance (Flore and Lakso, 1989; Kappel and Flore, 1983). The percentage nitrogen content of the leaves decreased linearly as exposure to irradiance decreased, and was accompanied by reductions in maximum light saturated photosynthetic rate. The carbohydrates produced are allocated to the nearest fruits as they are at a competitive advantage (Hansen, 1969). The improved availability and allocation of carbohydrates to the more exposed fruit is supported by the increased proportion of fruit dry mass, compared to fresh mass, with increasing light exposure. This was also found in apples as the majority of the photosynthates from the leaves of any spur are utilised by the fruits on that spur (Hansen, 1969, 1970). Shading of the whole branch enhanced shade induced

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effects on carbohydrate production and partitioning. If only the fruit was shaded the carbon balance effects on fruit size and mass would not be as evident as in this study. If the whole tree was shaded, however, the carbon balance would be affected to a greater degree.

Partitioning of the transpiration stream and its xylem derived nutrients to the more exposed foliage and fruit is potentially a mechanism of physiological responses to light exposure. In stone fruit there is a final stage of rapid fruit growth shortly before harvest, which is a determining factor in the final fruit size and yield that is obtained. Since stone fruit growth is very sensitive to water status during the final stage of fruit development, the improvement of fruit water status by reducing transpiration resulted in a more rapid increase in fruit volume (Li *et al.*, 2001; Marini *et al.*, 1991; Muleo *et al.*, 1994). The results showed that stomatal conductance and leaf transpiration increased with increasing light exposure due to high photosynthetic activity and an increased demand for CO_2. This led to increased water loss due to transpiration, but as water supply was not deficient, the plant rather attained higher photosynthetic rates, which were essential for fruit growth. The increase in midday leaf water potential with decreasing light exposure also supports the partitioning of the transpiration stream to the more exposed leaves and fruit. The lower transpiration rate and improved water status of the more shaded fruit is supported by the increased percentage water content of these fruit. Shading of the fruit only would probably have enhanced the effect of light exposure on partitioning of the transpiration stream and its nutrients to more exposed fruit. Shading of the whole tree, however, would have negated transpiration stream partitioning effects.

The increase in fruit diameter and mass with increasing light exposure, despite the poorer fruit water status of the more exposed fruit, showed that the improved allocation of carbohydrates throughout the growing season is important in determining the final fruit diameter and mass. The shade treatments were only started after the cell division stage was complete and this showed that the effect of shade on fruit growth was still meaningful after the first four to five weeks after full bloom. The positive relationship

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between increased light exposure and increased fruit size and mass is valuable in terms of effective marketing of the fruit and income generated on the farm

Development of the fruit under different light microclimates led to variability in maturity at harvest. Variability in maturity leads to variable quality within a consignment and is detrimental to effective marketing. Flesh firmness of plums has been found to provide a useful means for establishing harvest maturity (Taylor *et al.*, 1993). Firmness of both 'Laetitia' and 'Songold' plums at harvest decreased with increasing light exposure. After storage and ripening the trends in firmness were comparable to those at harvest but the absolute differences between the treatments were probably too small to affect eating quality or marketability. Thus the exposed fruit had an advanced maturity at harvest, and the maturity of the shaded plums was delayed but attained a similar level of maturity during storage. Fruit were harvested at a higher firmness in the second season due to unseasonable rainfall just prior to harvest. Decreased firmness at harvest has been associated with advanced maturity, and firmness has been noted to decrease further during storage (Abdi *et al.*, 1997; Kruger *et al.*, 2001). The difference in fruit maturity at harvest due to the pre-harvest exposure to differing levels of light and the ability of shaded fruit to attain similar levels of maturity during storage was well illustrated by the response of ground colour development during storage.

Exposed 'Laetitia' plums had a more yellow ground colour than shaded plums at harvest. After storage the same trend was present but the absolute difference between exposed and shaded fruit was too small to affect visual appearance. The differences in the ground colour of 'Songold' plums at harvest were too small to affect visual appearance. After the ripening period the exposed fruit had a more yellow ground colour than the shaded fruit. The fact that the decline in chlorophyll and increase in carotenoids was more rapid in exposed than in shaded fruit, confirms that the maturity of the former was more advanced at harvest. The positive relationship between increasing light exposure and ground colour is contradictory to the findings of Marini *et al.* (1991) and Corelli-Grappadelli and Coston (1991) who found that ground colour of peaches was negatively correlated with exposure to light. It has been noted that ground colour

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becomes more yellow during storage (Kruger *et al.*, 2001; Taylor *et al.*, 1993). The effect of pre-harvest light exposure on ground colour of the 'Laetitia' and 'Songold' plums was probably due to the maturity effect already discussed.

Fruit red colour formation results from anthocyanin production, which is strongly dependent on light (Jackson, 1980). Proctor and Creasy (1971) reported that anthocyanin production in apple increases linearly with irradiance up to at least 100 W m^{-2}. The blush colour at harvest of 'Laetitia' and the blush colour that developed after the ripening period of the 'Songold' plums increased with increasing pre-harvest light exposure. This finding is supported by previous studies on stone fruit (Marini *et al.*, 1991; Muleo *et al.*, 1994; Patten and Proebsting, 1986). At harvest, 'Laetitia' plums had a slightly improved blush colour in the first season, but this is likely due to the advanced maturity of fruit at harvest in the first season. Hue angle of plums has been noted to decrease with increasing periods of cool storage (Abdi *et al.*, 1997; Kruger *et al.*, 2001). Previous studies have found that hue angle, after storage, varies with the maturity of the fruit at harvest with the more mature fruit having smaller hue angles and therefore being redder (Abdi *et al.*, 1997). The positive relationship between blush colour and increased pre-harvest exposure to light persisted even after ripening. During both seasons the hue angle of the fruit at 70% PPFD decreased to a similar level and had the same red blush as the control fruit after ripening. It appears that the difference in hue angle at harvest between fruit at 70% and 100% PPFD was due to the advanced maturity of the latter. The fact that the more shaded fruit, unlike the fruit at 70% PPFD, were not able to fully colour up during storage suggested that this was not merely due to a maturity effect. Exposed fruit were redder after the ripening period and therefore improved the visual appearance of the fruit on the shelf and aided effective marketing.

These results lead us to believe that the effect of pre-harvest light exposure on blush colour is a dosage effect, i.e. exposure to a certain cumulative level of irradiance gives the fruit the potential to develop a certain amount of blush colour. If not exposed to that level of irradiance the fruit will not attain the same blush colour as the more exposed fruit during storage.

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Heinicke (1966) also found that the best blush developed on apples that received a cumulative radiation exposure of over 70% of the full exposure values. Inadequate blush developed where values were less than 40%. Marini *et al.* (1991) found very similar results for peach fruit, and confirmed that fruit redness depended on irradiance in the vicinity of the fruit. Fruit exposed to 45% PPFD had 14% less red colour than non-shaded fruit (Marini *et al.*, 1991).

'Laetitia' and 'Songold' plums showed a linear decrease in total soluble solid content with decreasing light exposure. This positive correlation between soluble solid content and increasing pre-harvest light exposure is supported by numerous previous studies on stone fruit (Marini *et al.*, 1991; Muleo *et al.*, 1994; Patten and Proebsting, 1986). Taylor *et al.* (1993) concluded that the variation in soluble solids due to canopy position of the fruit was probably as a result of a shading effect rather than differences in maturity. The positive relationship between TSS and pre-harvest light exposure is likely due to the improved carbohydrate assimilation and partitioning to exposed fruits, as discussed earlier. TSS of both cultivars decreased during the storage period in both seasons, and this has also been noted in previous studies (Abdi *et al.*, 1997; Kruger *et al.*, 2001). TSS of 'Laetitia' was lower in the second season and there was no significant trend over irradiance at harvest. This was likely due to harvesting the fruit at a less advanced maturity in the second season as compared to the first season. In both seasons, TSS of exposed fruit was higher after the ripening period, and thus improved eating quality and marketability of the fruit.

Mineral nutrients known to have an effect on internal disorders of 'Songold' plums, especially internal breakdown, include N, P, K, Ca, and Mg (Kotzé *et al.*, 1987). On a dry mass basis the concentrations of P, K, Ca (2000-2001 only), Mg and B (2000-2001 only) increased with decreasing pre-harvest light exposure. This was probably due to the smaller size of the shaded fruit. Other studies on apples have also shown that nutrient concentrations increase with decreasing pre-harvest light exposure (Barrit *et al.*, 1987; Doud and Ferree, 1980). It was also found in apples that nutrient concentrations

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did not differ in fruit of similar size produced under shaded or exposed positions, but smaller fruit had higher nutrient concentrations (Jackson *et al.*, 1977).

On a whole fruit basis the contents of K, Ca, Mg, Mn, Fe, and B increased with increasing light exposure. Redistribution of minerals via the phloem is the most important method of translocation of K, P, and Mg (Salisbury and Ross, 1992). Increasing light exposure would favour higher levels of these nutrients in the fruit as they are transported together with the carbohydrates in the phloem. The increased supply of carbohydrates in exposed branches has been shown. Other studies have shown a linear relationship between the dry mass increase of fruit and the increase in K and Mg levels (Tromp, 1975). Calcium and boron are mainly transported in the xylem together with the transpiration stream (Biddulph *et al*, 1959; Raven, 1977). Increasing light exposure would therefore also favour higher import rates of these nutrients into exposed branches and their fruit. This is important as the mineral status of fruit can often be a determining factor of the storage quality of the fruit. Increased N, K and Mg levels and low Ca and P levels are associated with a high incidence of internal breakdown of plums.

CONCLUSION

In this study it was found that pre-harvest light exposure affected plum quality at harvest, and also after storage and ripening. This effect could be due to unequal maturity at harvest. The shaded fruit, which were less mature at harvest, were able to attain a similar maturity level as the more exposed fruit during ripening and storage, but this was only the case for the fruit at 70% light exposure. The quality parameters associated with maturity were also able to attain similar levels as the exposed fruit after storage and ripening.

The study also suggested that increased light exposure resulted in an improved carbon balance, or increased transpiration resulting in greater partitioning of the transpiration stream and nutrient supply to more exposed sites in the canopy. Further studies on the effect of pre-harvest exposure to PPFD on internal disorders of plums after

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storage are necessary to further illustrate the effect of the partitioning of the transpiration stream and possible better nutrient supply to the more exposed foliage and fruit.

Increased exposure to light resulted in larger and redder fruit, and fruit with increased TSS levels. Thus, shelf quality of the fruit was improved and this aided effective marketing of the product, but exposure to different light microclimates will lead to variable fruit quality within a consignment. Practically, in order to increase uniformity and quality of fruit within a consignment, and aid effective marketing, the producer should focus on improving light distribution within the orchard canopy.

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TABLE I

Effect of shading of 'Laetitia' branches in 2001-2002 on the photosynthetic photon flux density (PPFD) around the branch. Values represent means ± standard deviation. Measurements were performed during the midday period on 21 January 2002.

Treatment	PPFD (µmol m^{-2} s^{-1})	PPFD (%)
Control	1730 ± 103	100
20% shade net	1237 ± 181	70
50% shade net	750 ± 171	45

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TABLE II

Effect of shading of 'Laetitia' branches in 2001-2002 on midday leaf and fruit skin temperature. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	14 November	21 November	14 December
	Leaf Temperature (°C)		
Control (100%)	24.1	20.7	29.3
70%	24.6	20.8	28.5
45%	25.7	21.4	29.1
Pr > F			
Linear	0.0001	0.1308	0.0001
Quadratic	0.0009	0.4283	0.0090
	Fruit SkinTemperature (°C)		
Control (100%)	26.8	23.7	31.7
70%	26.6	23.3	30.6
45%	27.4	23.9	31.2
Pr > F			
Linear	0.2612	0.7562	0.0446
Quadratic	0.1428	0.1643	0.0066

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TABLE III

Effect of shading of 'Laetitia' branches in 2001-2002 on leaf nitrogen concentration [N], as a percentage of dry mass and on a leaf area basis, and specific leaf mass (SLM). Leaves were harvested on 22 January 2002. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	[N] (%)	[N] (g cm^{-2})	SLM (g m^{-2})
Control (100%)	2.43	0.018	76
70%	2.33	0.017	72
45%	2.23	0.016	74
Pr > F			
Linear	0.0118	0.1007	0.6370
Quadratic	0.7302	0.7902	0.4051

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TABLE IV

Effect of shading of 'Laetitia' branches in 2001-2002 on midday leaf water potential (MPa). Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	13 November	19 November	3 December	11 December	18 December
Control (100%)	-1.03	-1.23	-1.22	-1.04	-1.15
70%	-0.79	-1.05	-1.05	-0.85	-0.86
45%	-0.79	-0.93	-0.88	-0.68	-0.72
Pr > F					
Linear	0.0001	0.0001	0.0001	0.0001	0.0001
Quadratic	0.0009	0.9102	0.1857	0.0077	0.0090

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TABLE V

Light saturated rate of net CO_2 assimilation (A_{max}) ($\mu mol\ m^{-2}\ s^{-1}$), apparent quantum efficiency (AQE) ($\mu mol\ CO_2\ \mu mol^{-1}$ quanta), stomatal conductance (g_S) ($mol\ m^{-2}\ s^{-1}$), transpiration rate (E) ($mol\ m^{-2}\ s^{-1}$), and daytime dark respiration rate (R_D) ($\mu mol\ m^{-2}\ s^{-1}$) of 'Laetitia' leaves in response to shading. Measurements were performed on 26 January 2001 and 28 January 2002 during the midday period. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	A_{max}	AQE	g_S	E	R_D
			2000-2001		
Control (100%)	7.4	0.04	0.131	3.59	2.02
70%	4.9	0.04	0.103	2.62	1.44
45%	4.4	0.04	0.055	3.91	1.23
25%	2.6	0.04	0.036	1.21	1.18
Pr > F					
Linear	0.0001	0.4614	0.0150	0.0202	0.0115
Quadratic	0.5775	0.9666	0.5494	0.1528	0.2507
			2001-2002		
Control (100%)	16.4	0.06	0.291	3.93	1.22
70%	7.6	0.06	0.093	1.48	0.49
45%	11.5	0.07	0.178	2.41	0.48
Pr > F					
Linear	0.0095	0.5874	0.0449	0.0358	0.0008
Quadratic	0.0043	0.2029	0.0363	0.0332	0.0376

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TABLE VI

Effect of shading of 'Laetitia' branches in 2001-2002 on fruit diameter (mm) of tagged fruit throughout the growing season until 12 days before harvest. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	15 November	4 December	19 December	10 January
Control (100%)	31.2	36.2	43.4	54.1
70%	29.9	34.8	40.1	49.7
45%	30.1	34.8	39.9	49.4
Pr > F				
Linear	0.0004	0.0017	0.0001	0.0001
Quadratic	0.0172	0.1430	0.0052	0.0051

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TABLE VII

Effect of shading of 'Laetitia' and 'Songold' branches on fruit diameter (mm). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Laetitia 2000-2001	
Control (100%)	57.9	57.8	54.7
70%	56.4	54.5	52.3
45%	54.3	54.8	51.8
25%	55.8	54.0	52.2
Pr > F			
Linear	0.0330	0.0601	0.0668
Quadratic	0.5150	0.2878	0.2757
		2001-2002	
Control (100%)	53.8	58.7	62.2
70%	50.2	55.3	55.6
45%	50.7	55.1	54.9
Pr > F			
Linear	0.0087	0.0027	0.0460
Quadratic	0.1844	0.2244	0.2646
		Songold 2000-2001	
Control (100%)	59.8	60.6	59.7
70%	59.8	59.7	59.7
45%	59.9	60.1	60.9
25%	58.9	58.6	59.6
Pr > F			
Linear	0.8452	0.4652	0.2337
Quadratic	0.9380	0.4161	0.3178

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TABLE VIII

Effect of shading of 'Laetitia' and 'Songold' branches on fruit fresh mass (grams). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Laetitia 2000-2001	
Control (100%)	104.5	105.9	88.1
70%	95.9	88.7	80.4
45%	86.4	88.6	79.9
25%	88.4	81.4	78.5
Pr > F			
Linear	0.0824	0.0123	0.1276
Quadratic	0.1625	0.1811	0.5943
		2001-2002	
Control (100%)	121.4	106.2	106.2
70%	94.8	90.1	90.1
45%	97.9	82.7	82.7
Pr > F			
Linear	0.0001	0.0001	0.0001
Quadratic	0.0054	0.6296	0.6296
		Songold 2000-2001	
Control (100%)	118.6	122.5	116.0
70%	117.4	115.5	118.5
45%	117.9	118.2	120.5
25%	109.9	107.7	113.6
Pr > F			
Linear	0.9723	0.3505	0.3526
Quadratic	0.9035	0.3318	0.9348

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TABLE IX

Effect of shading of 'Laetitia' and 'Songold' branches on fruit ground colour (chart values 0-5, where 0=green and 5=golden yellow), and on 'Songold' blush colour (chart values 0-12, where 0=no blush and 12=dark red blush). Ground colour of 'Laetitia' is not visible after ripening since fruit turn fully red and no blush colour of 'Songold' was observed at harvest or after storage. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening	After Ripening
		Laetitia 2000-2001		
Control (100%)	4.9	4.9		
70%	4.2	4.8		
45%	4.1	4.8		
25%	4.2	4.7		
Pr > F				
Linear	0.0002	0.0812		
Quadratic	0.0005	0.5693		
		2001-2002		
Control (100%)	4.8	5.0		
70%	4.1	4.6		
45%	3.9	4.4		
Pr > F				
Linear	0.0001	0.0001		
Quadratic	0.4054	0.9312		
		Songold 2000-2001		
		Ground Colour (chart values)		**Blush Colour (chart values)**
Control (100%)	3.2	3.2	4.7	8.6
70%	3.0	3.1	4.5	7.6
45%	2.9	3.0	4.3	7.3
	3.0	3.1	4.2	6.9
Pr > F				
Linear	0.0484	0.1794	0.0962	0.0838
Quadratic	0.8732	0.7044	0.7984	0.6788

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TABLE X

Effect of shading of 'Songold' branches in 2000-2001 on fruit firmness (kg). Values are means of replications (n=10) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
Control (100%)	5.5	4.1	1.8
70%	5.4	4.4	2.0
45%	5.9	4.6	2.4
25%	6.6	5.2	2.7
Pr > F			
Linear	0.2249	0.0290	0.1390
Quadratic	0.1683	0.9246	0.5347

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TABLE XI

Effect of shading of 'Laetitia' and 'Songold' branches on fruit total soluble solids concentration (% TSS). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Laetitia 2000-2001	
Control (100%)	13.0	11.2	11.2
70%	11.3	10.4	10.6
45%	11.2	10.1	10.3
25%	10.9	10.2	10.3
Pr > F			
Linear	0.0031	0.0002	0.0030
Quadratic	0.1086	0.0131	0.0311
		2001-2002	
Control (100%)	10.1	11.0	9.5
70%	10.0	10.3	9.1
45%	10.0	10.3	9.1
Pr > F			
Linear	0.8144	0.0046	0.0039
Quadratic	0.9190	0.1858	0.1766
		Songold 2000-2001	
Control (100%)	14.2	13.7	13.3
70%	13.9	13.5	13.3
45%	13.1	12.7	12.7
25%	12.9	12.6	12.8
Pr > F			
Linear	0.0019	0.0086	0.0754
Quadratic	0.1412	0.2894	0.1749

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TABLE XII

Effect of shading of 'Laetitia' and 'Songold' branches on fruit titratable acidity (TA) (% malic acid). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Laetitia 2000-2001	
Control (100%)	1.64	1.34	0.42
70%	1.66	1.48	0.35
45%	1.66	1.45	0.40
25%	1.63	1.43	0.40
Pr > F			
Linear	0.8938	0.2760	0.9199
Quadratic	0.5233	0.0985	0.6564
		2001-2002	
Control (100%)	1.62	1.42	1.23
70%	1.74	1.55	1.33
45%	1.74	1.58	1.44
Pr > F			
Linear	0.0194	0.0001	0.0002
Quadratic	0.2667	0.2296	0.5013
		Songold 2001-2002	
Control (100%)	1.34	1.14	1.23
70%	1.23	1.07	1.26
45%	1.24	1.12	1.30
25%	1.22	1.11	1.30
Pr > F			
Linear	0.0151	0.4121	0.0151
Quadratic	0.1808	0.0950	0.6942

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TABLE XIII

Effect of shading of 'Laetitia' branches on fruit macronutrient concentration (mg $100g^{-1}$ dry mass) at harvest. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	P	K	Ca	Mg
		2000-2001		
Control (100%)	104.4	1073	16.5	48.5
70%	102.7	1010	16.8	44.7
45%	115.8	1134	21.3	49.5
25%	131.6	1207	19.2	54.8
Pr > F				
Linear	0.0635	0.4352	0.1770	0.8626
Quadratic	0.0783	0.0812	0.3640	0.0671
		2001-2002		
Control (100%)	108.0	1057	26.1	53.3
70%	139.0	1168	25.0	56.8
45%	154.1	1220	26.0	59.3
Pr > F				
Linear	0.0001	0.0248	0.9755	0.0510
Quadratic	0.5683	0.8017	0.8339	0.9572

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TABLE XIV

Effect of shading of 'Laetitia' branches on fruit micronutrient concentration (mg kg^{-1} dry mass) at harvest. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	Na	Mn	Fe	Cu	Zn	B
			2000-2001			
Control (100%)	122.2	6.20	12.80	10.80	6.00	21.20
70%	106.8	5.20	13.40	19.20	10.20	22.00
45%	121.8	5.20	10.20	15.60	8.20	24.20
25%	113.9	5.03	10.63	8.450	7.38	25.63
Pr > F						
Linear	0.8725	0.2768	0.6075	0.6123	0.3951	0.0409
Quadratic	0.2609	0.6300	0.5854	0.5648	0.2840	0.3775
			2001-2002			
Control (100%)	50.57	8.67	6.34	71.34	37.76	54.66
70%	54.65	8.07	5.78	59.30	45.15	41.56
45%	59.55	7.82	5.98	97.86	46.68	50.86
Pr > F						
Linear	0.3168	0.3666	0.6755	0.6124	0.2414	0.5111
Quadratic	0.8529	0.9053	0.6666	0.2326	0.7440	0.1198

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TABLE XV

Effect of shading of 'Laetitia' branches in 2001-2002 on total fruit mineral nutrient content at harvest. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
					mg fruit^{-1}					
Control (100%)	3.2	31.0	0.72	1.5	0.15	0.024	0.018	0.18	0.11	0.15
70%	3.4	28.0	0.58	1.4	0.14	0.020	0.014	0.37	0.11	0.11
45%	2.9	23.0	0.54	1.1	0.11	0.015	0.012	0.14	0.09	0.08
Pr > F										
Linear	0.6409	0.0869	0.2539	0.0630	0.3186	0.0212	0.0837	0.9478	0.4850	0.0109
Quadratic	0.4042	0.5058	0.7804	0.6419	0.7177	0.8550	0.9418	0.0747	0.5067	0.2178

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CAPTIONS TO FIGURES

Figure 1: Effect of shading of 'Laetitia' branches in 2001-2002 on relative humidity (%) around the branch. Measurements were performed from 30 January to 1 February 2002.

Figure 2: Effect of shading of 'Laetitia' branches in 2001-2002 on air temperature around the branch. Measurements were performed from 30 January to 1 February 2002.

Figure 3: Response of single-leaf net CO_2 assimilation rate (A) to photosynthetic photon flux density (PPFD) in 'Laetitia' plum trees in response to shading of branches in (a) 2000-2001 and (b) 2001-2002. Symbols and functions represent means of five replicates per treatment.

Figure 4: Hue angle (°) of 'Laetitia' plums at harvest, after 18 days of dual temperature storage and after seven days of ripening at 15°C, in response to shading of branches in (a) 2000-2001 and (b) 2001-2002. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002). Linear polynomial contrast, *, $P \leq 0.05$, **, $P \leq 0.01$, ***, $P \leq 0.001$.

Figure 5: Firmness (kg) of 'Laetitia' plums at harvest, after 18 days of dual temperature storage and after seven days of ripening at 15°C, in response to shading of branches in (a) 2000-2001 and (b) 2001-2002. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002). Linear polynomial contrast, *, $P \leq 0.05$, **, $P \leq 0.01$, ***, $P \leq 0.001$.

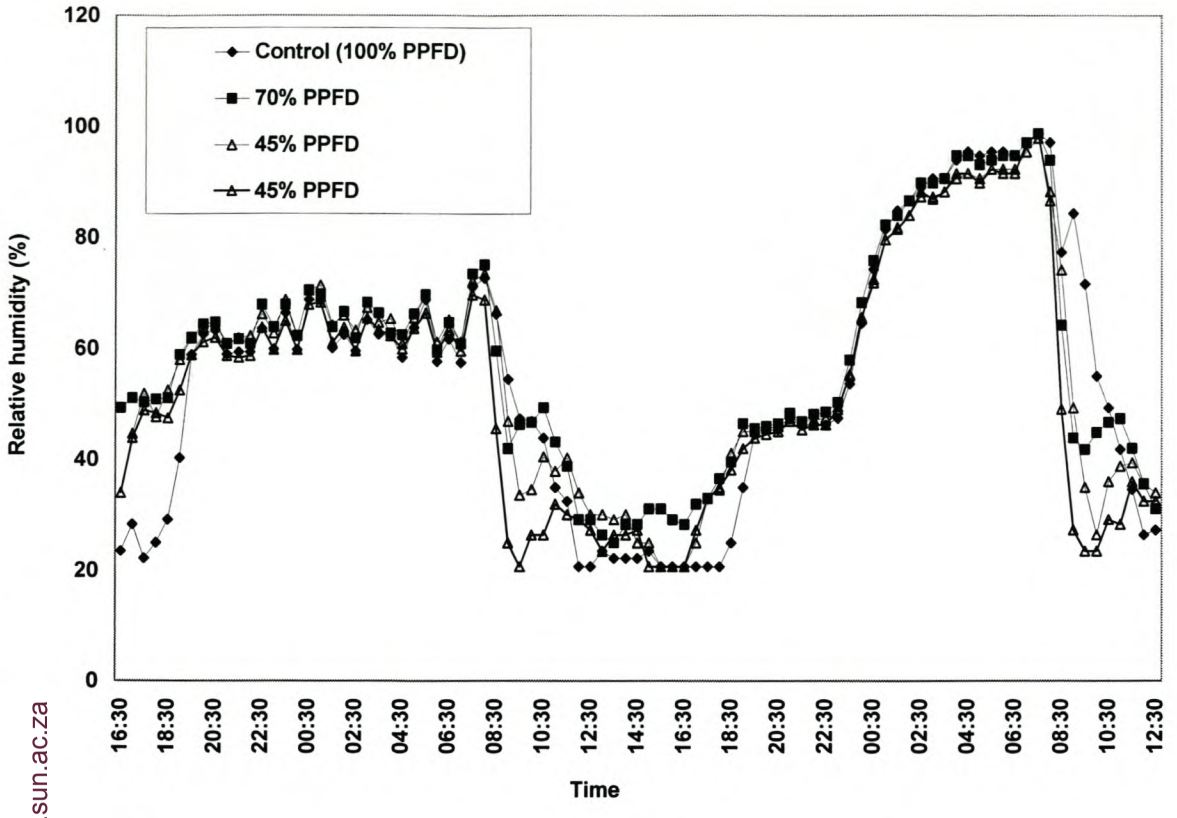

FIG. 1

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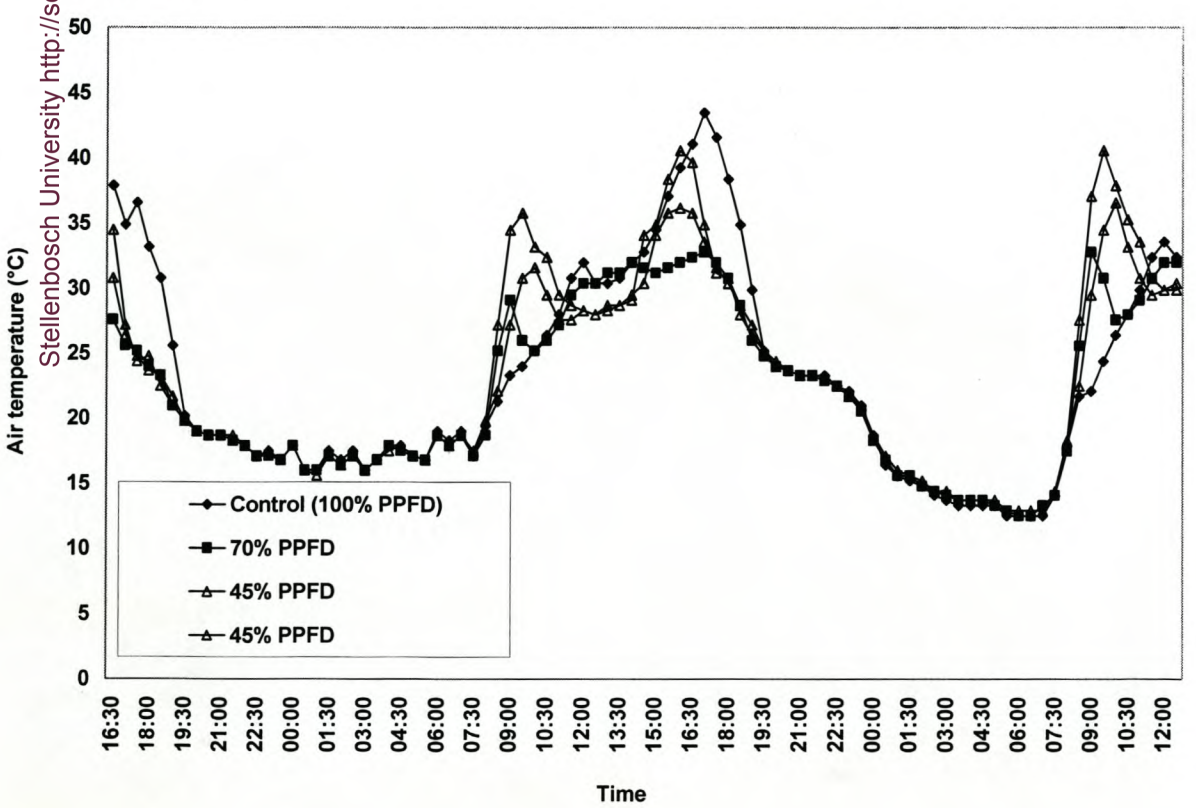

FIG. 2

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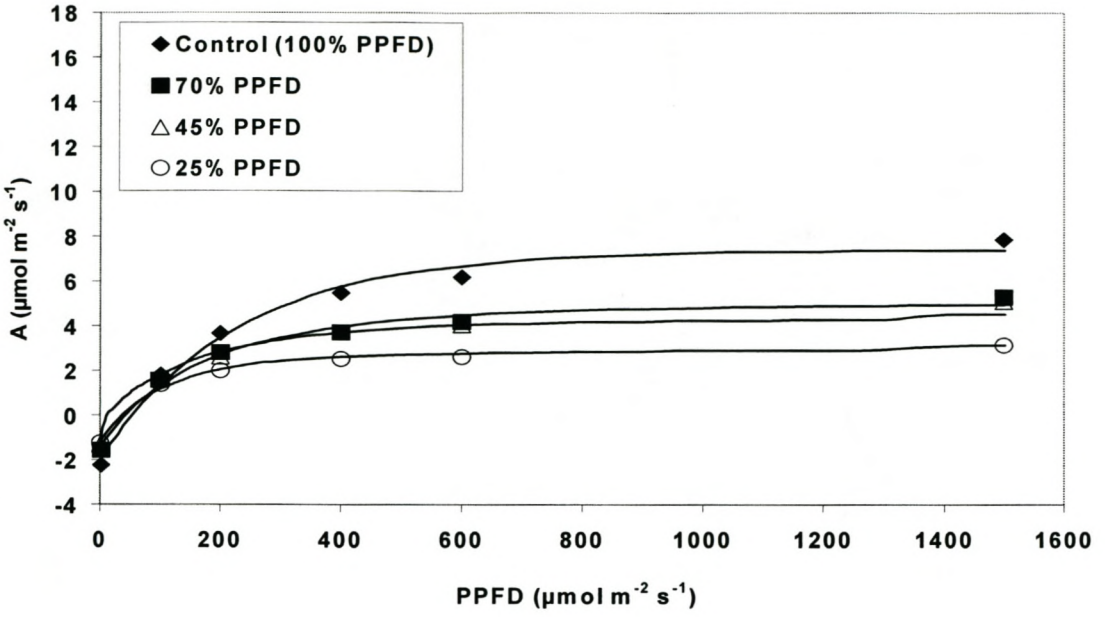

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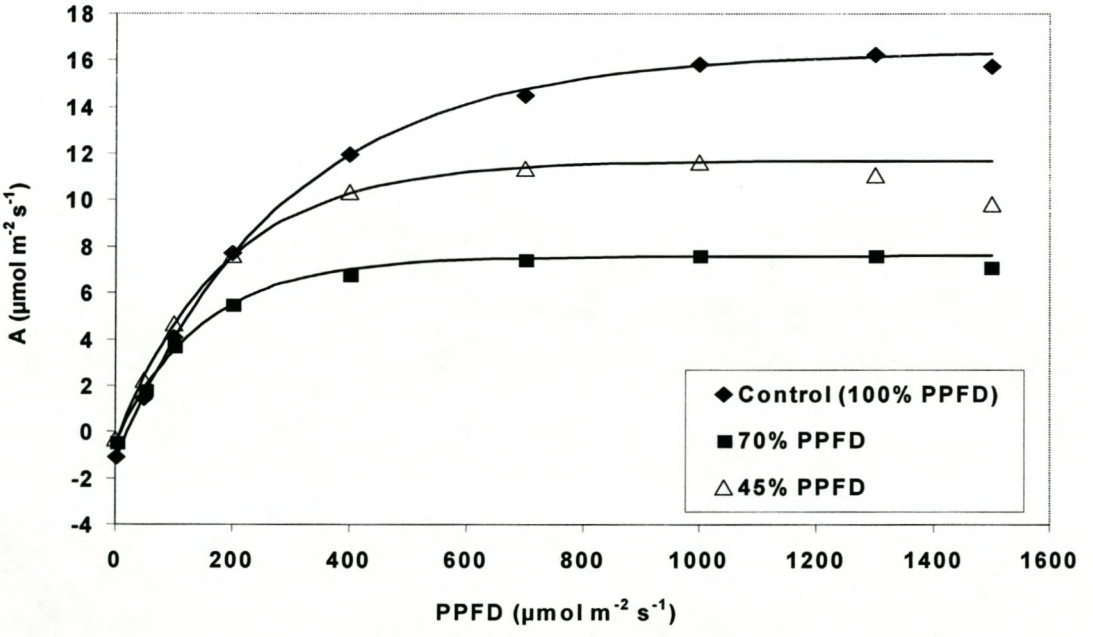

(b)

FIG. 3

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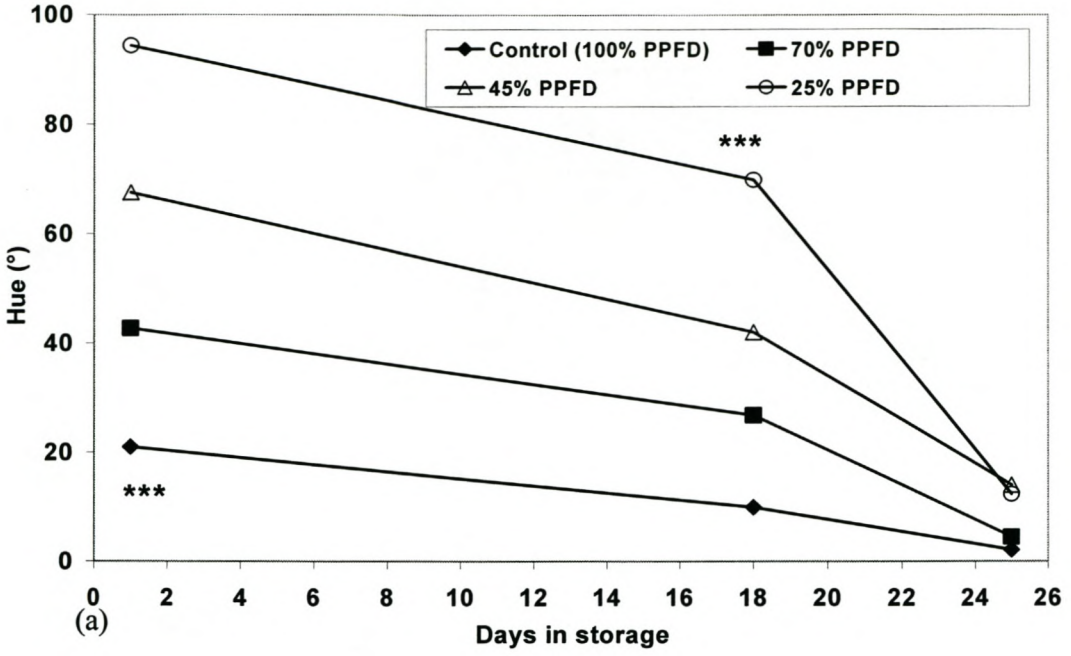
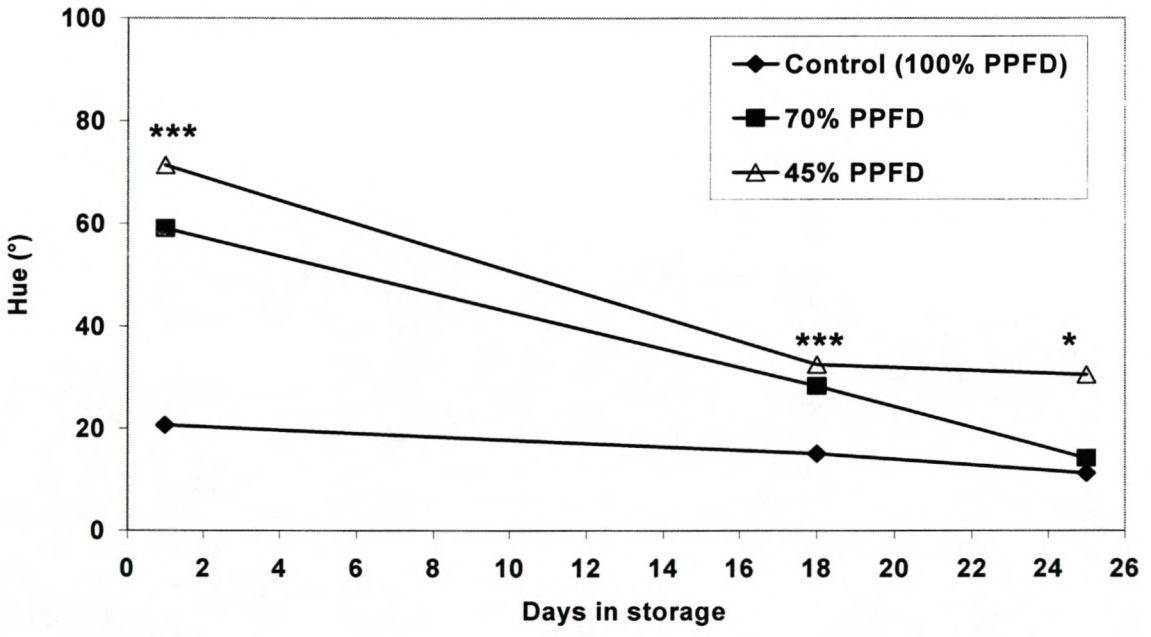


(a)



(b)

FIG. 4

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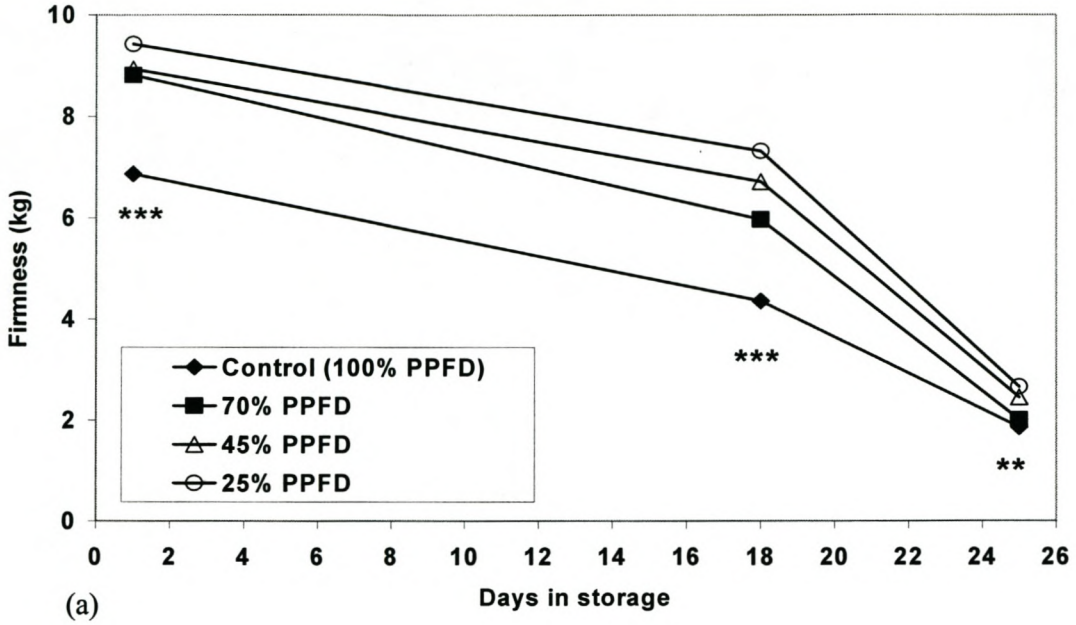
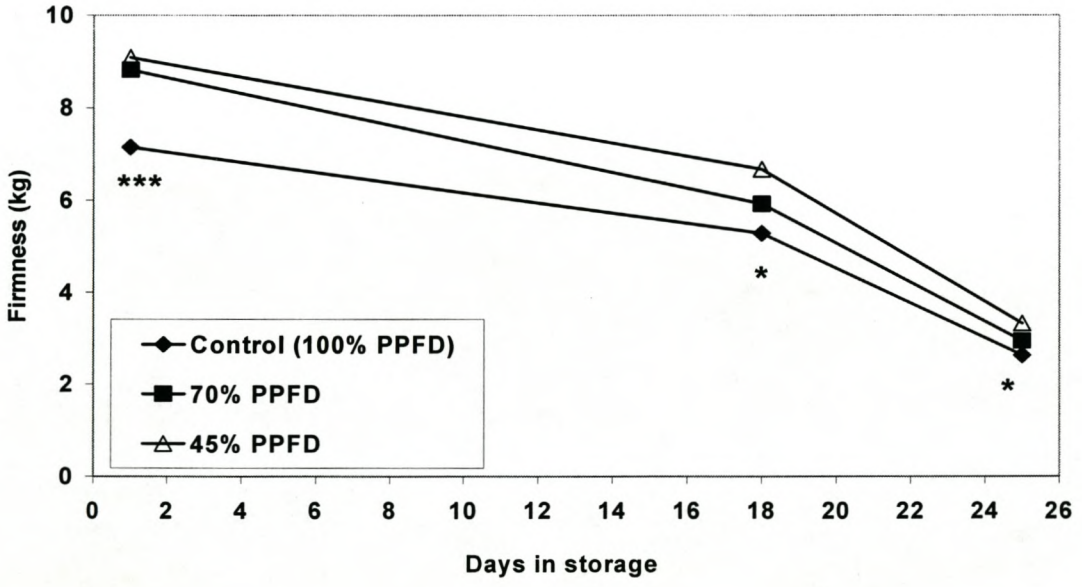


(a)



(b)

FIG. 5

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Chapter III:

Effect of shading on harvest maturity and postharvest quality of 'Cripps' Pink' apples and 'Rosemarie' pears

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ABSTRACT

Entire branches of 'Cripps' Pink' apple and 'Rosemarie' pear trees were bagged with different densities of shade netting after the end of cell division, giving 100% visible light transmission (no bags), 80%, 50% and 20% light transmission. The trial was conducted over two growing seasons. Increased exposure to irradiance led to increased leaf nitrogen content, photosynthesis, stomatal conductance, and transpiration in 'Cripps' Pink' trees. Fruit quality, in terms of diameter, mass, skin ground and blush colour, starch breakdown (apples only), flesh firmness, total soluble solids and titratable acidity, was assessed at harvest, after storage and after ripening. 'Cripps' Pink' apples were stored for six to eight weeks and 'Rosemarie' pears for 18 days at –0.5°C, followed by a seven day ripening period at 15°C. Fruit diameter, mass and proportion of dry mass of 'Cripps' Pink' apples at harvest increased as exposure to irradiance increased. Increased light exposure also resulted in increased blush colour, more yellow ground colour and increased total soluble solid content in 'Cripps' Pink' apples, but there was no effect on the other quality parameters. After storage and ripening periods, blush colour and TSS of apples increased with increased pre-harvest exposure to irradiance. At harvest, after storage and after ripening, increased light exposure resulted in increased blush colour of 'Rosemarie' pears, but had no effect on the other quality parameters. As exposure to irradiance increased so did whole fruit content of P, K, Ca, Mg, Mn, Fe, Cu and B. On a dry mass basis, the concentration of K, and Na (2001-2002) decreased as pre-harvest exposure to irradiance increased.

INTRODUCTION

The canopy microclimate is vital in terms of fruit production and particularly fruit quality in many fruit species. Increased exposure to irradiance shows a positive correlation with fruit size in apples (Barrit *et al.*, 1987; Campbell and Marini, 1992; Jackson *et al.*, 1977; Seeley *et al.*, 1980), pears (Kappel and Neilsen, 1994; Khemira *et al.*, 1993), and stone fruit (Marini *et al.*, 1991; Muleo *et al.*, 1994; Patten and Proebsting, 1986; Taylor, 1993). Fruit growth of apples occurs predominantly by cell division for

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four to five weeks after full bloom, thereafter, fruit growth is a result of cell enlargement (Jackson, 1980). For apple, it has been found that cell division rates were higher in exposed fruit compared with shaded fruit (Blanpied and Wilde, 1968). Lakso *et al.* (1989) found that within the range of natural light in the canopy of apple trees, the growth rate of apple fruit during the first five weeks after bloom was correlated with the exposure of spurs during that period. They further stated that the effect of canopy shade on final fruit size occurred primarily in this first five-week period after bloom, and that little additional effect could be attributed to changes in light availability the rest of the season.

As a result of the smaller size of shaded fruit, mineral nutrient concentrations of fruit have been found to decrease with increased exposure to irradiance in apple (Barrit *et al.*, 1987; Doud and Ferree, 1980). Calcium is the nutrient most commonly associated with postharvest disorders. Almost all pre-harvest factors that affect incidence of bitter pit in apple can be directly or indirectly related to calcium nutrition of the fruit (Ferguson *et al.*, 1999). Fruit calcium concentration has been shown to increase with increasing rates of transpiration (Stebbins and Dewey, 1972).

Previous findings on the effect of pre-harvest exposure to irradiance on starch content of apples and therefore on fruit maturity have been contradictory (Campbell and Marini, 1992; Jackson *et al.*, 1977; Seeley *et al.*, 1980). Advanced maturity at harvest is associated with a decrease in firmness and titratable acidity, and an increase in total soluble solid content (TSS) and colour development (Drake *et al.*, 2002; Drake and Kupferman, 2000). Blush colour development and TSS of apples has been found to increase with increasing exposure to light (Barrit *et al.*, 1987; Campbell and Marini, 1992).

The physiological responses to increased light exposure are possibly due to an improved carbon balance as a result of light striking the organ of interest (Lakso, 1994). Alternatively, light-induced differences in leaf and fruit temperature, transpiration rate, and the resultant partitioning of xylem-derived solutes may provide a better nutrient

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supply to exposed foliage and fruits (Neumann and Stein, 1983). Direct exposure of fruit increases fruit temperatures, and this would possibly increase fruit transpirational flux and the translocation of nutrients and hormones to the fruit sink, thus increasing sink strength (Thorpe, 1974).

This study aims to investigate the effects of pre-harvest light exposure on harvest maturity and fruit quality, possible mechanisms underlying these responses, and the response of fruit quality to storage and ripening in 'Cripps' Pink' apples and 'Rosemarie' pears. Exposure to different light microclimates is expected to result in varying fruit quality following ripening periods, and thus affecting eating quality and marketability of the fruit. This variation in quality could be due to an improved carbon balance in exposed foliage and fruit, or partitioning of the transpiration stream and its nutrients toward more exposed foliage and fruit. The third possible mechanism is variation in fruit maturity at harvest affecting the storage potential of the fruit.

MATERIALS AND METHODS

2000-2001.

Plant Material: 'Rosemarie' pear trees on BP1 rootstock were planted in 1992, and 'Cripps' Pink' apple trees on M793 rootstock were planted in 1998 on Welgevallen Experimental Farm in Stellenbosch, Republic of South Africa (33°55'S 18°53'E). The 'Rosemarie' trees were planted at 4.5m x 2m spacing and trained as central leaders, and the 'Cripps' Pink' trees were planted at 3.8m x 1.25m spacing and trained as central leader trees on a three-wire system. The row orientation was roughly north-east by south-west. Micro-jet sprinklers served as the irrigation system and irrigation scheduling was based on neutron moisture probe measurements. All cultural and physical orchard practices were in agreement with commercial norms for the region.

Treatments and experimental design: As previously described in Chapter II, pg. 58. The treatments were applied to the 'Rosemarie' trees on 20 December 2000 and to

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the 'Cripps' Pink' trees on 12 January 2001. Full bloom of 'Rosemarie' was on 20 September 2000 and for 'Cripps' Pink' on 17 October 2000.

Microclimate around branch: The photosynthetic photon flux density (PPFD) levels under the shade net and around the control branches were performed as previously described in Chapter II, pg. 61. The PPFD measurements were taken on 11 April 2001 which was a cloudless day. Measurements were only determined for the 'Cripps' Pink' trial.

Photosynthetic light response: The response of leaf net CO_2 assimilation rate (A) to PPFD, fitting of the response curves, light-saturated rate of net CO_2 assimilation (A_{max}), apparent quantum efficiency (AQE), daytime dark respiration rate (R_D), leaf transpiration rate (E) and stomatal conductance (g_S) were determined and calculated as previously described in Chapter II, pg. 59. The measurements were taken on 10 April 2001. The photosynthetic light response measurements were determined for the 'Cripps' Pink' trial only.

Harvest and postharvest quality determination: The 'Rosemarie' pears were harvested on 15 January 2001 and the 'Cripps' Pink' apples on 19 April 2001. The 20 tagged fruit per replicate were harvested and five fruit evaluated for quality. The remaining fruit were placed in storage. The pears were stored for 24 days and the apples for 13 weeks at –0.5°C, and this was followed by a seven-day ripening period at 15°C. Five fruit per replicate were evaluated after the initial storage period and five fruit after seven days of ripening. The following quality parameters were measured on each date:

Fruit diameter was measured around the equator using electronic callipers and individual fruit mass was determined. Ground and blush colour were evaluated using the respective colour charts for 'Rosemarie' pears and 'Cripps' Pink' apples provided by Hortec, Stellenbosch (Unifruco Research Services ground colour chart for apples and pears; Rosemarie blush colour chart, DFB P23; Australian apple and pear growers association, Pink Lady™, Minimum international quality specifications of fruit at

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destination, Blush colour). Fruit firmness was determined on peeled, opposite cheeks of the fruit with a penetrometer (Southtrade fruit pressure tester, FT 327, Alphonsine, Italy). Percentage starch breakdown of the apples was determined by placing a half of each apple in an iodine solution and evaluating the starch breakdown by using the chart provided by Hortec, Stellenbosch. Total soluble solids (TSS), titratable acidity (TA) and fruit mineral analysis was determined as previously described in Chapter II, pg. 60.

2001-2002.

Plant material: The trial was repeated on 'Cripps' Pink' apple trees on M793 rootstock, which were planted in 1994 on the commercial farm Auldearn in Elgin, Republic of South Africa (34°12'S 19°02'E). The trees were planted at 4.5m x 2m spacing and were free-standing trees trained as a pyramid shape. Row orientation was roughly east by west. Micro-jet sprinklers were used for irrigation and scheduling was based on neutron moisture probe measurements. All cultural and physical orchard practices were in agreement with commercial norms for the region.

Treatments and experimental design: The artificial shade treatments were applied in the same manner as in the first season, but the 80% density shade net treatment was not repeated. All branches selected were on the south side of the tree, of similar size, and exposed to a similar light microenvironment. A complete randomised block experimental design was again used but the number of blocks was increased to 12. The treatments were applied to the trees on 8 January 2002. Full bloom was on 10 October 2001.

Microclimate around branch: The PPFD levels under the shade net treatments and around the control branches were determined in the same manner as in 2000-2001. Measurements were taken on 11 April 2002.

The relative change in air temperature and relative humidity under the shade treatments as compared with the control treatment was measured with an RH and air temperature meter (SAM 990DW, Mannix Testing & Measurement Inc., New York, USA). Three RH and air temperature measurements were taken per replicate on 11 April

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2002 which was a cloudless day. Measurements were taken during the midday period (11h00 to 13h00), block by block. Leaf and fruit skin temperatures were determined on three dates as previously described in Chapter II, pg. 61.

Pre-harvest physiological responses: Leaf fresh mass, dry mass, leaf area, specific leaf mass (SLM) and percentage nitrogen concentration was determined as previously described in Chapter II, pg. 62. Leaf water potential was determined on three different dates as previously described in Chapter II, pg. 62.

The response of leaf net CO_2 assimilation rate (A) to PPFD was determined as previously described on one leaf from four trees of each treatment selected randomly from different blocks, using the LI-6400 (Li-Cor, Lincoln, Nebraska, USA). The same irradiance levels were used as in 2000-2001. Measurements were performed on 9 April 2002.

Fruit growth was determined by measuring fruit diameter of tagged fruits on four different dates during the growing season using electronic callipers.

Harvest and postharvest quality determination: The apples were harvested on 18 April 2002. The fruit were subjected to 12 weeks at –0.5°C and the ripening period was reduced to five days at 15°C. Fruit were again evaluated at harvest, after storage, and after ripening, using the same set of quality parameters as described for 2000-2001. The following additional measurements were performed in 2001-2002. A colorimeter (NR-3000, Nippon Denshoku, Tokyo, Japan) was used to evaluate the hue angle (°) of the apples. The evaluation was done on the blushed side at a point on the fruit where colour was most uniform. Fruit fresh mass, dry mass, percentage water content and mineral content on a whole fruit basis was determined and calculated as previously described in Chapter II, pg. 63.

Statistical analysis: Data analysis was performed as previously described in Chapter II, pg. 63.

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RESULTS

Microclimate around branch

Photosynthetic photon flux density (PPFD) transmission decreased substantially under the shade treatments of the 'Cripps' Pink' trees in 2000-2001 and 2001-2002 (Table I). The PPFD level under the 20% shade net was approximately 70% in both seasons, under the 50% shade net approximately 55% in 2000-2001 and 50% in 2001-2002, and under the 80% shade net approximately 30% of the PPFD around the control branch. The PPFD level around the 'Rosemarie' branches was estimated to be similar to the levels observed in the 'Cripps' Pink' trial, as the trees were of similar size, were planted in adjacent orchards, and the physical and cultural practices were similar for both 'Cripps' Pink' and 'Rosemarie' trees.

The relative humidity around the branch increased as the density of shade net increased, but the differences were not large, only 4.8% between the highest and lowest values (Table I). The differences in air temperature during the midday period were likewise not large, the biggest difference was an increase of approximately 2°C from 20% to 50% density shade net (Table I).

Leaf temperature decreased linearly on the first date and increased quadratically on the third date as exposure to PPFD decreased (Table II). The absolute differences between treatments were, however, small and unlikely to have a significant effect on tree physiological responses. No significant trends over irradiance were found for fruit skin temperature.

Pre-harvest physiological responses

Specific leaf mass (SLM) and leaf nitrogen concentration, expressed as a percentage of dry mass and on a leaf area basis, were highest in the control treatment and decreased linearly as exposure to PPFD decreased (Table III).

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On each of the three dates midday leaf water potential was lowest at 100% PPFD and increased quadratically as exposure to PPFD decreased (Table IV).

The light saturated rate of net CO_2 assimilation (A_{max}) decreased linearly as exposure to PPFD decreased in both seasons (Figure 1 (a) and (b), Table V). Apparent quantum efficiency (AQE) decreased linearly as exposure to PPFD decreased in 2000-2001 (Table V). There was no significant trend over irradiance for AQE in 2001-2002. Leaf stomatal conductance (g_S), transpiration rate (E) and daytime dark respiration rate (R_D) followed the same trend as A_{max} in 2000-2001, with a linear decrease as exposure to PPFD decreased (Table V). In 2001-2002, g_S followed the same linear trend over irradiance as A_{max}, but there was no significant trend over irradiance for E and R_D (Table V).

The diameters of tagged fruit were first measured seven days after the shade treatments were started. Control fruit already had the largest diameter, and fruit at 70% and 50% PPFD had similar, lower mean fruit diameters (Table VI). The biggest difference between treatment means was, however, only 1.3 mm. The measurement was repeated on three more occasions with the final measurement taken 10 days before harvest. On all three dates, a linear decrease in fruit diameter was found as exposure to PPFD decreased (Table VI). The percentage fruit water content increased linearly as exposure to PPFD decreased (data not shown).

Harvest and postharvest fruit quality

In 2000-2001, 'Cripps' Pink' fruit diameter decreased linearly as exposure to PPFD decreased when measured at harvest and after the seven day ripening period (Table VII). There was no significant trend over irradiance after the eight-week storage period. In 2001-2002, fruit diameter decreased linearly as pre-harvest exposure to PPFD decreased when measured after the ripening period (Table VII). There was no significant effect on 'Rosemarie' pear diameter (Table VII). During both seasons, different samples were measured at each evaluation date, and therefore differences in fruit diameter and mass due to storage and ripening periods could be an artefact of sample variability.

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During both seasons, 'Cripps' Pink' fruit mass at harvest and after ripening decreased linearly as PPFD decreased (Table VIII). There was no statistically significant effect on the mass of 'Rosemarie' pears (Table VIII).

In 2000-2001, 'Cripps' Pink' ground colour decreased quadratically as pre-harvest exposure to PPFD decreased when measured at each of the three evaluation dates (Table IX). In 2001-2002, there was no significant trend over irradiance of ground colour of 'Cripps' Pink' apples at harvest. After storage and ripening, ground colour decreased linearly as pre-harvest exposure to PPFD decreased, but the absolute differences between the treatments were too small to affect fruit visual appearance and marketability. At harvest and after storage, 'Rosemarie' ground colour (Table IX) decreased as pre-harvest exposure to PPFD decreased, but the absolute differences between the treatments were small. After the ripening period, there was no difference between treatments in ground colour of 'Rosemarie' pears.

Blush colour of 'Cripps' Pink' apples increased quadratically as pre-harvest exposure to PPFD increased in both seasons (Figure 2 (a), (b)). In 2001-2002, hue angle (°) of 'Cripps' Pink' apples decreased linearly as exposure to pre-harvest PPFD increased when measured at harvest (Figure 2 (c)). In 2000-2001 the blush colour of 'Cripps' Pink' apples improved during storage and ripening (Figure 2 (a), (b)), the differences between the treatments were, however, similar to those present at harvest. There was no improvement in blush colour or decrease in hue angle during storage and ripening in 2001-2002 (Figure 2 (a), (b), (c)). Blush colour of 'Rosemarie' pears decreased as pre-harvest exposure to PPFD decreased (Figure 3). The decrease in blush colour was linearly significant at harvest and after ripening, and quadratically significant after 18 days of storage. There was no improvement in blush colour during storage.

In 2000-2001, starch breakdown of 'Cripps' Pink' apples decreased linearly as pre-harvest exposure to PPFD increased when measured at harvest (Table X). The absolute differences between treatments were, however, small. No significant trends over

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irradiance in starch breakdown were present when measured after storage and ripening. In 2001-2002, there was a quadratic trend over irradiance for starch breakdown at harvest and a linear trend after ripening (Table X). The absolute differences between the treatments were, however, small and unlikely to have a meaningful effect on fruit eating quality and marketability.

In 2000-2001 and 2001-2002, firmness of 'Cripps' Pink' apples showed no significant trends over irradiance when measured at harvest, after storage or after ripening (Table XI). Fruit firmness of 'Rosemarie' pears increased linearly at harvest and after storage with decreasing PPFD, although not quite significantly (Table XI). Firmness decreased quadratically after the ripening period. The absolute differences between the treatments were small and unlikely to have a meaningful effect on fruit eating quality and marketability.

During both seasons, the total soluble solid (TSS) content of 'Cripps' Pink' apples decreased linearly as pre-harvest exposure to PPFD decreased both at harvest and after ripening (Table XII). TSS content of 'Rosemarie' pears decreased quadratically with decreasing PPFD when measured after storage, and linearly when measured after ripening (Table XII). In 2000-2001, titratable acidity (TA) of 'Cripps' Pink' apples at harvest decreased linearly with decreasing light, but not in 2001-2002 (Table XIII). There was no significant effect on TA of 'Cripps' Pink' apples after storage or ripening during both years. There was a linear increase in TA of 'Rosemarie' pears as exposure to PPFD decreased when measured at harvest, after storage and after ripening (Table XIII). The absolute differences in TSS and TA between the treatments were, however, small and unlikely to have a meaningful effect on eating quality of the fruit.

Mineral nutrient analysis

In 2001-2002, the concentration of potassium increased linearly as shading increased (Table XIV). Macronutrient concentration of 'Rosemarie' pears was not affected by pre-harvest exposure to PPFD (Table XIV). Of the micronutrients, only Na of 'Cripps' Pink' apples increased linearly as pre-harvest exposure to PPFD decreased

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(Table XV). Micronutrient concentration of 'Rosemarie' pears was not affected by pre-harvest exposure to PPFD (Table XV). The 'Cripps' Pink' total fruit content of potassium, calcium, magnesium, manganese, iron, copper and boron decreased significantly as PPFD decreased (Table XVI). With the exception of Mn, whole fruit content of the previously mentioned nutrients increased quadratically with increased PPFD. Nutrient contents decreased substantially between the control and first shade treatment (70%), but differences were smaller between the shaded treatments.

DISCUSSION

Harvest maturity, postharvest storage, ripening, and final shelf quality of 'Cripps' Pink' apples and 'Rosemarie' pears was affected by pre-harvest exposure to different light microclimates. These results and their mechanisms have clear implications for orchard and harvest management.

The microclimate varied slightly between the two seasons in terms of the level of irradiance under the shade nets. Differences in temperature and relative humidity under the shade nets were small, and unlikely to have an effect on the results obtained in the study.

As previously discussed, an improved carbon balance due to direct light exposure effects is a potential mechanism underlying physiological fruit and foliage responses to light exposure (Lakso, 1994). Final 'Cripps' Pink' apple diameter and mass increased with increasing pre-harvest exposure to light. This has also been found in previous studies on apples (Jackson *et al.*, 1977; Barrit *et al.*, 1987; Wagenmakers and Callesen, 1995) and pears (Kappel and Neilsen, 1994). This could result from reduced resources for growth, and allocation of the available resources to the strongest sinks. The effect on the leaves of reduced exposure to light was the development of typical shade leaf characteristics. Leaf nitrogen content and photosynthetic capacities of leaves are positively correlated in peach (DeJong and Doyle, 1985), nectarine (Rosati *et al.*, 1999), pear (Kappel and Nielsen, 1994), and walnut tree canopies (Klein *et al.*, 1991). Shade

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reduces specific leaf mass (SLM), and there is a positive linear relationship between SLM and rate of net photosynthesis of apple leaves (Barden, 1978). Photosynthetic rates decline with decreasing exposure to irradiance (Heinicke, 1965). In this study, SLM and percentage nitrogen content of the leaves increased linearly with increasing exposure to light, and was accompanied by lower maximum light saturated photosynthetic rate.

The reduced photosynthetic potential of the shaded leaves reduced the synthesis of carbohydrates and partitioning of these carbohydrates to the fruit. The carbohydrates produced are partitioned toward the nearest fruits as they are at a competitive advantage. The improved availability and allocation of carbohydrates to the more exposed fruit is supported by the increased proportion of fruit dry mass, compared to fresh mass, with increasing light exposure. This was also found in apples as the majority of the photosynthates from the leaves of any spur are utilised by the fruits on that spur (Hansen, 1969, 1970).

The initial phase of cell division is the most important stage of fruit growth in apples, and a lack of sufficient photoassimilates during this period will result in smaller fruit and a lower yield (Hansen and Grauslund, 1973). Numerous previous studies show that the effect of shade on final fruit size of apples is determined primarily in this cell division period (Bepete and Lakso, 1998; Lakso *et al.*, 1989; Tustin *et al.*, 1992). In our study, shade treatments were only started after the cell division stage of fruit growth was complete and this shows that the effect of shade on fruit growth is still meaningful after the initial stage of cell division. Improved allocation of carbohydrates throughout the growing season is determining in the final fruit diameter and mass as demonstrated by the increase in diameter and mass of 'Cripps' Pink' apples with increased exposure to light. This effect on fruit size and mass has an effect on marketability of the fruit as well as on income generated on the farm.

Shading of the whole branch enhanced the effect of shade on the production and allocation of carbohydrates. Whereas, it would be expected that if only the fruit was shaded the carbon balance would not be affected, and if the whole tree was shaded the

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carbon balance would be affected to a greater degree than by only shading the branch. The increased diameter and mass of apples in the second season could possibly be attributed to differences in orchard and tree design, and also to the different locations used in the two seasons.

Partitioning of the transpiration stream and its xylem derived solutes may provide a better nutrient supply to exposed foliage and fruits and potentially be the mechanism of physiological responses to light exposure (Neumann and Stein, 1983). The results show that stomatal conductance in both seasons increased with increasing light exposure due to high photosynthetic activity and increased demand for CO_2. This led to increased water loss due to transpiration, but as water supply was not deficient, in these irrigated orchards, the plant rather attained higher photosynthetic rates, which were essential for fruit growth. The partitioning of the transpiration stream to the more exposed leaves and fruit is also supported by the midday leaf water potential that decreased with increasing exposure to light. The percentage water content of the fruit decreased with increasing exposure to light, suggesting that these fruit also lost more water through transpiration. Partitioning of the transpiration stream to the best exposed sites in the canopy has previously been found in apples (Lakso *et al.*, 1989). The effect of shade on partitioning of the transpiration stream toward more exposed fruit would be expected to be more apparent if only the fruit had been shaded, whereas, if the whole tree had been shaded it would be expected that the effect would be less apparent as compared to this study.

Variability in fruit maturity at harvest because of exposure to different light microclimates and subsequent differences in storage potential of the fruit could indirectly be the cause of variable fruit quality within a consignment, thus affecting fruit marketability. Starch breakdown in the fruit flesh has often been used as a measure of maturity for scheduling the harvest of apples (Beaudry *et al.*, 1993; Drake and Kupferman, 2000; Fan *et al.*, 1995; Lau, 1988; Smith *et al.*, 1979). Other studies have shown that starch may not be a reliable indicator of apple maturity (Blanpied, 1974; Knee *et al.*, 1989). Nevertheless, starch breakdown is used extensively in the commercial apple industry as an indicator of apple maturity. The shaded fruits did not seem to be

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simply physiologically less mature than exposed fruit at harvest, as the absolute differences in starch breakdown between the treatments were small. The absence of an effect of pre-harvest light exposure on apple starch breakdown has been reported previously (Campbell and Marini, 1992). Other studies have found that starch breakdown of apples is generally accelerated with increased shading, but also suggest that shaded fruit are not physiologically retarded versions of exposed fruit (Jackson *et al.*, 1977; Seeley *et al.*, 1980). At harvest, there was greater starch breakdown in 'Cripps' Pink' apples in 2001-2002, as compared to results in 2000-2001. Thus, at harvest, apples had a slightly advanced maturity in the second season. This difference in maturity could provide an explanation for variability in results between the seasons.

Firmness of 'Cripps' Pink' apples was likewise not affected by pre-harvest exposure to light. This has also been found in previous studies on apples (Campbell and Marini, 1992; Seeley *et al.*, 1980). With the exception of the values at harvest in 2000-2001, titratable acidity of 'Cripps' Pink' apples was also not affected by pre-harvest light exposure. Delaying harvest and therefore harvesting more mature apples results in a decrease in firmness and TA at harvest and after extended storage periods (Drake *et al.*, 2002; Drake and Kupferman, 2000). The absence of an effect of pre-harvest light exposure on these parameters confirms that the shaded fruit were not physiologically less mature than exposed fruit. Firmness and TA of apples decrease during storage but any differences present at harvest are also present after storage (Drake *et al.*, 2002; Drake and Kupferman, 2000).

'Cripps' Pink' apples showed a linear increase in TSS with increasing light exposure when measured at harvest, after storage and after ripening. This positive correlation between TSS and pre-harvest exposure to light is supported by numerous previous studies on apples (Campbell and Marini, 1992; Robinson *et al.*, 1983). Seeley *et al.* (1980) confirmed that TSS in apples is highly correlated with the pre-harvest exposure to light both at harvest and after 105 days of cold storage. Increased TSS has been associated with advanced maturity of apples at harvest, and after storage the same differences in TSS were present as the differences observed at harvest (Drake *et al.*,

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2002; Drake and Kupferman, 2000). Taylor *et al.* (1993) concluded that the variation in TSS due to canopy position of 'Songold' plums was probably because of a shading effect rather than differences in maturity. The positive relationship between TSS and pre-harvest exposure to light is likely due to the improved carbohydrate assimilation and partitioning to exposed fruits as discussed earlier. Consumer preference for apples have been found to improve with increased TSS to TA ratios (Boylston *et al.*, 1994), therefore, increasing pre-harvest exposure to light improves eating quality of apples. The improved eating quality of the more exposed apples was present after the ripening period and would therefore improve shelf quality of the apples and aid effective marketing.

Exposed 'Cripps' Pink' apples had a more yellow ground colour than shaded apples at harvest, after storage and after ripening. Ground colour of the apples became more yellow during storage and ripening but the trend over irradiance remained significant. Ground colour was therefore related to pre-harvest exposure to light, which has been found in previous studies on apples (Tustin *et al.*, 1988). This is in contrast to the results of Morgan *et al.* (1984) which suggested that ground colour was not related to light exposure but changed significantly as maturity approached, to the extent that it was used as a maturity indicator.

Anthocyanin production and therefore fruit red colour formation is strongly dependant on light (Jackson, 1980). Proctor and Creasy (1971) found that anthocyanin production in apples increases linearly with irradiance up to at least 100 W m^{-2}. Blush colour and hue angle of 'Cripps' Pink' apples were positively correlated to pre-harvest light exposure. The statistically significant trends over irradiance were present after storage and after the ripening period. Blush colour improved during storage in 2000-2001, but blush colour and hue angle remained constant during storage in the second season. The increased blush colour in the second season and the improvement of blush during storage in the first season could be attributed to the following factors: At harvest, the apples in the first season were less mature than in the second season, and the Stellenbosch area is warmer than the Elgin area and therefore is less conducive to blush colour formation. The increase in pink colour of 'Cripps' Pink' apples during storage has

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been found previously and was attributed to the probable loss of chlorophyll during storage (Drake *et al.*, 2002). The results lead us to believe that blush colour of 'Cripps' Pink' apples is directly related to pre-harvest light exposure. This has been reported for apples in numerous previous studies (Barrit *et al.*, 1987; Campbell and Marini, 1992; Doud and Ferree, 1980; Jackson *et al.*, 1977; Wagenmakers and Callesen, 1995). Increased blush colour due to pre-harvest light exposure was present after the ripening period, and would affect shelf quality of the apples. More uniform light distribution in the orchard canopy would result in more uniform blush colour within a consignment and thus aid effective marketing.

The final size and mass of 'Rosemarie' pears was not affected by increased shading. Pre-harvest light exposure did not have a meaningful effect on total soluble solid content of 'Rosemarie' pears at harvest or after storage and ripening. This is in contrast to previous studies that found TSS of pears to be positively correlated to increased pre-harvest exposure to irradiance (Kappel, 1989 ; Kappel and Nielsen, 1994). Flesh firmness was also not affected. Previous studies are contradictory in their findings concerning this, Kappel and Neilsen (1994) found that firmness of 'Anjou' pears was not correlated with pre-harvest exposure to light, whereas Khemira *et al.*, (1993) found that 'Anjou' pears were larger and softer under more exposed conditions. There were significant trends over irradiance for ground colour of 'Rosemarie' pears, the absolute differences between treatments were, however, small and unlikely to affect the visual appearance of the fruit. The shade treatments were only on the 'Rosemarie' trees for 26 days before harvest, and this time period was possibly too short to have a meaningful effect on the carbon balance and possible partitioning of the transpiration stream of the tree, and the subsequent effect on fruit quality.

Blush colour of 'Rosemarie' pears was the only quality parameter positively correlated with increasing light exposure. Blush colour remained relatively unchanged after storage and ripening periods. The positive correlation of blush colour in pears with increasing light exposure has been reported previously (Kappel and Neilsen, 1994). The results lead us to believe that the anthocyanin content of 'Rosemarie' pears is sensitive to

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irradiance even at the end of the growing season. The reduced blush could be due to the breakdown of the limited amount of anthocyanin in the fruit skin (Steyn *et al.*, 2001). This variability in blush colour development due to pre-harvest exposure to light leads to variable quality within a consignment

On a dry mass basis, the increase in concentration of certain nutrients with decreasing light exposure was probably due to the greater proportion of fruit dry mass of the exposed fruit. Other studies on apples have also shown that nutrient concentrations increase as exposure to irradiance decreases (Barrit *et al.*, 1987; Doud and Ferree, 1980). It was also found in apples that nutrient concentrations did not differ in fruit of similar size produced under shaded or exposed conditions, smaller fruit did have higher nutrient concentrations (Jackson *et al.*, 1977).

On a whole fruit basis, the contents of K, Ca, Mg, Mn, Fe, Cu and B increased with increasing light exposure. Redistribution of minerals via the phloem is the most important method of translocation of K, P, and Mg (Salisbury and Ross, 1992). Increasing light exposure would favour higher levels of these nutrients in the fruit as they are transported together with the carbohydrates in the phloem. The increased supply of carbohydrates in exposed branches has been shown. Other studies have shown a linear relationship between the dry mass increase of fruit and the increase in K and Mg levels (Tromp, 1975). Calcium and boron are mainly transported in the xylem together with the transpiration stream (Biddulph *et al*, 1959; Raven, 1977). Increasing light exposure would therefore also favour higher import rates of these nutrients into exposed branches and their fruit. Increased nutrient concentrations are important in terms of decreasing the incidence of internal disorders of fruit. Calcium nutrition of the fruit is highly correlated with the development of bitter pit in apples. Further investigation of the effect of pre-harvest light exposure on nutrient contents of fruit, and the subsequent effect on the incidence of internal disorders is necessary due to the absence of internal disorders in this study. Whole fruit mineral nutrient content decreased substantially between the control treatment and the 20% density shade net treatment, but differences between shade net treatments were small, and this resulted in the significant quadratic trend over irradiance.

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The difference, therefore, between 100% exposure to light and shading had an effect on whole fruit nutrient content.

CONCLUSION

In this study it was found that pre-harvest light exposure had an effect on certain parameters of 'Cripps' Pink' apple quality at harvest, after storage and after ripening. The effects on apple quality were due to the direct effects of increased light exposure and the associated improved carbon balance and partitioning of the transpiration stream, and not due to the indirect effect of shaded fruit being physiologically less mature versions of exposed fruit. Exposed apples were larger, redder and had an increased total soluble solid content, thus improving eating quality, aiding effective marketing and increasing income generated on the farm. 'Rosemarie' pear trees were only subjected to shade treatments for a short period, but blush colour of fruit at harvest, after storage and after ripening were still strongly influenced.

The study suggests that increased light exposure of whole branches leads to an improved carbon balance, as well as increased transpiration resulting in greater partitioning of the transpiration stream and nutrient supply to more exposed foliage and fruit. Further investigation of the effect of pre-harvest light exposure on the accumulation of nutrients in the fruit and the incidence of internal disorders is necessary. Practically, efforts to increase uniformity and quality of fruit within a consignment, and aid effective marketing, should focus on improving light distribution within the orchard canopy. Improved and uniform light distribution will increase fruit size and mass, blush colour, TSS and reduce within-tree variability.

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TABLE I

Effect of shading of 'Cripps' Pink' branches in 2000-2001 and 2001-2002 on the photosynthetic photon flux density (PPFD), air temperature and relative humidity (RH) around the branch. Values represent means ± standard deviation,. Measurements were performed during the midday period on 11 April during both seasons.

Treatment	PPFD (µmol m^{-2} s^{-1})	PPFD (%)	Air temperature (°C)	RH (%)
		2000-2001		
Control	1787 ± 80	100		
20% shade net	1262 ± 151	70		
50% shade net	987 ± 171	55		
80% shade net	543 ± 137	30		
		2001-2002		
Control	1717 ± 76	100	25.0 ± 2.4	51.7 ± 7.2
20% shade net	1205 ± 118	70	24.4 ± 3.4	54.4 ± 6.1
50% shade net	866 ± 110	50	26.4 ± 1.1	56.5 ± 6.9

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TABLE II

Effect of shading of 'Cripps' Pink' branches in 2001-2002 on midday leaf and fruit skin temperature. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	18 February	13 March	8 April
	Leaf Temperature (°C)		
Control (100%)	21.5	21.9	20.0
70%	20.5	21.6	20.3
50%	20.2	21.2	21.8
Pr > F			
Linear	0.0002	0.1033	0.0001
Quadratic	0.3489	0.7667	0.0001
	Fruit SkinTemperature (°C)		
Control (100%)	22.5	23.5	22.6
70%	22.1	23.7	23.0
50%	21.3	23.0	22.9
Pr > F			
Linear	0.2217	0.2891	0.2511
Quadratic	0.7302	0.7505	0.4700

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TABLE III

Effect of shading of 'Cripps' Pink' branches in 2001-2002 on leaf nitrogen concentration [N], as a percentage of dry mass and on a leaf area basis, and specific leaf mass (SLM). Leaves were harvested on 18 April 2002. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	[N] (%)	[N] (g cm^{-2})	SLM (g m^{-2})
Control (100%)	1.61	0.066	43
70%	1.51	0.056	35
50%	1.43	0.051	35
Pr > F			
Linear	0.0003	0.0052	0.0125
Quadratic	0.9199	0.8357	0.2896

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TABLE IV

Effect of shading of 'Cripps' Pink' branches in 2001-2002 on midday leaf water potential (MPa). Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	14 February	13 March	8 April
Control (100%)	-1.42	-1.34	-1.42
70%	-1.22	-1.12	-1.29
50%	-0.97	-0.97	-0.99
Pr > F			
Linear	0.0001	0.0001	0.0001
Quadratic	0.0019	0.0044	0.0001

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TABLE V

Light saturated rate of net CO_2 assimilation (A_{max}) ($\mu mol\ m^{-2}\ s^{-1}$), apparent quantum efficiency (AQE) ($\mu mol\ CO_2\ \mu mol^{-1}$ quanta), stomatal conductance (g_S) ($mol\ m^{-2}\ s^{-1}$), transpiration rate (E) ($mol\ m^{-2}\ s^{-1}$), and daytime dark respiration rate (R_D) ($\mu mol\ m^{-2}\ s^{-1}$) of 'Cripps' Pink' leaves in response to shading. Measurements were performed on 10 April 2001 and 9 April 2002 during the midday period. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	A_{max}	AQE	g_S	E	R_D
			2000-2001		
Control (100%)	18.4	0.06	0.639	4.48	1.00
70%	15.9	0.06	0.435	3.65	0.83
55%	10.7	0.05	0.377	3.24	0.48
30%	8.8	0.04	0.247	2.29	0.38
Pr > F					
Linear	0.0001	0.0274	0.0001	0.0001	0.0001
Quadratic	0.0948	0.1465	0.2841	0.7044	0.7424
			2001-2002		
Control (100%)	16.3	0.07	0.421	3.17	0.44
70%	11.9	0.08	0.306	2.48	0.43
50%	7.7	0.07	0.225	3.63	0.42
Pr > F					
Linear	0.0019	0.9839	0.0150	0.7777	0.9203
Quadratic	0.6320	0.3542	0.9260	0.3646	0.9907

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TABLE VI

Effect of shading of 'Cripps' Pink' branches in 2001-2002 on fruit diameter (mm) of tagged fruit throughout the growing season until 10 days before harvest. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	15 January	18 February	13 March	8 April
Control (100%)	31.2	59.8	67.3	71.0
70%	29.9	57.4	63.9	66.9
50%	30.2	56.2	60.6	64.8
Pr > F				
Linear	0.0010	0.0001	0.0001	0.0001
Quadratic	0.0101	0.6494	0.3799	0.5355

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TABLE VII

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit diameter (mm). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Cripps' Pink 2000-2001	
Control (100%)	65.3	63.4	65.3
70%	63.8	63.7	62.1
55%	62.2	62.4	63.5
30%	62.2	64.0	61.9
Pr > F			
Linear	0.0056	0.2776	0.0029
Quadratic	0.3941	0.2246	0.1477
		2001-2002	
Control (100%)	73.1	69.6	70.5
70%	71.1	68.5	68.5
50%	69.0	67.5	67.2
Pr > F			
Linear	0.2297	0.1138	0.0064
Quadratic	0.1183	0.9197	0.9532
		Rosemarie 2000-2001	
Control (100%)	61.4	61.8	62.7
70%	63.2	61.4	62.3
55%	61.2	62.9	62.4
30%	61.3	62.9	60.4
Pr > F			
Linear	0.2457	0.2776	0.3082
Quadratic	0.5108	0.8477	0.5992

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TABLE VIII

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit fresh mass (grams). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Cripps' Pink 2000-2001	
Control (100%)	116.5	116.6	116.0
70%	109.5	107.1	99.7
55%	100.5	102.6	107.5
30%	101.5	109.2	96.2
Pr > F			
Linear	0.0009	0.2709	0.0061
Quadratic	0.1536	0.2137	0.0779
		2001-2002	
Control (100%)	157.4	156.7	152.7
70%	156.9	149.0	135.7
50%	140.9	144.7	130.5
Pr > F			
Linear	0.0219	0.1241	0.0015
Quadratic	0.0555	0.9339	0.5022
		Rosemarie 2000-2001	
Control (100%)	130.2	132.4	131.3
70%	145.0	132.8	138.1
55%	135.8	141.7	135.0
30%	134.8	142.1	130.9
Pr > F			
Linear	0.8479	0.1717	0.9833
Quadratic	0.3405	0.9755	0.4966

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TABLE IX

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit ground colour (chart values 0-5, where 0=green and 5=golden yellow). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Cripps' Pink 2000-2001	
Control (100%)	3.4	4.3	4.7
70%	2.2	3.7	3.9
55%	1.4	3.4	3.7
30%	1.1	3.2	3.9
Pr > F			
Linear	0.0001	0.0001	0.0001
Quadratic	0.0135	0.0291	0.0014
		2001-2002	
Control (100%)	3.4	4.0	4.1
70%	3.3	3.7	3.8
50%	3.4	3.6	3.7
Pr > F			
Linear	0.3810	0.0013	0.0072
Quadratic	0.0901	0.2519	0.6831
		Rosemarie 2000-2001	
Control (100%)	3.3	3.6	5.0
70%	3.0	3.3	4.9
55%	2.9	3.2	4.9
30%	3.0	3.3	4.9
Pr > F			
Linear	0.0052	0.0106	0.0981
Quadratic	0.0497	0.0269	0.6458

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TABLE X

Effect of shading of 'Cripps' Pink' branches on percentage fruit starch breakdown. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		2000-2001	
Control (100%)	44.0	42.3	52.6
70%	51.8	44.6	52.6
55%	51.8	53.4	58.3
30%	51.8	48.1	52.1
Pr > F			
Linear	0.0116	0.0940	0.7734
Quadratic	0.6570	0.1764	0.4039
		2001-2002	
Control (100%)	40.2	38.1	35.2
70%	36.7	35.5	37.2
50%	46.1	40.2	40.5
Pr > F			
Linear	0.1759	0.4967	0.0263
Quadratic	0.0424	0.1017	0.5355

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TABLE XI

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit firmness (kg). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Cripps' Pink	
		2000-2001	
Control (100%)	9.7	7.9	7.0
70%	9.7	7.9	7.1
55%	9.8	7.9	6.7
30%	9.9	8.2	7.2
Pr > F			
Linear	0.0631	0.2612	0.5831
Quadratic	0.3034	0.5921	0.1668
		2001-2002	
Control (100%)	7.9	7.7	7.3
70%	8.0	8.7	7.5
50%	8.0	8.1	7.3
Pr > F			
Linear	0.7478	0.4501	0.8587
Quadratic	0.5141	0.1361	0.0572
		Rosemarie	
		2000-2001	
Control (100%)	5.7	5.6	1.5
70%	5.8	6.0	1.6
55%	6.0	6.0	1.5
30%	6.0	6.0	1.4
Pr > F			
Linear	0.0516	0.0554	0.0353
Quadratic	0.4679	0.1356	0.0260

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TABLE XII

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit total soluble solids concentration (% TSS). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Cripps' Pink 2000-2001	
Control (100%)	15.1	14.7	15.7
70%	14.8	14.9	15.1
55%	14.8	14.5	14.9
30%	14.3	14.3	14.4
Pr > F			
Linear	0.0084	0.7221	0.0004
Quadratic	0.6492	0.4478	0.8239
		2001-2002	
Control (100%)	14.3	14.1	13.6
70%	13.7	13.8	13.3
50%	13.6	13.3	12.9
Pr > F			
Linear	0.0539	0.0012	0.0059
Quadratic	0.5135	0.4513	0.5359
		Rosemarie 2000-2001	
Control (100%)	10.7	11.7	11.0
70%	10.9	12.0	10.8
55%	10.8	11.7	10.8
30%	10.6	11.7	10.7
Pr > F			
Linear	0.6972	0.1016	0.0022
Quadratic	0.3643	0.0217	0.1164

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TABLE XIII

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit titratable acidity (TA) (% malic acid). Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	At Harvest	After Storage	After Ripening
		Cripps' Pink 2000-2001	
Control (100%)	0.67	0.55	0.57
70%	0.61	0.54	0.56
55%	0.58	0.57	0.54
30%	0.55	0.57	0.57
Pr > F			
Linear	0.0001	0.5975	0.1332
Quadratic	0.3694	0.2313	0.6864
		2001-2002	
Control (100%)	0.70	0.64	0.59
70%	0.69	0.64	0.61
50%	0.67	0.66	0.60
Pr > F			
Linear	0.1918	0.3232	0.5907
Quadratic	0.5576	0.5336	0.4310
		Rosemarie 2000-2001	
Control (100%)	0.17	0.14	0.16
70%	0.19	0.15	0.16
55%	0.21	0.16	0.18
30%	0.21	0.17	0.17
Pr > F			
Linear	0.0022	0.0003	0.0109
Quadratic	0.1164	0.7726	0.7754

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TABLE XIV

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit macronutrient concentration (mg 100 g^{-1} dry mass) at harvest. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	P	K	Ca	Mg
		Cripps' Pink 2000-2001		
Control (100%)	48.5	768	31.4	32.7
70%	59.1	806	34.6	35.3
55%	54.2	793	33.3	36.7
30%	68.0	841	25.7	37.0
Pr > F				
Linear	0.3697	0.6689	0.7513	0.0830
Quadratic	0.2671	0.6864	0.7402	0.9066
		2001-2002		
Control (100%)	66.8	517	24.0	44.0
70%	78.3	645	23.1	48.2
50%	83.3	665	25.0	46.1
Pr > F				
Linear	0.0932	0.0377	0.8423	0.2459
Quadratic	0.8323	0.4613	0.6268	0.1615
		Rosemarie 2000-2001		
Control (100%)	67.2	769	42.3	46.9
70%	70.0	767	39.3	43.3
55%	71.1	817	37.7	46.1
30%	72.0	855	41.8	47.0
Pr > F				
Linear	0.5380	0.4597	0.5282	0.6714
Quadratic	0.9990	0.5394	0.9683	0.2036

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TABLE XV

Effect of shading of 'Cripps' Pink' and 'Rosemarie' branches on fruit micronutrient concentration (mg kg^{-1} dry mass) at harvest. Values are means of replications (n=10 in 2000-2001, n=12 in 2001-2002) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	Na	Mn	Fe	Cu	Zn	B
			Cripps' Pink 2000-2001			
Control (100%)	130.2	4.69	11.8	6.80	3.87	28.80
70%	98.00	4.89	12.4	26.8	6.89	30.20
55%	106.2	5.89	14.8	21.8	6.60	28.40
30%	110.8	3.89	13.2	15.6	3.80	31.00
Pr > F						
Linear	0.1068	0.2186	0.0726	0.1264	0.3507	0.9540
Quadratic	0.2043	0.5096	0.3624	0.2345	0.6322	0.5610
			2001-2002			
Control (100%)	113.1	12.7	28.7	3.1	8.61	41.2
70%	167.6	13.6	31.0	2.0	11.6	46.6
50%	172.6	13.2	38.2	2.0	12.2	46.8
Pr > F						
Linear	0.0097	0.5538	0.0754	0.0863	0.1047	0.0960
Quadratic	0.2594	0.3485	0.3869	0.3980	0.5968	0.4466
			Rosemarie 2000-2001			
Control (100%)	91.3	6.99	14.5	89.5	20.6	21.0
70%	93.0	7.00	14.4	102	36.0	22.0
55%	103	7.40	22.8	112	30.0	21.6
30%	87.5	6.72	27.2	147	28.5	20.4
Pr > F						
Linear	0.2366	0.4805	0.3221	0.8267	0.7113	0.5858
Quadratic	0.4667	0.5893	0.4203	0.9945	0.6796	0.5529

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TABLE XVI

Effect of shading of 'Cripps' Pink' branches in 2001-2002 on total fruit mineral nutrient content at harvest. Values are means of replications (n=12) and statistical probabilities are given for linear and quadratic trends over irradiance.

Treatment (% PPFD relative to control)	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
						mg fruit^{-1}				
Control (100%)	1.49	11.65	0.52	0.98	0.26	0.03	0.06	0.007	0.02	0.09
70%	0.92	7.59	0.29	0.59	0.20	0.02	0.04	0.002	0.01	0.06
50%	1.01	7.91	0.30	0.56	0.21	0.02	0.05	0.003	0.01	0.06
Pr > F										
Linear	0.0005	0.0008	0.0013	0.0003	0.2221	0.0014	0.0119	0.0125	0.1376	0.0003
Quadratic	0.0067	0.0236	0.0470	0.0562	0.4628	0.1192	0.0127	0.0676	0.4100	0.0217

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CAPTIONS TO FIGURES

Figure 1: Response of single-leaf net CO_2 assimilation rate (A) to photosynthetic photon flux density (PPFD) in 'Cripps' Pink' apple trees in response to shading of branches in (a) 2000-2001 and (b) 2001-2002. Symbols and functions represent means of five replicates per treatment.

Figure 2: Blush colour (chart values 0-12, where 0=no blush and 12=complete dark red blush) of 'Cripps' Pink' apples in (a) 2000-2001, (b) 2001-2002 and (c) hue angle (°) in 2001-2002 as measured at harvest, after 8 weeks of storage at –0.5°C and after seven days of ripening at 15°C in response to shading of branches. Values are means of replications (n=10). Linear polynomial contrast, *, $P \leq 0.05$, **, $P \leq 0.01$, ***, $P \leq 0.001$, and quadratic polynomial contrast, +, $P \leq 0.05$, ++, $P \leq 0.01$, +++, $P \leq 0.001$.

Figure 3: Blush colour (chart values 0-16, where 0=no blush and 16=complete dark red blush) of 'Rosemarie' pears at harvest, after 18 days of storage at –0.5°C and after seven days of ripening at 15°C in response to shading of branches in 2000-2001. Values are means of replications (n=10). Linear polynomial contrast, *, $P \leq 0.05$, **, $P \leq 0.01$, ***, $P \leq 0.001$, and quadratic polynomial contrast, +, $P \leq 0.05$, ++, $P \leq 0.01$, +++, $P \leq 0.001$.

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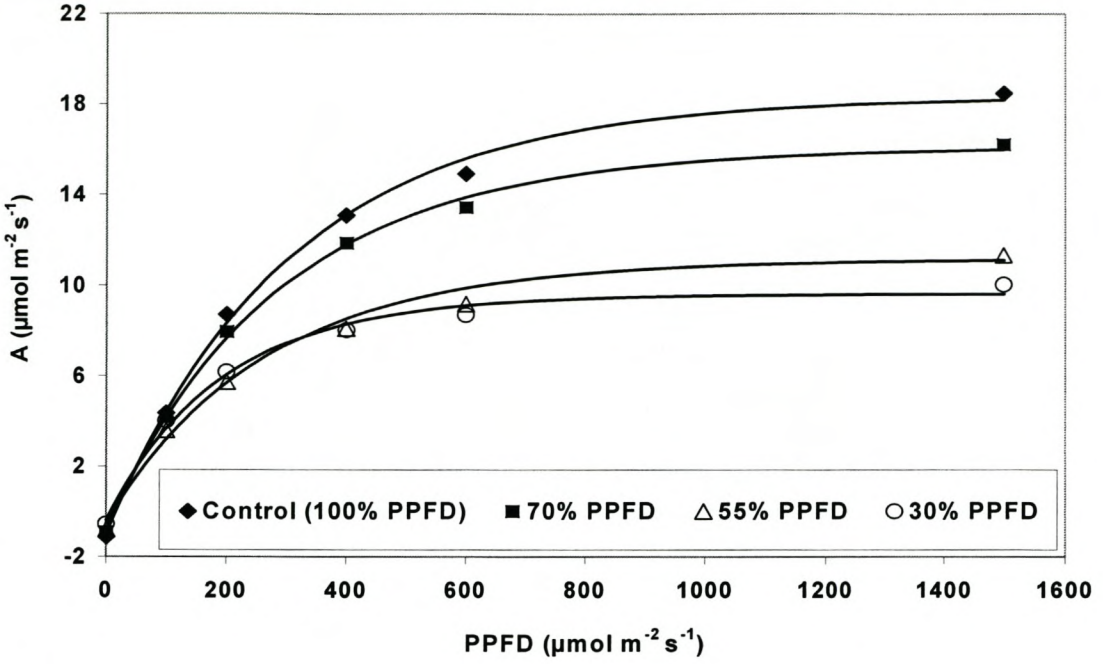
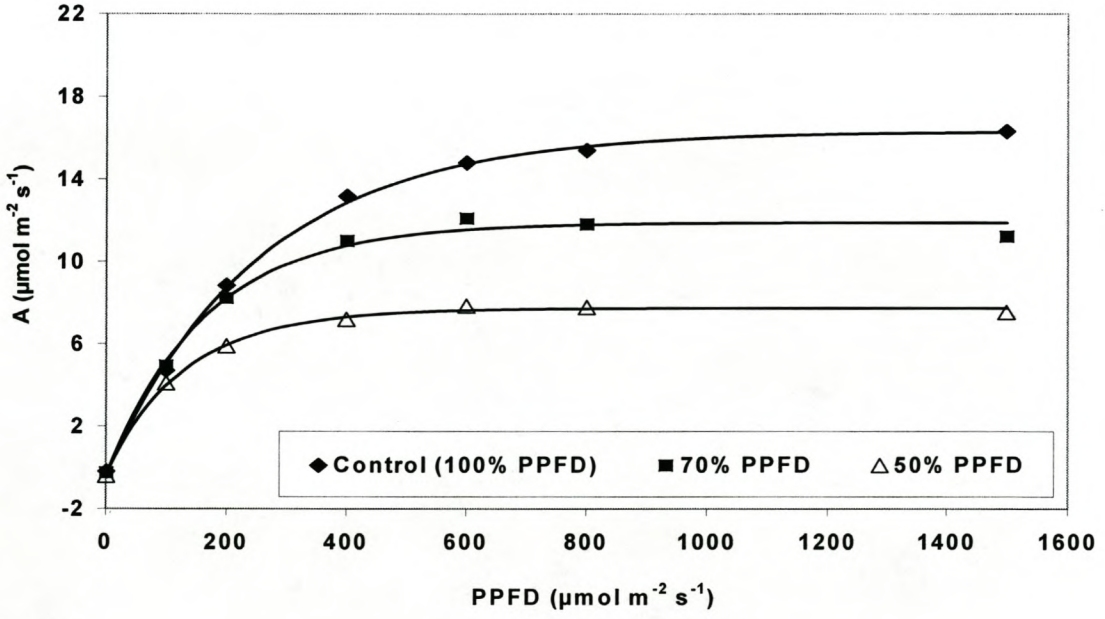


(a)



(b)

FIG. 1

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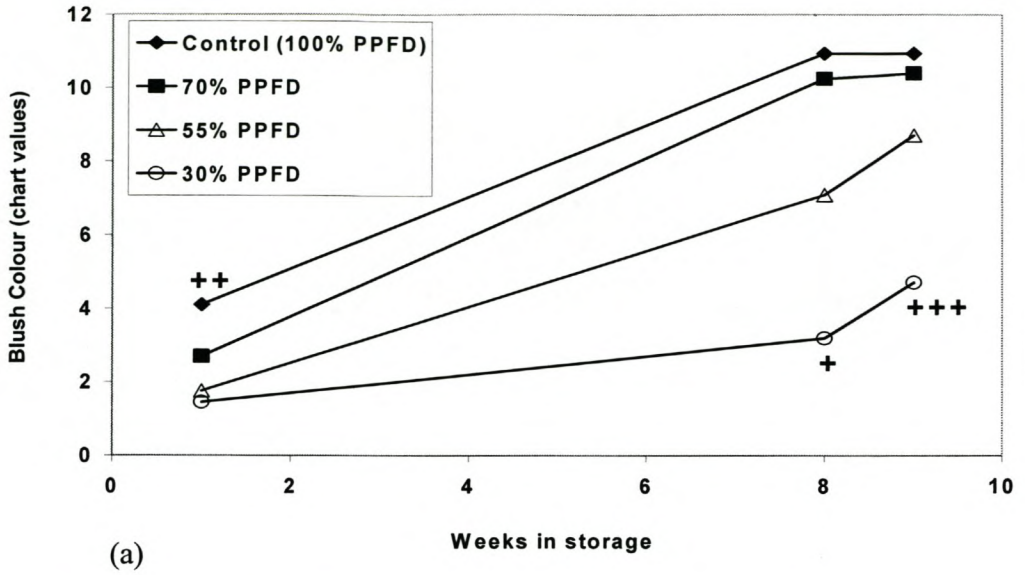
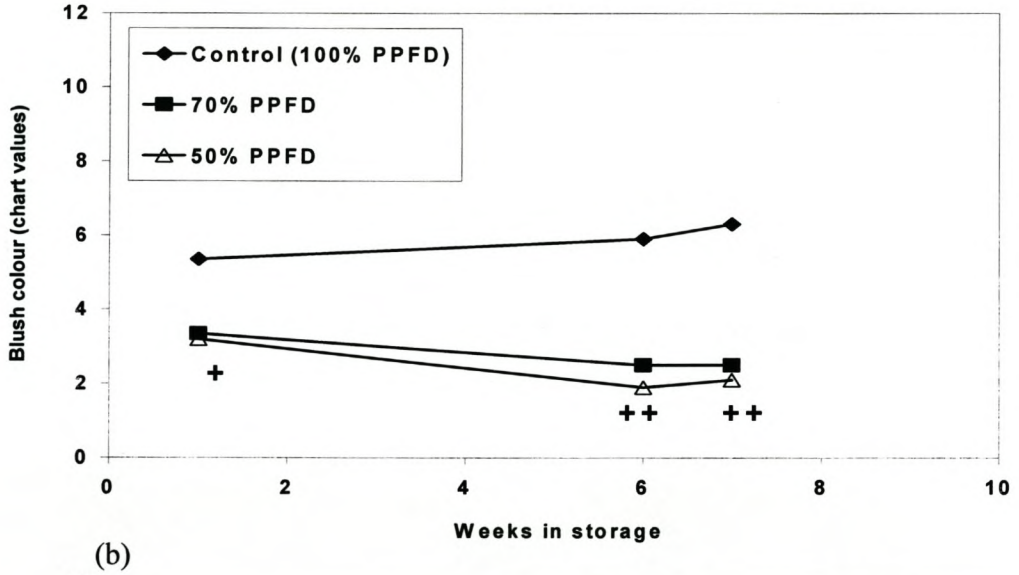


(a)



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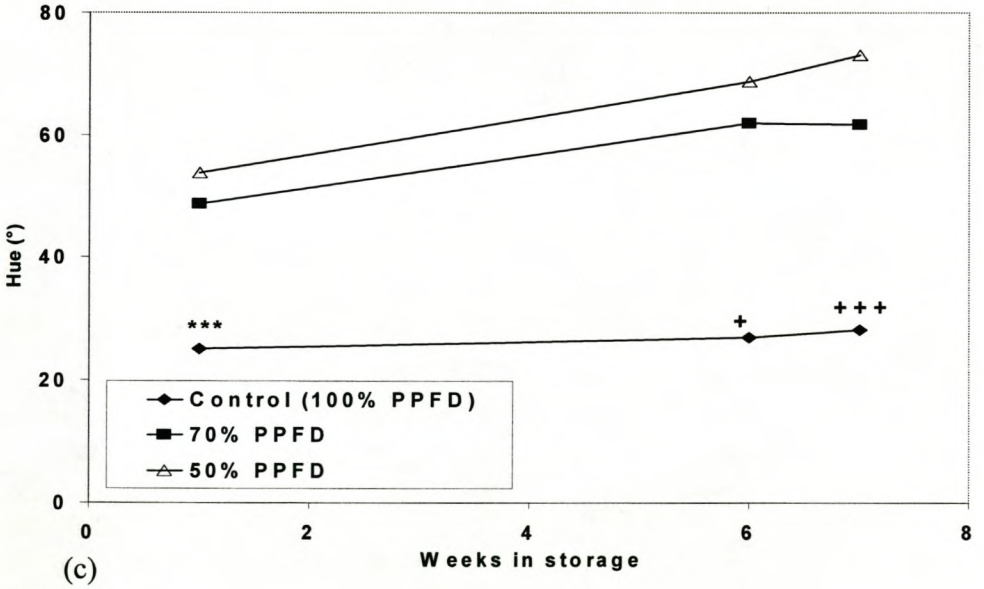

(c)

FIG. 2

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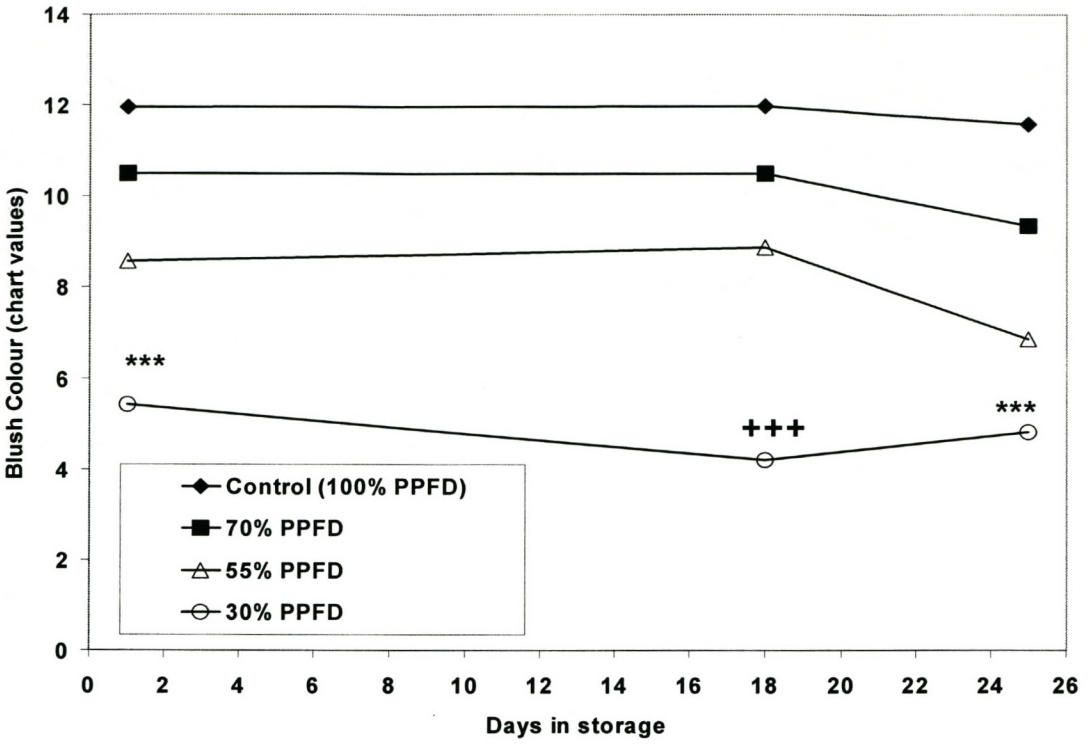

FIG. 3

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Chapter IV:

Harvest and postharvest quality of 'Songold' plums as influenced by irrigation system, pre-harvest soil drying and harvest date

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ABSTRACT

In 2000-2001 and 2001-2002, harvest maturity and quality of 'Songold' plums from drip- and micro-irrigated trees were investigated. In both seasons, fruit were harvested on five dates, every second day over a nine-day period. In 2000-2001, irrigation of 'Songold' plum trees was terminated ten and five days before harvest of micro- and drip-irrigated trees respectively. In 2001-2002, the termination of irrigation prior to harvest was not investigated due to unseasonable rainfall prior to and during the harvesting period. Fruit maturity and quality were assessed at each harvest date, after an 18-day storage period and again after ripening. The storage regime comprised ten days at –0.5°C, followed by eight days at 7.5°C. This was followed by a ripening period which lasted for seven days in 2000-2001 and five days in 2001-2002 at 15°C. On each evaluation date, fruit size and mass, skin ground and blush colour, flesh firmness, total soluble solids and titratable acidity were assessed. At harvest, fruit size and mass was greater for micro-irrigated fruit, and for fruit that were not subjected to soil drying. Drip-irrigation and soil drying resulted in increased total soluble solids, and fruit that were firmer and had a more yellow ground colour. The extended harvest period did result in softer fruit at the later harvest dates, but the firmness of fruit from each of the five harvest dates was similar after storage and ripening. The concentrations of K, Mg and P (2000-2001) were higher in micro-irrigated fruit and in fruit not subjected to soil drying. The smaller fruit had higher concentrations of certain micronutrients. The relationship between treatments, nutrient concentrations and the incidence of internal disorders needs to be investigated further due to the virtual absence of disorders in this study. After ripening, drip-irrigated fruit and fruit subjected to soil-drying were of similar size and mass, were more marketable and had a better eating quality than micro-irrigated fruit and fruit not subjected to soil drying. The extended harvest period gave immature and smaller fruit at the first date the opportunity to attain a more advanced maturity and larger size at the end of the harvest period.

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INTRODUCTION

The termination of irrigation shortly before harvest in order to advance the maturity of all the fruit to a similar level, and the subsequent strip harvest of the fruit on a single harvest date, is a practice commonly used by South African plum producers to reduce cost and ostensibly to improve fruit quality. There is little information on the assumed benefits and possible negative effects of this practice under South African conditions, particularly with respect to storage potential and ripening processes.

The sensitivity of stone fruit to water stress over the different stages of fruit growth has been investigated in several previous studies (Lampinen *et al.*, 1995; Marsal and Girona, 1997; Naor *et al.*, 2001; Torrecillas *et al.*, 2000). Final size of stone fruit seems to be affected by fruit water status during the final stage of rapid fruit growth. In previous studies, covering individual peach and nectarine fruit with plastic or aluminium foil modified the microenvironment around the fruit by increasing humidity (Li *et al.*, 2001; Muleo *et al.*, 1994). Higher humidity limited fruit transpiration and consequently fruit water status was improved, which resulted in a more rapid increase in fruit volume (Li *et al.*, 2001; Muleo *et al.*, 1994). Fruit growth is retarded by water stress during the first two stages of fruit growth, but these fruit show a compensatory growth rate in the final stage of growth and attain a similar size to control fruit at harvest. Fruit subjected to water stress during the final rapid stage of fruit growth are smaller and this results in a reduced yield at harvest (Torrecillas *et al.*, 2000).

It has also been noted that water stressed fruit are smaller but have higher levels of total soluble solids (Besset *et al.*, 2001). Water stress triggers the physiological function of osmoregulation (Meyer and Boyer, 1981). Osmoregulation is the accumulation of solutes in cells, in order to decrease the osmotic potential of cells, so that water can be absorbed from the water source by cells without losing cell turgor or decreasing cell volume. The ability of many plants to tolerate water stress is largely dependent on their capacity for osmoregulation for maintaining cell turgor through the accumulation of solutes (Morgan, 1984). Previous investigations have observed

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osmoregulation in stems (Meyer and Boyer, 1981), roots, and leaves (Ranney *et al.*, 1991). Water-stressed plants have been found to accumulate more sugars than unstressed plants (Meyer and Boyer, 1981). In a study conducted on 'Satsuma' mandarin fruit, osmotic potential of juice vesicles in water stressed fruit decreased, and sugars accumulated in vesicle cells. The results suggested that sugar accumulation in 'Satsuma' mandarin fruit was due to active osmoregulation in response to water stress, and not due to dehydration under water stress (Yakushiji *et al.*, 1996).

Irrigation technique affects root spread, growth, productivity and overall water status of the tree. Comparison of micro- and drip-irrigation systems indicates that roots spread less and trees grew more slowly under drip-irrigation of a peach orchard (Mitchell and Chalmers, 1983). A decrease in tree vigour under drip-irrigation as compared to micro-irrigation has also been found in apple trees (Proebsting *et al.*, 1977). Peach and apple trees under drip-irrigation do, however, crop earlier (Mitchell and Chalmers, 1983; Proebsting *et al.*, 1977).

The response of the fruit to an extended harvest period has been studied previously, and it has been found that the maturity of fruit harvested later is advanced and that this results in an increased incidence of internal disorders in plums (Taylor *et al.*, 1993). The delayed harvest of fruit does however allow the fruit to increase nutrient concentration levels (Taylor *et al.*, 1993).

This study aims to investigate the effects of micro- and drip-irrigation, and the effects that the termination of irrigation has on plum maturity and quality over an extended harvesting period, as well as on the postharvest storage and shelf quality of plums. The results of this study are expected to indicate that drip-irrigation and the effects of soil drying shortly before harvest result in an improved fruit quality in terms of marketability and eating quality. This could also be achieved by harvesting over an extended harvesting period, thus giving the immature fruit at the start of the harvesting period the potential to attain an optimal level of maturity.

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MATERIALS AND METHODS

Plant material

'Songold' plum trees on Mariana rootstock were planted in 1996 on Sandrivier commercial farm in North Agter-Paarl, Western Cape, Republic of South Africa (33°37'S 18°47'E). In 2000-2001 and 2001-2002, adjacent blocks of micro-jet sprinkler and drip-irrigated trees were used. The trees were planted at 3.5m x 1m spacing and trained as central leaders on a three-wire system. The row orientation was north by south. Irrigation scheduling was based on neutron moisture probe measurements. All cultural and physical orchard practices were in agreement with commercial norms for the region.

Treatments and experimental design: In both seasons, eight rows, with 10 trees per row, were used for each irrigation system. Within each irrigation system, the experiment was designed as a randomised complete block, with four blocks of two treatments. In 2000-2001, both treatments (soil drying and control) were used. In 2000-2001, soil drying treatments were created by terminating irrigation in a randomly selected row of each block, within each irrigation system. Micro-jet sprinkler irrigation was terminated on 26 January 2001, 10 days prior to the first harvest date, and drip irrigation was terminated on 31 January 2001, five days prior to the first harvest date. Irrigation was continued as scheduled in the remaining control rows throughout the harvesting period. In 2001-2002, soil drying treatments were not used due to unseasonable rainfall prior to and during the harvesting period. Soil moisture was not monitored, as the neutron moisture probe was not in the immediate vicinity of the rows used in the study. In both seasons, plums were harvested on five dates, every second day over a nine-day period. In 2000-2001, the harvest period was from 5 February until 13 February 2001. In 2001-2002, the harvest period was from 23 January until 31 January 2002.

Harvest and postharvest quality determination: In both seasons, at each harvest date, 30 fruit per replicate were harvested and 10 fruit evaluated for quality. The remaining fruit were immediately placed in storage at –0.5°C. These fruit were subjected

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to a dual temperature storage regime with 10 days at –0.5°C, followed by eight days at 7.5°C, and a ripening period at 15°C for seven days in 2000-2001 and for five days in 2001-2002. After 18 days of dual temperature storage and again after the ripening period, a random set of 10 fruit per replicate were evaluated according to each of the following quality parameters:

Fruit diameter was measured around the equator using electronic callipers, and individual fruit mass determined. Ground colour was evaluated using the colour chart for 'Songold' plums provided by Hortec, Stellenbosch (Unifruco Research Services ground colour chart for apples and pears). Blush colour was evaluated after the seven-day ripening period in 2001-2002 using the colour chart for 'Songold' plums provided by Hortec, Stellenbosch (Songold colour DFB PL. 19). Fruit firmness was determined on peeled, opposite cheeks of the fruit using a penetrometer (Southtrade fruit pressure tester, FT 327, Alphonsine, Italy) fitted with an 11 mm tip. Slices cut from each side of each of the five fruit were juiced together and a total soluble solids (TSS) reading taken using a hand held refractometer (Atago PR-100 9501, Japan). Juice obtained for TSS was also analysed for titratable acidity (TA) by titration with 0.1 M NaOH to a pH of 8.2 using an automated titrator (Tritino 719S and Sample Changer 674, Metrolum Ltd., Herisau, Switzerland). Results were expressed as percent malic acid.

Internal browning, gel breakdown, aerated flesh (air-filled cells in mesocarp giving fruit a dull appearance) and over-ripeness, as described by Taylor (1996), as well as incidence of decay were rated. These ratings were done as a percentage of the five fruit evaluated per replicate, both after storage and again after ripening. Slices cut from each side of each of the five fruit per replicate were freeze-dried and milled together. The samples were analysed for phosphorus, potassium, calcium, magnesium, sodium, manganese, iron, copper, zinc and boron concentration, expressed as a percentage of dry mass. Mineral analysis was only done for samples at harvest at a commercial laboratory (Bemlab, Stellenbosch) according to standard methods.

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Statistical analysis: The data were analysed with the General Linear Models (GLM) procedure of SAS (SAS release 6.12P; SAS Institute, 1996, Cary, NC). Data were analysed using three-way Analysis of Variance (ANOVA) with irrigation system, soil drying treatment and date of harvest as factors. Although irrigation system treatments were not laid out in a blocked design, the soil and orchard conditions in the adjacent irrigation blocks were regarded as sufficiently similar to justify this statistical treatment.

RESULTS

Fruit diameter

2000-2001: At harvest, the irrigation system and the interaction between soil drying treatment and harvest date significantly affected plum diameter (Table I, Figure 1(a)). Diameter of the micro-irrigated plums was significantly greater than the drip-irrigated plums. With one exception (7 Feb), the soil drying treatment resulted in smaller fruit over the five harvest dates compared with the control. After 18 days of storage, plum diameter was greater for the fruit that had not been subjected to soil drying and remained higher the later they had been picked (Table I, Figure 1(b)). The effect of the irrigation system on diameter was negated during storage. After the ripening period, there was no significant effect of any of the parameters on plum diameter (Table I, Figure 1(c)). Results and differences over the three evaluation dates concerning fruit diameter may be an artefact of sample variability. Different samples were evaluated at each evaluation date, whereas if the same sample was measured on the three dates differences could have been smaller.

2001-2002: Plum diameter increased over the five harvest dates, but after 18 days of storage the effect of harvest date on diameter was reversed and it decreased over the five harvest dates (Table I). There was no significant effect on plum diameter after ripening (Table I).

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Fruit fresh mass

2000-2001: At harvest, the irrigation system and the interaction between soil drying treatment and harvest date significantly affected plum fresh mass (data not shown). Fresh mass of the micro-irrigated plums was significantly greater than the drip-irrigated plums. The soil drying treatment resulted in a general decrease in mass over the five harvest dates, with the exception being on the third harvest date when the plums subjected to soil drying were heavier. After 18 days of storage, fresh mass of plums was affected by a significant interaction between irrigation system and soil drying treatment, and by harvest date. Fresh mass of micro-irrigated plums and plums that had not been subjected to soil drying were, overall, greater. Fresh mass was also greater the later the fruit were harvested. After the ripening period, micro-irrigated plums had greater mass. Fresh mass was also affected by harvest date, but this was probably due to sampling variability.

2001-2002: Fruit fresh mass at harvest and after storage was not affected significantly by the irrigation system or the time of harvest (data not shown). After the ripening period, mass of the micro-irrigated fruit was greater than that of the drip-irrigated fruit. Fruit mass was generally greater the later the fruit were harvested.

Fruit ground colour

2000-2001: At harvest, ground colour was significantly affected by the interaction between irrigation system and soil drying treatment, as well as by the interaction of these two factors with the harvest date (Table II, Figure 2 (a)). Drip-irrigated fruit had a more yellow ground colour than micro-irrigated fruit. Fruit that were subjected to the soil drying treatment generally had a more yellow ground colour than the control fruit. The absolute differences in ground colour between irrigation systems and soil drying treatments were meaningful on the first harvest date in terms of visual appearance and marketability. Ground colour of all the fruit became more yellow the later they were harvested, but particularly so in micro-irrigated fruit. This resulted in the ground colour values of all the treatments to be similar on the last harvest date, in terms of visual appearance. After 18 days of storage, drip-irrigated fruit still generally had a more

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yellow ground colour than micro-irrigated fruit (Table II, Figure 2 (b)). Fruit subjected to soil drying had a more yellow ground colour than the control fruit. After the ripening period, ground colour of all the fruit had improved to the most yellow value on the colour chart, and there were no differences between treatments (data not shown).

2001-2002: At harvest there was a significant decrease in ground colour over the harvesting period (Table II). However, the absolute values were not meaningful in terms of visual appearance. After storage, ground colour increased the later the fruit were harvested. The absolute values were, however, not meaningful in terms of visual appearance (Table II). After the ripening period, ground colour of all the fruit had improved to the most yellow value on the colour chart and there were no differences between treatments (data not shown).

Blush colour

2001-2002: Blush colour developed during the ripening period and was only significantly affected by harvest date (Table III). Blush colour development was most advanced in the fruit from the first and last harvest dates, and remained at a consistently lower level of blush on the other three dates.

Flesh firmness

2000-2001: At harvest, flesh firmness was significantly affected by a three-way interaction between irrigation system, soil drying treatment and harvest date (Table IV, Figure 3 (a)). The general trend was that drip-irrigated fruit were firmer than micro-irrigated fruit, and that firmness of all the fruit decreased over the harvest period. After 18 days of storage, drip-irrigated fruit subjected to soil drying were the firmest over the five harvest dates, and the micro-irrigated fruit that were not subjected to soil drying were the least firm (Table IV, Figure 3 (b)). There was a significant interaction between irrigation system and soil drying treatment, this showed that fruit subjected to soil drying and drip-irrigation were firmer than micro-irrigated and control fruit. The absolute difference between the micro-irrigated fruit subjected to soil drying and the drip-irrigated fruit subjected to soil drying was only 0.3 kg, which is not meaningful in terms of

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marketability. Although harvest date was significant, the biggest difference in firmness between the five harvest dates was only 0.3 kg, which is not meaningful in terms of marketability. After the ripening period, flesh firmness of the fruit picked on the first and final harvest dates was very similar, with variability in-between (Table IV, Figure 3 (c)). In general, micro-irrigated fruit not subjected to soil drying were softer than the other fruit, and the drip-irrigated fruit subjected to soil drying were the firmest.

2001-2002: At harvest, after storage and after ripening, flesh firmness decreased over the five harvest dates (Table IV). After 18 days of storage, drip-irrigated fruit were firmer than micro-irrigated fruit with the exception of one harvest date (Table IV). After ripening, differences in firmness were small and unlikely to have an effect on fruit marketability.

Total soluble solid content (%)

2000-2001: At harvest, TSS content was greater for drip-irrigated fruit, and for fruit subjected to soil drying, and there was also an increase over the five harvest dates (Table V, Figure 4 (a)). After 18 days of storage and after ripening, drip-irrigated fruit had the highest TSS content (Table V, Figure 4 (b), (c)). Fruit of each irrigation system which were subjected to soil drying had a greater TSS content than the control fruit, but the absolute differences were bigger for micro-irrigated fruit. After 18 days of storage, the TSS content increased over the five harvest dates, but there were no differences after ripening.

2001-2002: At harvest, after storage and after ripening, TSS content increased over the five harvest dates (Table V). After ripening, TSS content was greater for drip-irrigated fruit, but only if they had been harvested earlier, this could be ascribed to sample variability.

Titratable acidity (% malic acid)

2000-2001: At harvest, there was no significant effect of treatments on TA of the fruit (Table VI, Figure 5 (a)). After 18 days of storage, TA was slightly higher in drip-

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irrigated fruit, and dropped sharply in fruit harvested on the final harvest date (Table VI, Figure 5 (b)). After ripening, TA was greater in drip-irrigated fruit and in fruit subjected to soil drying. The differences over the five harvest dates were significant but unlikely to be meaningful in terms of absolute differences (Table VI, Figure 5 (c)).

2001-2002: At harvest, after storage and after ripening, TA was greater in drip-irrigated fruit (Table VI). At harvest and after storage the TA fluctuated over the five harvest dates, the absolute differences were, however, small.

Macronutrient analysis

2000-2001: There was a higher concentration of P in micro-irrigated fruit, especially those that were subjected to soil drying (Table VII, Figure 6). Drip-irrigated fruit that were subjected to soil drying had a lower concentration of P than the drip-irrigated control fruit, but only on the first two and the last harvest dates. The concentration fluctuated over the five harvest dates. The concentration of K was higher in micro-irrigated fruit that were harvested earlier, and increased significantly in the fruit that were harvested later in both systems. The concentration of Ca fluctuated over the five harvest dates and for the two irrigation systems but there was no clear trend. The concentration of Mg was higher in micro-irrigated fruit and fluctuated over the five harvest dates, but with a general increase in later harvests.

2001-2002: The concentrations of P, K, Ca and Mg generally decreased for both irrigation systems over the five harvest dates (Table VII). There were no clear differences between systems.

Micronutrient analysis

2000-2001: The concentration of Fe increased over the five harvest dates (Table VIII, Figure 7, 8). The concentration of Na was higher in drip-irrigated fruit, and of Mn was higher in micro-irrigated fruit but lower in fruit subjected to soil drying. The concentration of B decreased over the five harvest dates.

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2001-2002: The concentrations of Na, Mn and Fe were higher in drip-irrigated fruit (Table VIII). There were no significant treatment effects on the concentrations of Cu, Zn and B.

DISCUSSION

Drip-irrigated fruit and fruit subjected to soil drying shortly before harvest were smaller than micro-irrigated and non-droughted fruit. Stone fruit growth and final diameter have been found to respond differently to water stress or deficit irrigation during different phenological periods of fruit growth. Fruit growth is retarded by water stress in the first two stages of fruit growth, but fruit show a compensatory increase in growth rate in the final stage of growth and attain a similar size to control fruit at harvest. Fruit subjected to water stress during the final rapid stage of fruit growth are smaller and reduce yield at harvest (Torrecillas *et al.*, 2000). The final stage of rapid fruit growth in stone fruit has been shown to be a determining factor in final fruit size and yield (Li *et al.*, 2001; Marini *et al.*, 1991). Stone fruit growth is very sensitive to water status during the final stage of fruit development (Lampinen *et al.*, 1995). The improvement of fruit water status results in a more rapid increase in fruit volume (Lampinen *et al.*, 1995; Li *et al.*, 2001; Marini *et al.*, 1991; Marsal and Girona, 1997; Muleo *et al.*, 1994; Naor *et al.*, 2001).

It has been found that light water stress has no effect on yield but that severe stress reduces yield (Besset *et al.*, 2001). Fruit growth is dependent on the accumulation of osmotically active solutes (Berman and DeJong, 1996). Severe irrigation stress induces a reduction in yield due to a limitation of assimilates supplied to the fruit. This is possibly related to limitations in leaf photosynthesis caused by the stress (Besset *et al.*, 2001; Berman and DeJong, 1996).

The results of this study suggest that micro-irrigated fruit had better water status than drip-irrigated fruit, and therefore had improved diameter and mass at harvest. The micro-irrigated fruit and fruit not subjected to soil drying were inflated with water at

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harvest. During storage and ripening, however, these fruit lost more water and were eventually of a similar size and mass to the fruit that were drip-irrigated and droughted. Differences in size were present at harvest, but the absolute differences were small and would probably not affect marketability of the fruit.

Flesh firmness and titratable acidity (TA) of plums has been found to provide a useful means for establishing harvest maturity (Taylor *et al.*, 1993). Drip-irrigated fruit and fruit subjected to soil drying were firmer than micro-irrigated and non-droughted fruit. This indicated that micro-irrigated and non-droughted fruit may have been more mature at harvest, but these fruit were also inflated with water which would result in decreased firmness. Therefore, in terms of firmness, soil drying was particularly beneficial for micro-irrigated fruit and improved the marketability of these fruit. TA of drip-irrigated fruit was higher than micro-irrigated fruit and this indicated that the micro-irrigated fruit had an advanced maturity at harvest. The lower TA of micro-irrigated fruit could also be due to a dilution effect because of the increased water content of the fruit. The differences in firmness and TA due to irrigation system and soil drying treatment were present after storage and ripening.

In the second season the fruit were harvested at higher TA levels and firmness measurements. This was due to unseasonable rainfall and was probably the cause of differences in quality between the seasons. This was likely the cause of the smaller fruit in the second season, as the fruit were not able to attain optimal size or growth during the final stage of fruit growth.

Ground colour of drip-irrigated fruit and fruit subjected to soil drying was more yellow than micro-irrigated and non-droughted fruit. During storage and ripening, the ground colour of all the fruit attained a similar level and there was no meaningful difference in terms of visual appearance. The decline in chlorophyll and increase in carotenoids has been noted to be an ethylene induced effect (Kader, 1985). It is known that increased water stress will increase ethylene production (Kader, 1985). This also

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indicates that micro-irrigated and non-droughted fruit had an improved water status compared to drip-irrigated fruit and fruit subjected to soil drying.

At harvest, after storage and after ripening, TSS was higher in drip irrigated fruit and in fruit subjected to soil drying. The lower TSS levels in the second season were likely due to the harvest maturity effect as previously discussed and the unseasonable rainfall prior to and during the harvest period. Water stress triggers the physiological function of osmoregulation, and water-stressed plants have been found to accumulate more sugars than unstressed plants (Meyer and Boyer, 1981). It has been shown that sugar accumulation in 'Satsuma' mandarin fruit was due to active osmoregulation in response to water stress, and not due to dehydration under water stress (Yakushiji *et al.*, 1996). Other studies on citrus fruit have also shown that irrigation stress causes an increase in TSS content (Peng and Rabe, 1998; Verreynne *et al.*, 2001; Yakushiji *et al.*, 1998). In peaches it was found that the more severe the stress the higher the TSS (Besset *et al.*, 2001; Crisosto *et al.*, 1994). The decreased TSS of micro-irrigated and non-droughted fruit could also be due to a dilution effect or passive osmotic adjustment (Flore and Lakso, 1989). It is likely that the increased TSS of drip irrigated fruit and in fruit subjected to soil drying was due to a combination of active and passive osmotic adjustment. Thus, drip-irrigated fruit and fruit subjected to soil drying exhibited characteristics of fruit subjected to water-stress when compared to micro-irrigated and control fruit. Plum eating quality increased when subjected to drip-irrigation and soil drying. The effect of soil drying on increasing TSS in fruit was particularly beneficial for micro-irrigated fruit.

At harvest, size and mass of plums increased over the five harvest dates. After storage and ripening, size and mass were similar for each of the five harvest dates, and therefore did not have an effect on the marketability of the fruit. At harvest, the maturity of the fruit was more advanced the later the fruit were picked. This is evident in the decrease in firmness and TA over the five harvest dates. Advanced maturity of fruit harvested later has also been found in previous studies on plums (Kruger *et al.*, 2001; Taylor *et al.*, 1993). After ripening, firmness and TA were similar at each harvest date

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and therefore the extended harvesting period did not result in the fruit harvested later being overripe, and did not affect the eating quality and marketability of the fruit.

Ground colour of the fruit harvested later was also more yellow. At harvest, the decline in chlorophyll and increase in carotenoids of the fruit harvested later was also an indication of the advanced maturity of these fruit. After ripening, there were no differences in ground colour over the five harvest dates. At harvest and after storage, TSS increased over the five harvest dates. This increase over the five harvest dates was due to continued accumulation of soluble solids. The increase in TSS over an extended harvesting period has also been found in previous studies (Kruger *et al.*, 2001; Taylor *et al.*, 1993). After ripening, TSS was similar for all five harvest dates and therefore had no effect on the eating quality of the fruit.

The possible negative effect of soil drying and drip-irrigation on leaf photosynthesis, due to its possible effect on fruit growth, could have an effect on the accumulation of minerals in these fruit. This could possibly explain the increased concentration of K, Mg and P (2000-2001) in the micro-irrigated fruit as they are also transported together with the carbohydrates in the phloem, even though the nutrients are mainly transported in the xylem (Biddulph *et al*, 1959; Raven, 1977; Salisbury and Ross, 1992). It can also be assumed that there was increased sap flow into the micro-irrigated fruit and the fruit not subjected to soil drying bringing with it more nutrients. The increased concentration of micronutrients in the drip-irrigated fruit could possibly be because these fruit were smaller. The results concerning internal disorders were inconclusive due to the very low incidence of any disorders in 'Songold' plums in both seasons.

CONCLUSION

The results of this study show that the irrigation system and pre-harvest soil drying treatment had an effect on fruit quality after storage and on the shelf. Drip-irrigated fruit had similar quality characteristics as fruit that had been subjected to pre-

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harvest soil drying. The termination of irrigation shortly before harvest subjects the fruit to water stress. Drip-irrigated fruit and fruit subjected to soil drying were generally smaller, firmer, had a more yellow ground colour at harvest and had a higher total soluble solid content, especially during the earlier harvests. Soil drying therefore did have the expected effect of accelerating maturation. Soil drying was especially beneficial for micro-irrigated fruit. The extended harvest period did not result in the fruit harvested later becoming overripe compared to the fruit harvested first. Later harvests allowed the smaller, immature fruit to attain an advanced level of maturity, increased total soluble solid content and improved ground colour at harvest.

After the ripening period, drip-irrigated fruit and fruit subjected to soil drying were firmer, had a higher TSS content and were a similar size and mass to the micro-irrigated fruit and control fruit. The shelf quality of the drip-irrigated fruit and fruit subjected to soil drying was therefore better than micro-irrigated fruit and non-droughted fruit, in terms of marketability and eating quality. Micro-irrigated fruit subjected to soil drying also had improved marketability and eating quality.

Further studies on the effect of irrigation system and pre-harvest irrigation stress on the occurrence of internal disorders are necessary. This is also important for evaluating the advantages of the extended harvesting period, as Taylor *et al.* (1993) found that delayed harvest resulted in advanced maturity and this caused a substantial increase in internal disorders, especially gel-breakdown.

Practically, soil drying should be used especially for micro-irrigated orchards as soil drying was more beneficial for micro-irrigated fruit. There is also a possibility that scheduling for drip-irrigation was sub-optimal resulting in unintentional stress, and therefore recommendations cannot be generalised for all drip-irrigation systems. Fruit should also be harvested over an extended period.

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TABLE I

Effect of irrigation system, soil drying treatment (2000-2001 only), harvest date and the interaction between these factors on 'Songold' plum diameter (mm). Analysis of variance was performed for a three-way interaction in 2000-2001 and a two-way interaction in 2001-2002. Refer to Figure 1 for 2000-2001 results.

	At harvest	After storage	After ripening
Pr > F		**2000-2001**	
System	0.0001	0.1326	0.7072
Soil drying	0.6075	0.0016	0.8776
Block	0.0001	0.0068	0.5372
Harvest	0.0007	0.0199	0.8261
System*Soil drying	0.2679	0.6556	0.9865
System*Harvest	0.0763	0.3976	0.9959
Soil drying*Harvest	0.0001	0.5419	0.9994
System*Soil drying*Harvest	0.9931	0.6828	0.1678
		2001-2002	
Micro, 23 Jan	52.2	53.4	48.7
Micro, 25 Jan	50.6	53.4	48.1
Micro, 27 Jan	50.5	51.7	48.9
Micro, 29 Jan	50.9	48.6	49.7
Micro, 31 Jan	52.5	50.8	54.6
Drip, 23 Jan	50.4	54.0	48.5
Drip, 25 Jan	50.7	51.9	50.4
Drip, 27 Jan	51.3	52.8	49.7
Drip, 29 Jan	52.6	50.6	48.4
Drip, 31 Jan	53.6	52.4	51.5
Pr > F			
System	0.3283	0.0955	0.3131
Block	0.3172	0.0622	0.4180
Harvest	0.0045	0.0001	0.4425
System*Harvest	0.0592	0.1162	0.4866

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TABLE II

Effect of irrigation system, soil drying treatment (2000-2001 only), harvest date and the interaction between these factors on 'Songold' plum ground colour (chart values). Analysis of variance was performed for a three-way interaction in 2000-2001 and a two-way interaction in 2001-2002. Refer to Figure 2 for 2000-2001 results.

	At harvest	After storage	After ripening
Pr > F		**2000-2001**	
System	0.0001	0.0001	.
Soil drying	0.0004	0.0003	.
Block	0.0001	0.0038	.
Harvest	0.0001	0.0001	.
System*Soil drying	0.0180	0.5991	.
System*Harvest	0.0009	0.0168	.
Soil drying*Harvest	0.0104	0.6881	.
System*Soil drying*Harvest	0.2111	0.8614	.
		2001-2002	
Micro, 23 Jan	3.7	3.9	.
Micro, 25 Jan	3.7	4.0	.
Micro, 27 Jan	3.7	4.2	.
Micro, 29 Jan	3.4	4.1	.
Micro, 31 Jan	3.4	4.4	.
Drip, 23 Jan	3.6	3.8	.
Drip, 25 Jan	3.6	4.0	.
Drip, 27 Jan	3.6	4.4	.
Drip, 29 Jan	3.4	4.1	.
Drip, 31 Jan	3.5	4.3	.
Pr > F			
System	0.8852	0.7115	.
Block	0.0356	0.7602	.
Harvest	0.0050	0.0001	.
System*Harvest	0.9065	0.4305	.

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TABLE III

Effect of irrigation system and harvest date and the interaction between these factors on 'Songold' plum blush colour (chart values) in 2001-2002. Analysis of variance was performed for a two-way interaction.

	After ripening
Micro, 23 Jan	5.8
Micro, 25 Jan	4.6
Micro, 27 Jan	4.6
Micro, 29 Jan	4.6
Micro, 31 Jan	5.9
Drip, 23 Jan	5.8
Drip, 25 Jan	4.6
Drip, 27 Jan	4.7
Drip, 29 Jan	4.4
Drip, 31 Jan	5.9
Pr > F	
System	0.8853
Block	0.2284
Harvest	0.0001
System*Harvest	0.7300

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TABLE IV

Effect of irrigation system, soil drying treatment (2000-2001 only), harvest date and the interaction between these factors on 'Songold' plum firmness (kg). Analysis of variance was performed for a three-way interaction in 2000-2001 and a two-way interaction in 2001-2002. Refer to Figure 3 for 2000-2001 results.

	At harvest	After storage	After ripening
Pr > F		**2000-2001**	
System	0.0001	0.0001	0.0001
Soil drying	0.7535	0.0001	0.0001
Block	0.0001	0.0001	0.0001
Harvest	0.0001	0.0001	0.0001
System*Soil drying	0.0707	0.0024	0.0001
System*Harvest	0.0007	0.9603	0.0001
Soil drying*Harvest	0.0001	0.6948	0.0001
System*Soil drying*Harvest	0.0022	0.3431	0.0299
		2001-2002	
Micro, 23 Jan	7.0	3.0	2.7
Micro, 25 Jan	7.0	3.4	2.3
Micro, 27 Jan	6.6	3.0	2.2
Micro, 29 Jan	6.5	4.1	1.7
Micro, 31 Jan	6.2	2.3	2.2
Drip, 23 Jan	7.7	4.3	2.2
Drip, 25 Jan	7.2	4.6	2.4
Drip, 27 Jan	6.6	4.6	2.2
Drip, 29 Jan	6.5	4.0	1.6
Drip, 31 Jan	5.9	2.9	2.2
Pr > F			
System	0.3014	0.0001	0.1727
Block	0.6648	0.1203	0.2081
Harvest	0.0001	0.0001	0.0001
System*Harvest	0.1350	0.0017	0.0290

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TABLE V

Effect of irrigation system, soil drying treatment (2000-2001 only), harvest date and the interaction between these factors on 'Songold' plum total soluble solid content (%). Analysis of variance was performed for a three-way interaction in 2000-2001 and a two-way interaction in 2001-2002. Refer to Figure 4 for 2000-2001 results.

	At harvest	After storage	After ripening
Pr > F		**2000-2001**	
System	0.0001	0.0001	0.0001
Soil drying	0.0002	0.0001	0.0016
Block	0.0001	0.0001	0.0001
Harvest	0.0009	0.0001	0.3578
System*Soil drying	0.4821	0.0015	0.1035
System*Harvest	0.3672	0.1928	0.9958
Soil drying*Harvest	0.4280	0.8866	0.9049
System*Soil drying*Harvest	0.9140	0.6571	0.8741
		2001-2002	
Micro, 23 Jan	13.0	13.1	12.6
Micro, 25 Jan	13.5	13.3	13.1
Micro, 27 Jan	13.6	13.2	12.9
Micro, 29 Jan	13.7	13.1	13.1
Micro, 31 Jan	14.0	14.0	13.4
Drip, 23 Jan	13.0	13.3	13.0
Drip, 25 Jan	14.0	13.7	14.6
Drip, 27 Jan	14.6	13.4	14.3
Drip, 29 Jan	14.0	13.3	13.0
Drip, 31 Jan	13.9	14.0	13.7
Pr > F			
System	0.0826	0.2465	0.0001
Block	0.0353	0.2761	0.6559
Harvest	0.0099	0.0050	0.0001
System*Harvest	0.3995	0.9172	0.0014

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TABLE VI

Effect of irrigation system, soil drying treatment (2000-2001 only), harvest date and the interaction between these factors on 'Songold' plum titratable acidity (% malic acid). Analysis of variance was performed for a three-way interaction in 2000-2001 and a two-way interaction in 2001-2002. Refer to Figure 5 for 2000-2001 results.

	At harvest	After storage	After ripening
Pr > F		**2000-2001**	
System	0.7487	0.0119	0.0001
Soil drying	0.1226	0.7297	0.0001
Block	0.0240	0.0021	0.0007
Harvest	0.0903	0.0001	0.0001
System*Soil drying	0.6039	0.3835	0.8342
System*Harvest	0.4245	0.0790	0.4657
Soil drying*Harvest	0.0639	0.7083	0.6048
System*Soil drying*Harvest	0.2551	0.8863	0.4648
		2001-2002	
Micro, 23 Jan	1.9	1.4	1.2
Micro, 25 Jan	1.9	1.3	1.2
Micro, 27 Jan	1.7	1.4	1.2
Micro, 29 Jan	1.8	1.3	1.2
Micro, 31 Jan	1.8	1.3	1.2
Drip, 23 Jan	2.1	1.4	1.4
Drip, 25 Jan	2.0	1.4	1.4
Drip, 27 Jan	1.7	1.6	1.4
Drip, 29 Jan	1.9	1.6	1.4
Drip, 31 Jan	1.9	1.5	1.4
Pr > F			
System	0.0001	0.0001	0.0001
Block	0.0021	0.2343	0.0368
Harvest	0.0001	0.0001	0.8350
System*Harvest	0.1236	0.0003	0.9892

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TABLE VII

Effect of irrigation system, soil drying treatment (2000-2001 only), harvest date and the interaction between these factors on 'Songold' plum macronutrient concentration. Analysis of variance was performed for a three-way interaction in 2000-2001 and a two-way interaction in 2001-2002. Refer to Figure 6 for 2000-2001 results.

	P	K	Ca	Mg
Pr > F		**2000-2001**		
System	0.0001	0.0053	0.1163	0.0001
Soil drying	0.9958	0.1841	0.0674	0.0572
Block	0.4967	0.2787	0.0716	0.7696
Harvest	0.0027	0.0001	0.0053	0.0002
System*Soil drying	0.0186	0.9310	0.7807	0.5648
System*Harvest	0.0735	0.0062	0.0025	0.1463
Soil drying*Harvest	0.0391	0.1780	0.0979	0.2887
System*Soil drying*Harvest	0.1803	0.0562	0.9414	0.6149
		2001-2002		
		mg 100g^{-1} dry mass		
Micro, 23 Jan	.	.	.	.
Micro, 25 Jan	129.7	1136	23.5	51.0
Micro, 27 Jan	125.7	1094	22.6	50.8
Micro, 29 Jan	101.9	983	18.7	43.0
Micro, 31 Jan	119.3	1070	20.0	46.7
Drip, 23 Jan	.	.	.	.
Drip, 25 Jan	140.6	1085	24.8	48.5
Drip, 27 Jan	115.3	1112	23.1	48.5
Drip, 29 Jan	110.5	1019	18.2	45.3
Drip, 31 Jan	98.3	987	20.5	44.7
Pr > F				
System	0.0001	0.0370	0.0001	0.0001
Block	0.0001	0.0040	0.0001	0.0001
Harvest	0.0001	0.0001	0.0001	0.0001
System*Harvest	0.0001	0.0001	0.0001	0.0001

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TABLE VIII

Effect of irrigation system, soil drying treatment (2000-2001 only), harvest date and the interaction between these factors on 'Songold' plum diameter (mm). Analysis of variance was performed for a three-way interaction in 2000-2001 and a two-way interaction in 2001-2002. Refer to Figures 7 and 8 for 2000-2001 results.

	Na	Mn	Fe	Cu	Zn	B
Pr > F			**2000-2001**			
System	0.0005	0.0035	0.4110	0.5138	0.6445	0.6800
Soil drying	0.0659	0.0180	0.4043	0.2084	0.2518	0.5523
Block	0.0048	0.7157	0.3527	0.6331	0.8604	0.5523
Harvest	0.0535	0.1823	0.0332	0.5682	0.4158	0.0115
System*Soil drying	0.6575	0.4687	0.6723	0.6411	0.5989	0.0105
System*Harvest	0.5073	0.1973	0.4561	0.6367	0.7358	0.5508
Soil drying*Harvest	0.1254	0.2224	0.5350	0.5029	0.3993	0.6715
System*Soil drying*Harvest	0.0624	0.3313	0.8348	0.8495	0.9350	0.9731
			2001-2002			
			mg kg^{-1} dry mass			
Micro, 23 Jan	.	.	.	.	.	.
Micro, 25 Jan	26.7	8.4	14.5	15.6	27.0	35.3
Micro, 27 Jan	28.3	8.0	9.2	3.5	53.9	34.5
Micro, 29 Jan	23.8	7.9	13.1	7.4	21.7	32.0
Micro, 31 Jan	28.9	7.1	17.8	1.2	39.5	35.7
Drip, 23 Jan	.	.	.	.	.	.
Drip, 25 Jan	31.7	9.6	13.4	8.8	24.5	39.4
Drip, 27 Jan	32.9	8.5	8.9	3.4	34.5	35.4
Drip, 29 Jan	27.0	9.4	15.5	6.9	30.6	33.2
Drip, 31 Jan	42.1	9.5	18.9	5.6	59.3	40.2
Pr > F						
System	0.1404	0.1053	0.3258	0.3669	0.5498	0.7510
Block	0.2104	0.0040	0.0671	0.7163	0.6075	0.0026
Harvest	0.0788	0.0453	0.0031	0.0764	0.1190	0.0670
System*Harvest	0.0136	0.0076	0.0042	0.1809	0.4619	0.1035

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CAPTIONS TO FIGURES

FIG. 1: Effects of irrigation system, soil drying treatment and harvest date on fruit diameter at (a) harvest, (b) after 18 days of dual temperature storage and (c) after 7 days of ripening at 15°C in 2000-2001. Where Ms = micro irrigation system not subjected to soil drying; MS = micro irrigation system with irrigation terminated on 26 January 2001; Ds = drip irrigation system not subjected to soil drying; DS = drip irrigation system with irrigation terminated on 31 January 2001. Values are means of replications (n=4). Refer to Table I for statistical results.

FIG. 2: Effects of irrigation system, soil drying treatment and harvest date on fruit ground colour (chart values 0-5, where 0=green and 5=golden yellow) at (a) harvest and (b) after 18 days of dual temperature storage in 2000-2001. Abbreviations as for Figure 1. Values are means of replications (n=4). Refer to Table II for statistical results.

FIG. 3: Effects of irrigation system, soil drying treatment and harvest date on fruit firmness at (a) harvest, (b) after 18 days of dual temperature storage and (c) after 7 days of ripening at 15°C in 2000-2001. Abbreviations as for Figure 1. Values are means of replications (n=4). Refer to Table IV for statistical results.

FIG. 4: Effects of irrigation system, soil drying treatment and harvest date on percentage total soluble solid content at (a) harvest, (b) after 18 days of dual temperature storage and (c) after 7 days of ripening at 15°C in 2000-2001. Abbreviations as for Figure 1. Values are means of replications (n=4). Refer to Table V for statistical results.

FIG. 5: Effects of irrigation system, soil drying treatment and harvest date on titratable acidity at (a) harvest, (b) after 18 days of dual temperature storage and (c) after 7 days of ripening at 15°C in 2000-2001. Abbreviations as for Figure 1. Values are means of replications (n=4). Refer to Table VI for statistical results.

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FIG. 6: Effects of irrigation system, soil drying treatment and harvest date on the fruit concentration (mg $100g^{-1}$ dry mass) of (a) phosphorus, (b) potassium, (c) calcium, and (d) magnesium at harvest in 2000-2001. Abbreviations as for Figure 1. Value are means of replications (n=4). Refer to Table VII for statistical results.

FIG. 7: Effects of irrigation system, soil drying treatment and harvest date on the fruit concentration (mg kg^{-1} dry mass) of (a) sodium, (b) manganese, and (c) iron at harvest in 2000-2001. Abbreviations as for Figure 1. Value are means of replications (n=4). Refer to Table VIII for statistical results.

FIG. 8: Effects of irrigation system, soil drying treatment and harvest date on the fruit concentration (mg kg^{-1} dry mass) of (a) copper, (b) zinc, and (c) boron at harvest in 2000-2001. Abbreviations as for Figure 1. Value are means of replications (n=4). Refer to Table VIII for statistical results.

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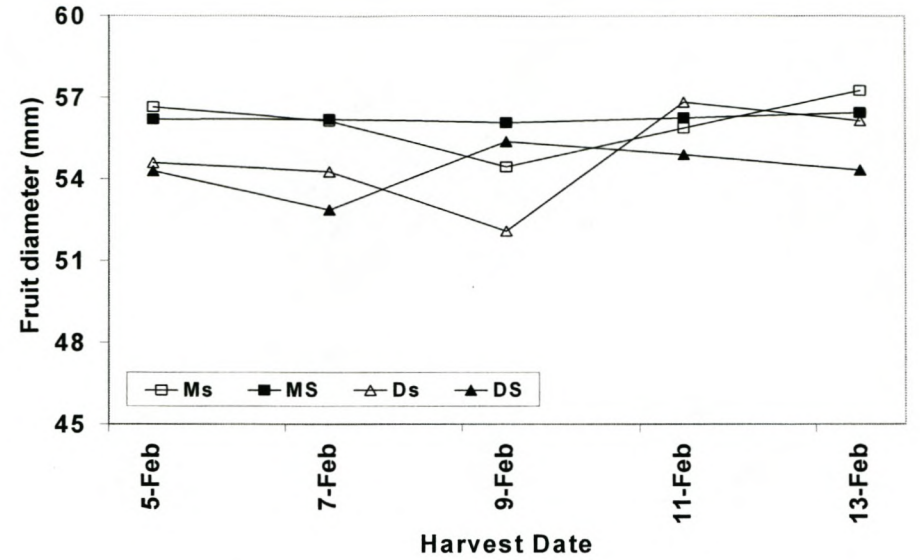

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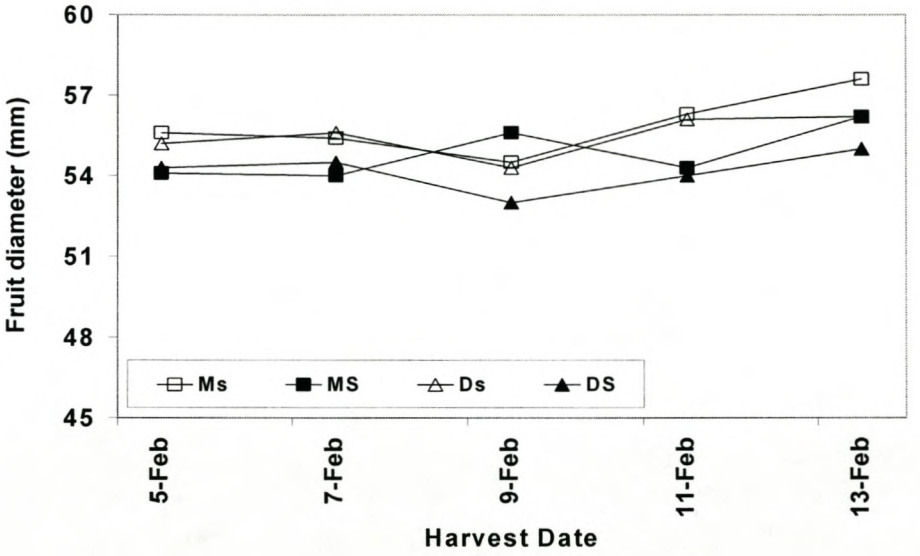

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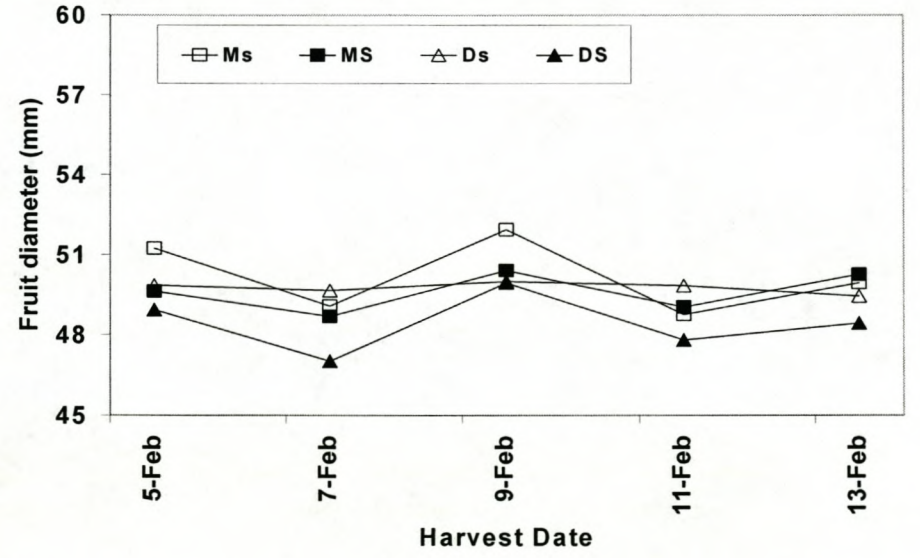

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FIG. 1

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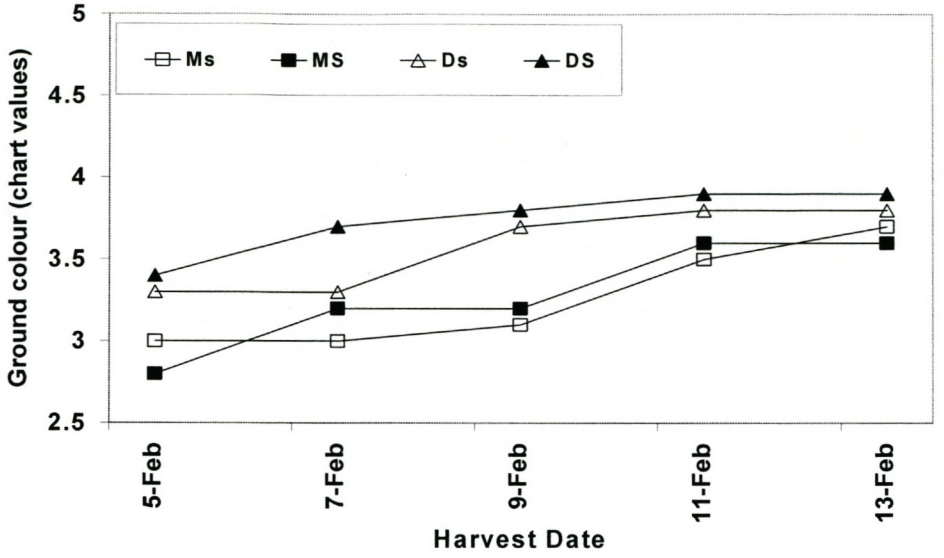

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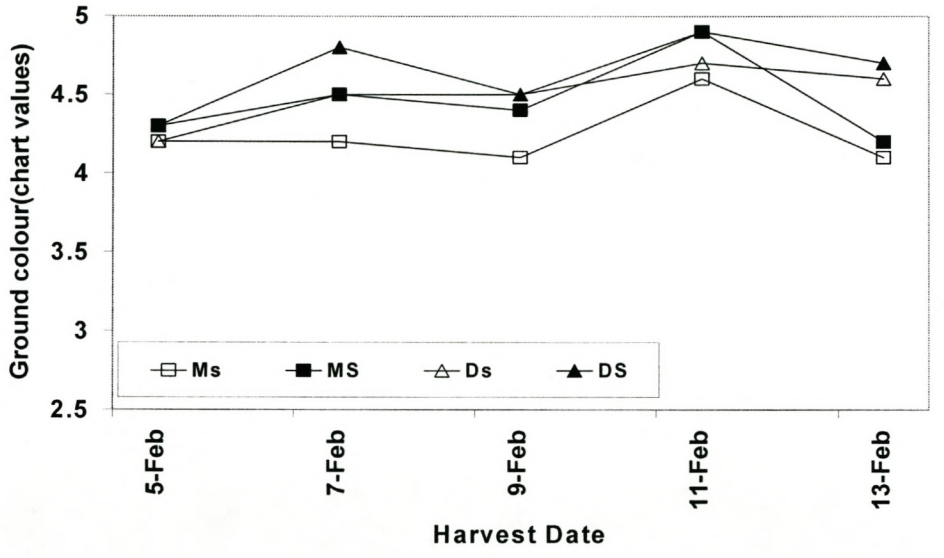

(b)

FIG. 2

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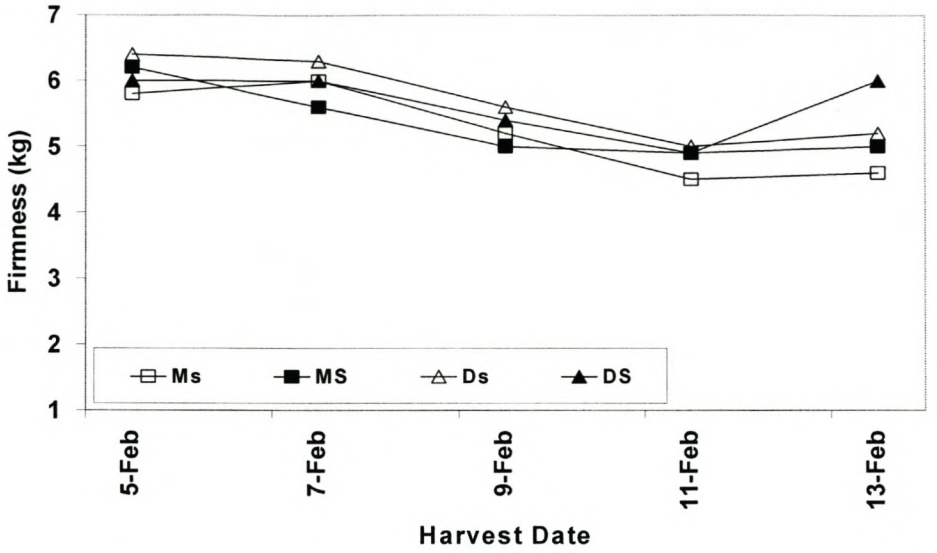

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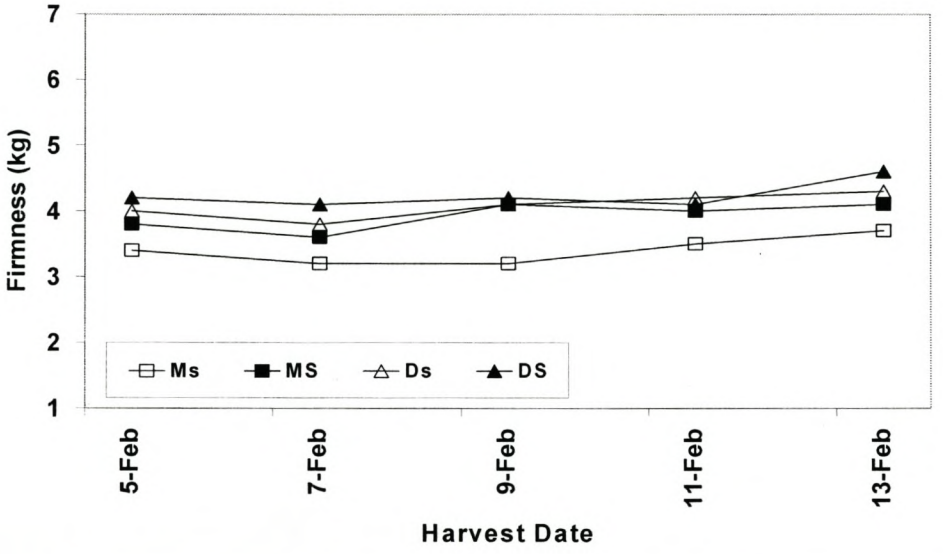

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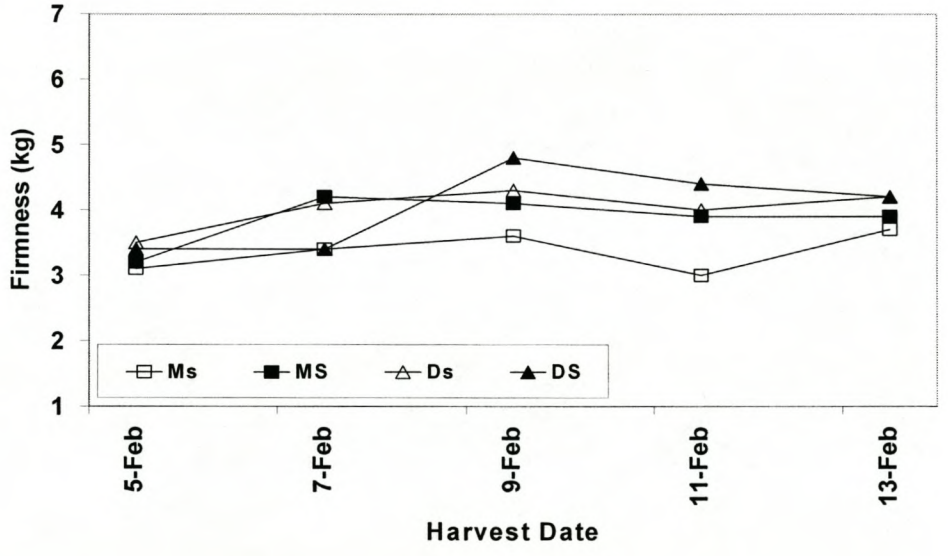

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FIG. 3

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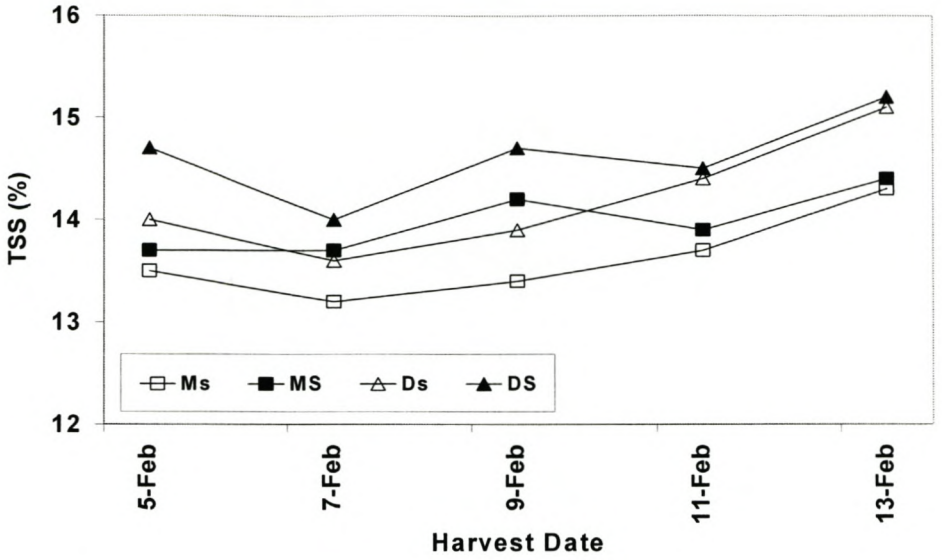

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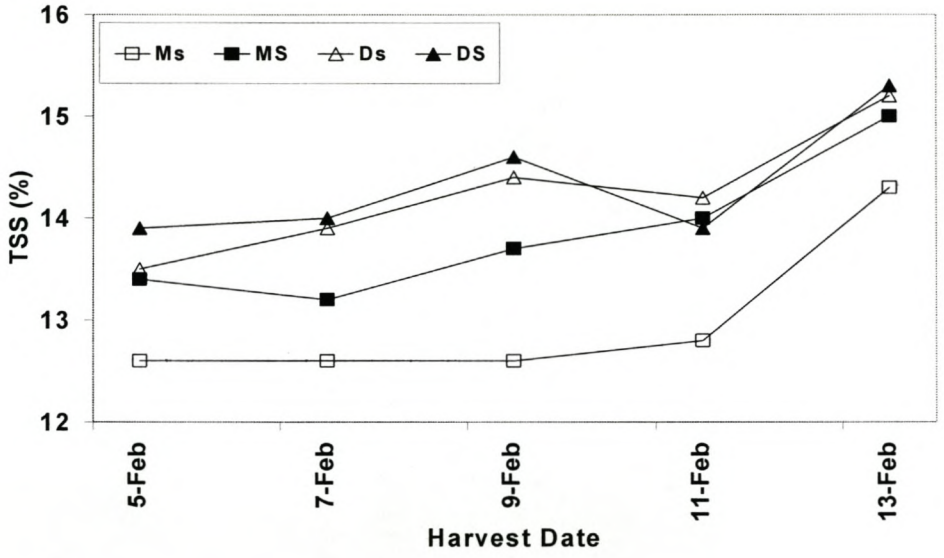

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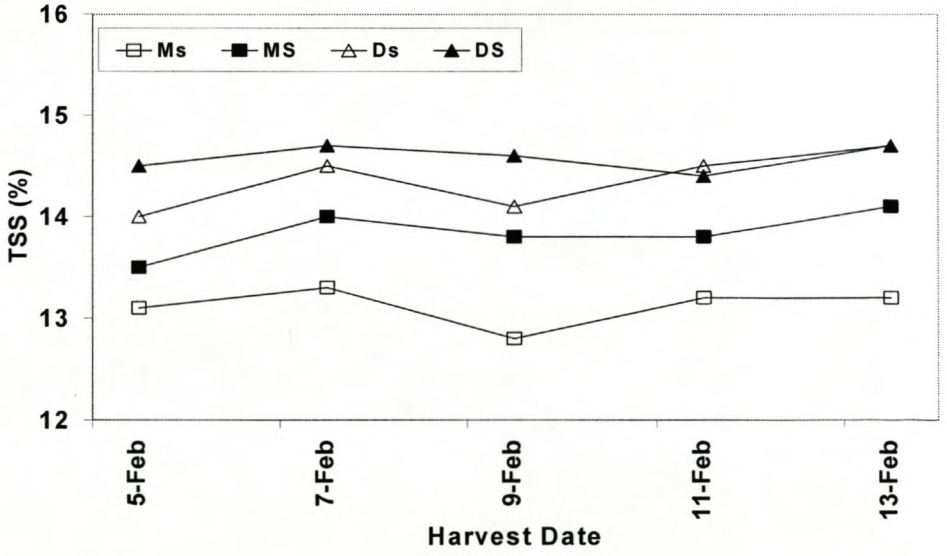

FIG. 4

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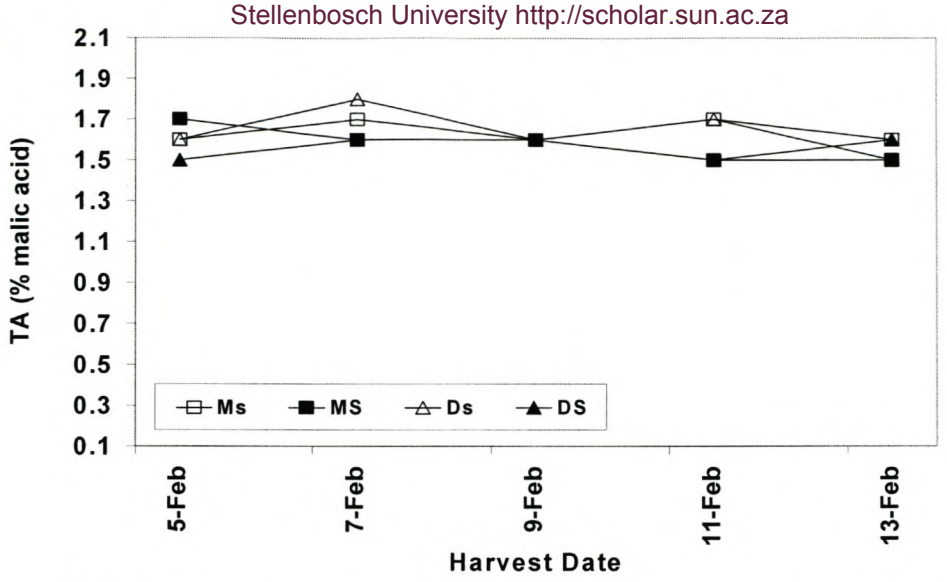

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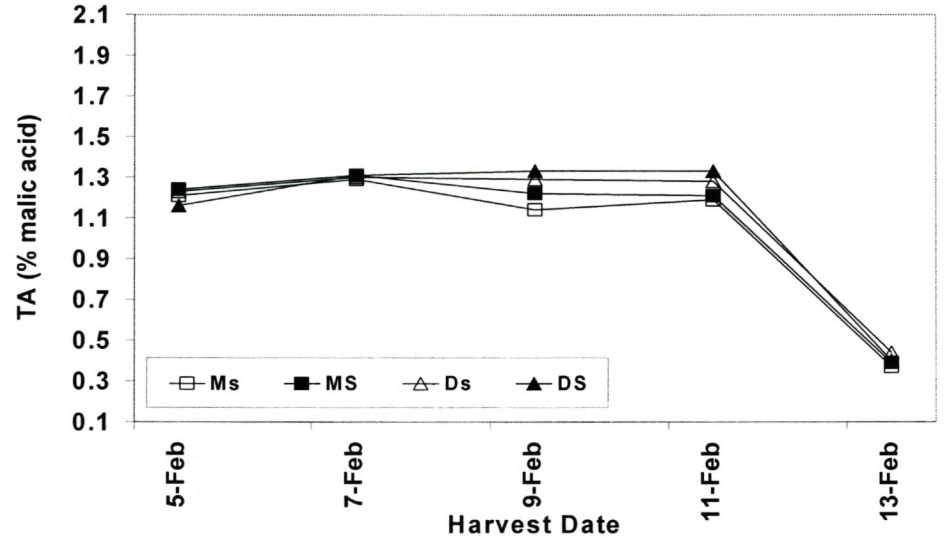

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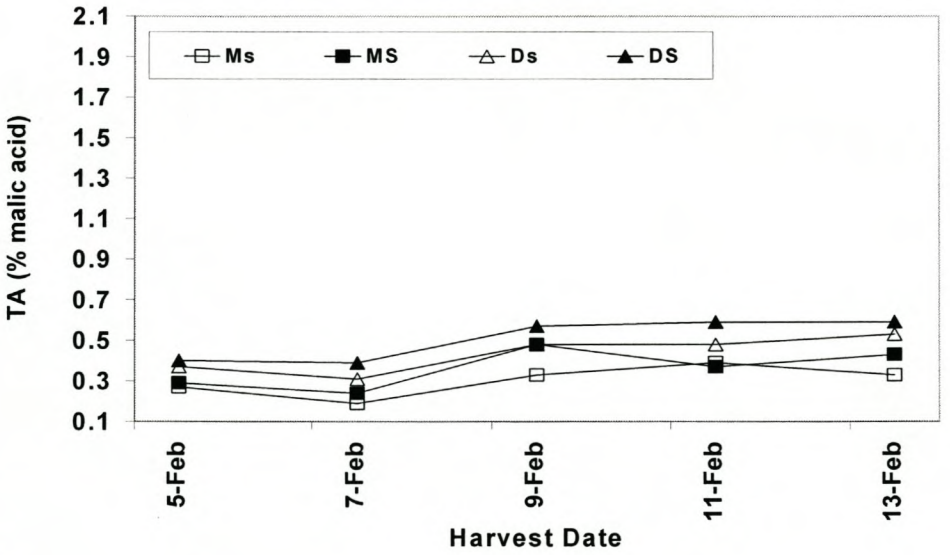

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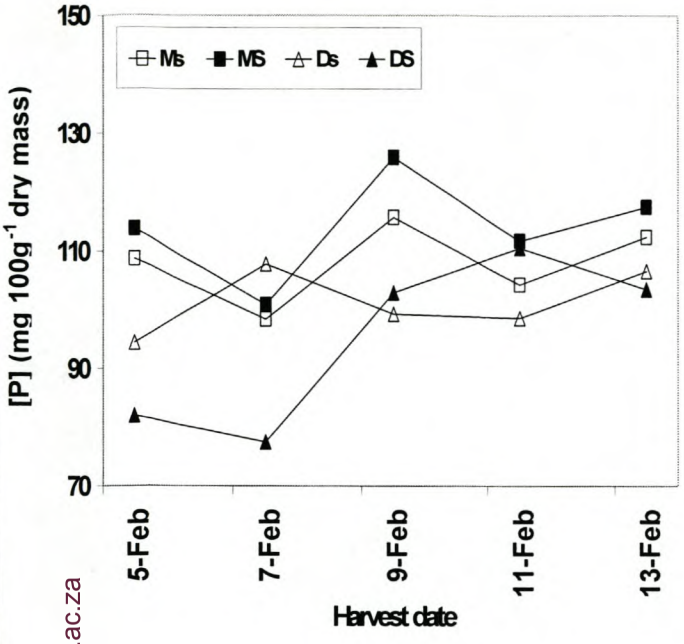
FIG. 5



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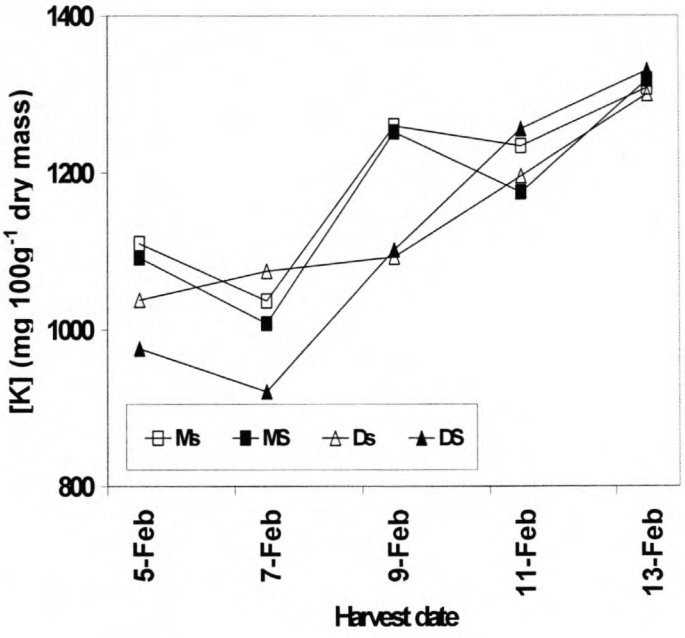

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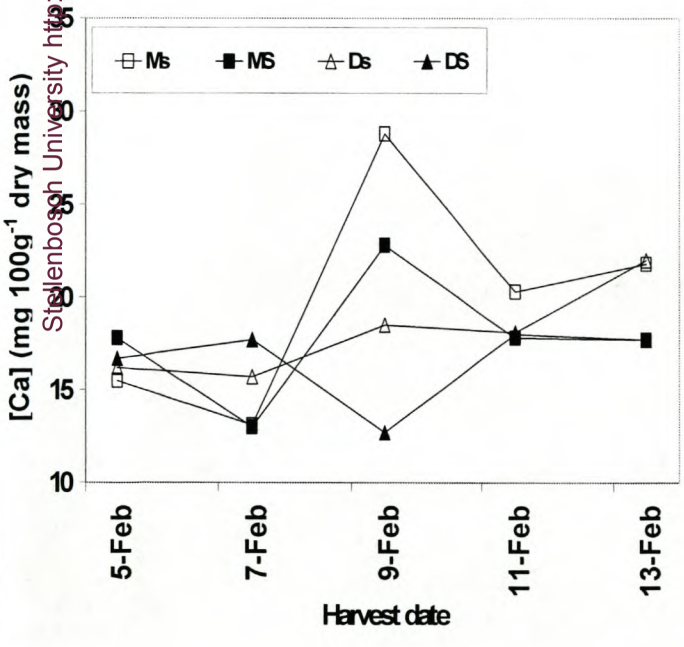

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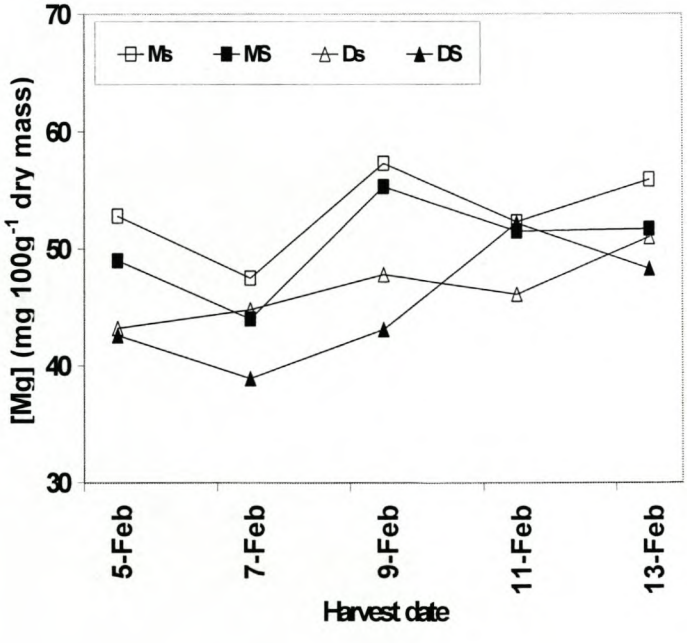

(d)

FIG. 6

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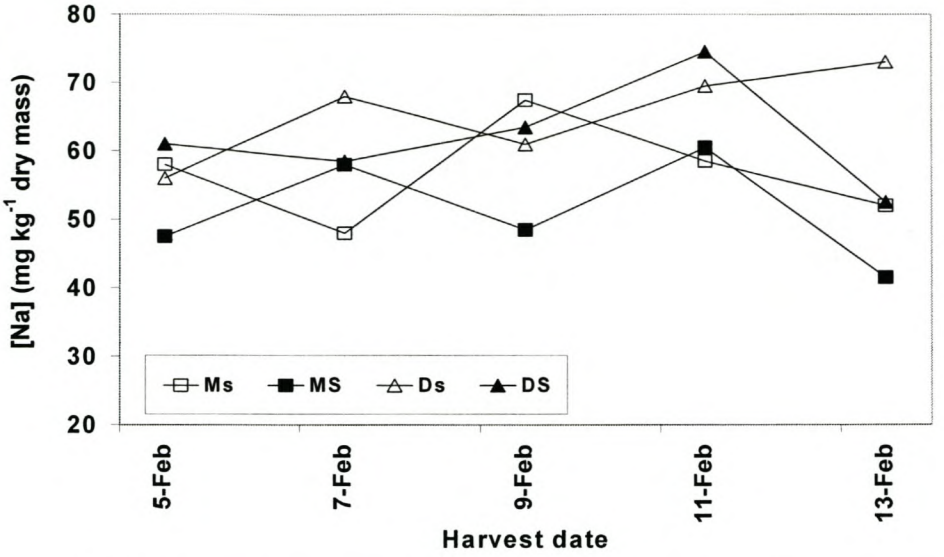

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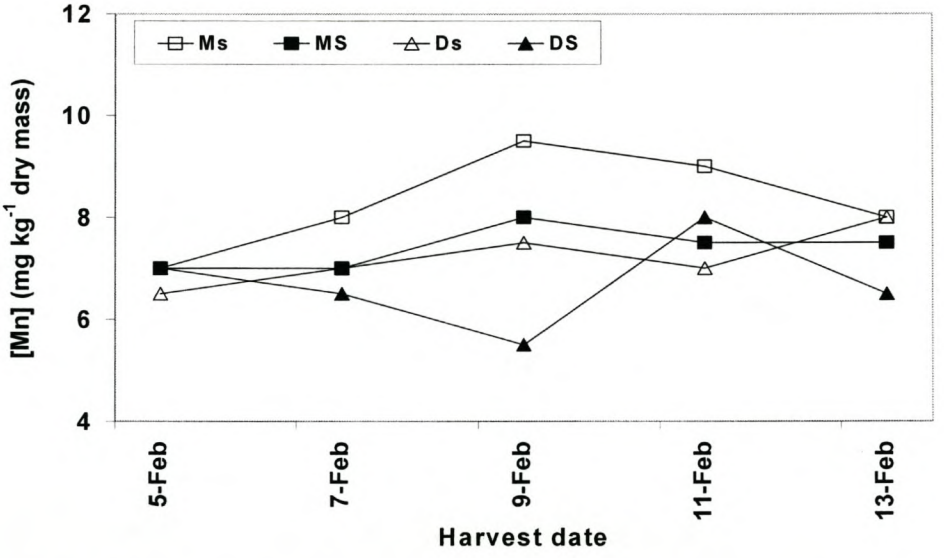

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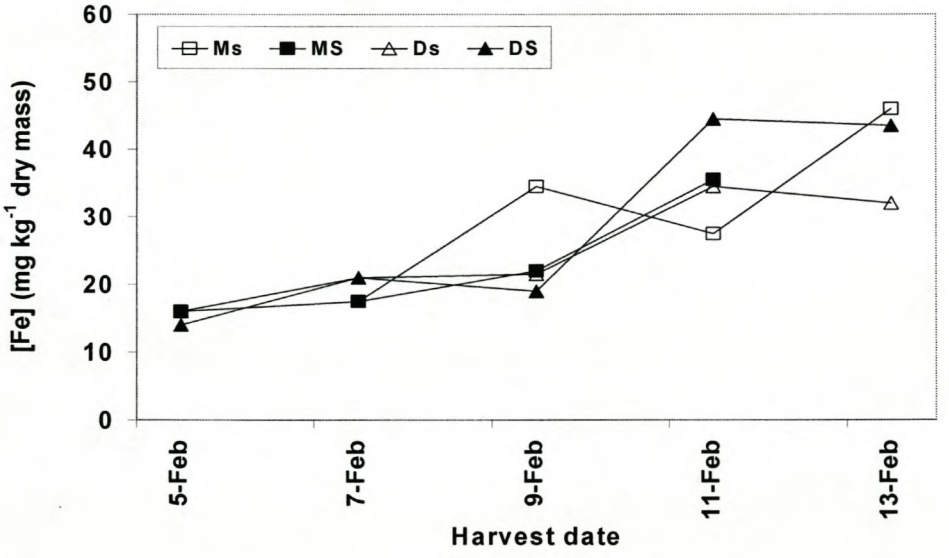

(c)

FIG. 7

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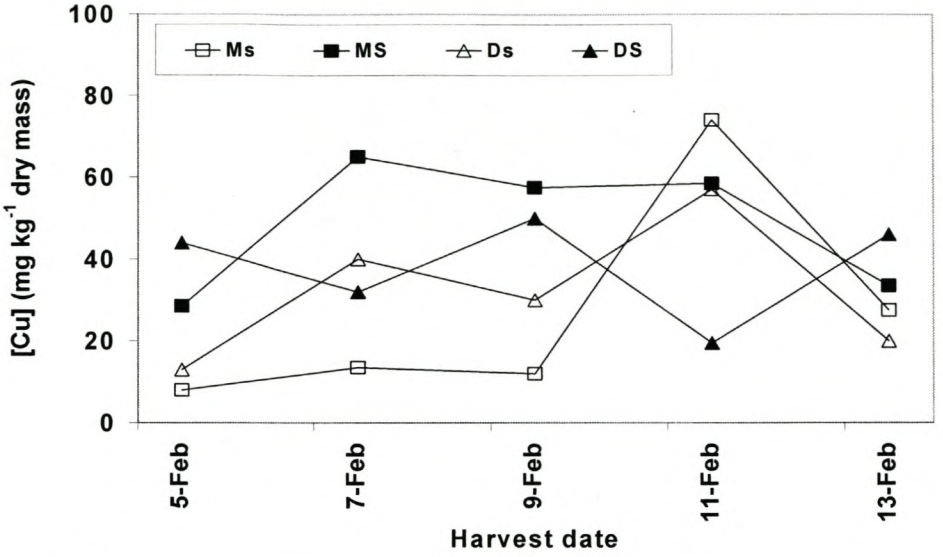
(a)



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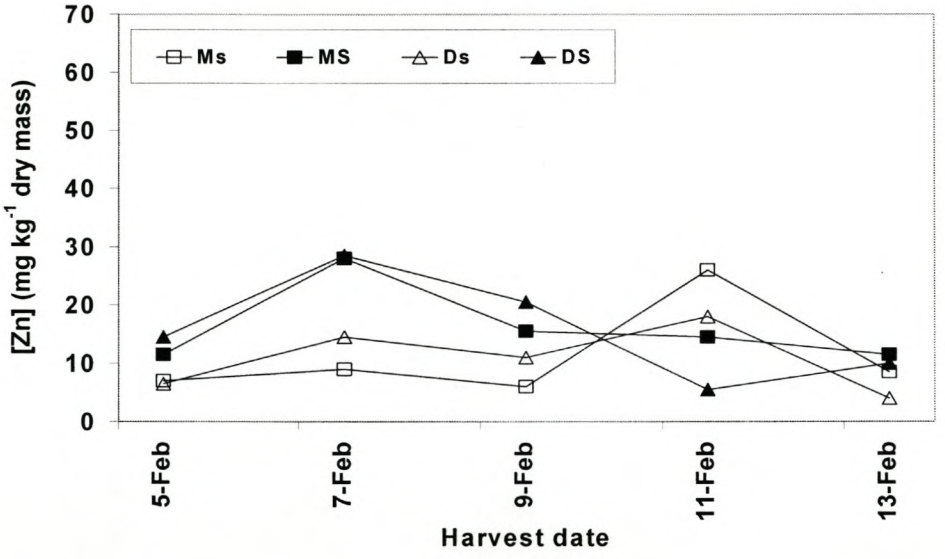

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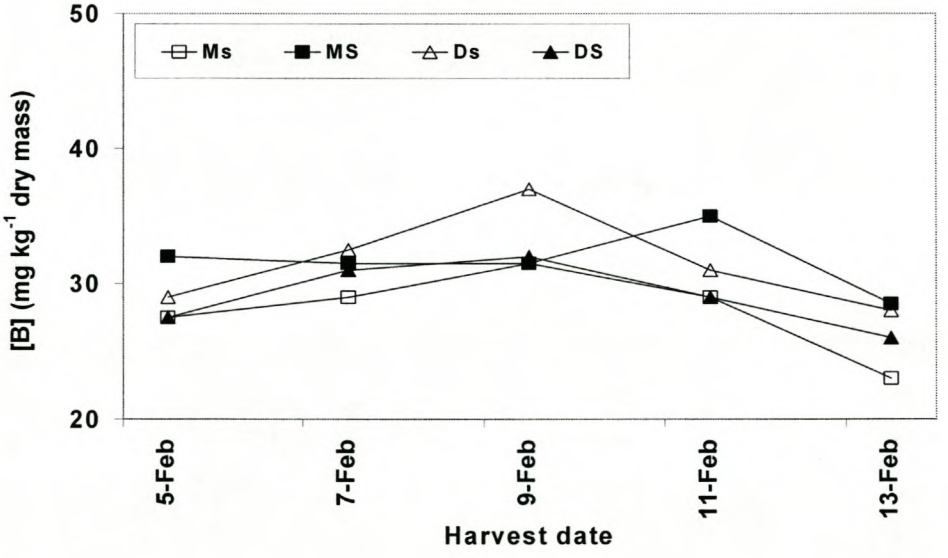

FIG. 8