Ripening patterns, ethylene production and improvement of quality of plums (*Prunus salicina* Lindl.)

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.

Signature Date

SUMMARY

Ripening patterns, ethylene production and improvement of quality of plums (*Prunus salicina* Lindl.)

Internal breakdown (internal browning – IB and gel breakdown – GB), over maturity and immaturity are the main factors adversely affecting the quality of exported South African plums. Maturity problems occur when plums are strip harvested, i.e., all the fruit in a block or orchard are harvested once, when the majority of the fruit are at optimum maturity. This results in both overmature and immature fruit being harvested and contributes to a high percentage of fruit being rejected for export. In general, internal browning occurs when plums are exported under a single low temperature regime and gel breakdown occurs when plums are exported under a dual temperature regime. However, GB can also occur at harvest in fruit that are very ripe and may occur at single low temperatures, where it would be masked by IB. While it is known that some cultivars, like 'Angeleno', can withstand a single temperature regime, others cannot. To the best of our knowledge, the reason for this difference is not understood.

Many factors affect the quality of plums, including light incidence in the canopy, mineral nutrition and harvest maturity. Plums that were grown on high density training systems such as a V– or spindle system yielded consistently high quality fruit with low incidences of gel breakdown. This was in contrast to earlier findings where low-density training systems produced high levels of GB, especially in the lower part of the tree canopy. Branches that were shaded with 80% shade netting yielded fruit with high levels of GB, indicating that the main effect of improved canopy structure on quality was improved light management.

A postharvest boron application on 'Songold' plums prior to storage had no effect on the incidence of internal breakdown in the fruit, but did damage the cuticle, resulting in severe shrivel. However, internal conductivity and firmness measurements indicated that there was some effect of the boron on cell membranes. A more thorough investigation of pre- and postharvest application of boron is recommended in order to determine whether there could be a positive effect of boron in improving fruit quality in plums.

Four cultivars of plums ('Pioneer', 'Sapphire', 'Songold' and 'Angeleno') were harvested throughout, and extending beyond, the commercial harvesting period. In all cultivars, the drop in firmness between harvests was not as great as expected and the later harvested fruit were of a

similar, if not superior, quality as compared to the earlier harvested fruit. Later harvested plums tended to have higher TSS and better colour development. Contrary to what was expected, later harvested fruit did not have more internal disorders than earlier harvested fruit. This indicates the importance of harvesting at optimum maturity. 'Angeleno' plums had no internal disorders, even after five weeks of cold storage at a single low temperature.

'Pioneer' and 'Sapphire' plums were classified as climacteric and 'Songold' and 'Angeleno' were classified as suppressed climacteric based on ethylene production. The climacteric plums respired and produced ethylene at a higher rate than the suppressed climacteric plums. Climacteric plums ripened faster during shelf life than suppressed climacteric plums. Furthermore, while climacteric plums did not need a cold storage period prior to ripening, suppressed climacteric plums needed a cold storage period in order to ripen normally. The longer the cold storage period prior to transfer to higher temperatures, the faster the plums ripened and the higher the ethylene production at the higher temperature. The suppressed climacteric genotype could possibly be incorporated into plum breeding programs in order to extend the storage period and shelf life of new plum cultivars.

The long storage times required to ship plums from South Africa to the export markets has necessitated research on postharvest physiology and quality of this fruit. The use of the climacteric and suppressed climacteric system to classify fruit is expected to assist in understanding the different physiological responses of the cultivars and assist in developing handling protocols. Preharvest factors, particularly light and nutrition, also play a role in postharvest quality.

OPSOMMING

Rypwordingspatrone, etileen produksie en kwaliteitsverbetering in pruime (*Prunus salicina* Lindl.)

Interne verval (interne verbruining en gelverval), oorrypheid en onryp vrugte, is die hoof faktore wat die uitvoer van Suid Afrikaanse pruime negatief beïnvloed. Rypheidsprobleme ontstaan wanneer pruime gestroop-oes word, met ander woorde, al die vrugte in 'n blok of boord word geoes wanneer die meerderheid vrugte optimum rypheid bereik het. As gevolg hiervan word 'n groot persentasie vrugte vir uitvoer afgekeur, omdat hulle te ryp of nie ryp genoeg is nie. Oor die algemeen vind interne verbruining plaas wanneer vrugte onder 'n enkel lae temperatuur uitgevoer word en gelvervel vind plaas wanneer vrugte onder 'n dubbele temperatuur regime vervoer word. Gel verval kan egter in baie ryp vrugte by oes voorkom en mag by enkel lae temperature voorkom ,waar dit deur interne verbruining gemaskeer sal word. Kultivars soos 'Angeleno' kan onder enkel lae temperatuur uitgevoer word sonder interne probleme, terwyl ander pruimkultivars nie so uitgevoer kan word nie. So ver ons weet, word die rede hiervoor nie goed verstaan nie.

Daar is baie faktore wat die kwaliteit van pruime beïnvloed, onder meer lighuishouding, minerale voeding en die rypheid waarby die pruime geoes word. Pruime wat in hoë-digtheid sisteme soos 'n V– of "spindle" groei het goeie kwaliteit vrugte met 'n lae persentasie gelverval gelewer. Dit is in teenstelling met vroeër bevindinge, waar vrugte van lae digtheid boorde hoë persentasies geverval gelewer het, veral in die onderste gedeeltes van die boom. Takke wat met 80% skadunet bedek is het hoër persentasies gelverval as die kontrole gelewer, wat aandui dat die hoof effek van die verbeterde boom struktuur op kwaliteit, verbeterde lighuishouding was.

'n Na-oes aanwending van boor op 'Songold' pruime het geen effek op die voorkoms van gelverval gehad nie, maar het die kutikula beskadig en tot hoë persentasies verrimpeling gelei. Fermheid en interne weerstand lesings het egter getoon dat daar wel 'n effek van die boor op die selmembrane en selwande was. 'n Meer omvattende ondersoek van voor- en na-oes aanwending van boor word aanbeveel om vas te stel of daar wel 'n positiewe effek van boor in die verbetering van pruim kwaliteit is.

Vier pruim kultivars, ('Pioneer', 'Sapphire', 'Songold' en 'Angeleno'), is gedurende, sowel as later as die kommersiële oesperiode geoes. In al die kultivars was die afname in fermheid kleiner as wat verwag is, en vrugte wat later geoes is het dieselfde, en soms beter, kwaliteit as die vrugte wat

vroeër geoes is gehad. Pruime wat later geoes is het beter kleur en gewoonlik hoër suikers gehad. In teenstelling met wat verwag is, het pruime wat later geoes is nie meer interne verval gehad as die pruime wat vroeër geoes is nie. Dit dui die belangrikheid van optimale oesrypheid aan. 'Angeleno' het geen interne verval gehad nie, selfs na vyf weke opberging by -0.5°C.

'Pioneer' en 'Sapphire' pruime is as klimakteries en 'Songold' en 'Angeleno' as onderdrukte klimakteries geklassifiseer, gebaseer op etileen produksie. Die klimakteriese pruime het teen 'n hoër tempo gerespireer en etileen geproduseer as die onderdrukte klimakteriese pruime. Gedurende raklewe het klimakteriese vrugte vinniger as onderdrukte klimakteriese vrugte ryp geword. Verder, terwyl klimakteriese pruime nie opbgerging by 'n lae temperatuur nodig gehad het nie, het onderdrukte klimakteriese vrugte wel opberging by 'n lae temperatuur nodig gehad om normaal ryp te word. Hoe langer die koel opbergingsperiode was, hoe vinniger het die pruime ryp geword by raklewe en hoe hoër was hulle etileen produksie. Die onderdrukte klimakteriese genotipe kan moontlik in teelprogramme geïnkorporeer word om kultivars met verlengde opbergings- en raklewe te teel.

Die lang vervoer tye wat benodig word om Suid Afrikaanse pruime by die uitvoer markte te kry het dit nodig gemaak om navorsing oor die na-oes fisiologie en kwaliteit van pruime te doen. Die klassifisering van pruime as klimakteries of onderdrukte klimakteries kan ons in staat stel om die verskillende fisiologiese reaksies van die kultivars te verstaan en om hanterings prosedures te ontwikkel. Voor-oes faktore, veral lighuishouding en mineraalvoeding speel ook 'n rol in na-oes kwaliteit van pruime.

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CONTENTS

1. Literature review

1.1. Introduction

South African plums, particularly those produced in the Western Cape, often receive inadequate winter chilling. This results in protracted blossoming, due to the failure of the tree to overcome dormancy. As a result, in the most severe cases, one could find some fruit on the tree that ripen up to two months later than others. This leads to plums of mixed maturities being harvested at any one time. Difficulties related to assessing harvest maturity, particularly when using ground colour, aggravate this problem. For example, the maturity of plums with a dark purple to black colour at harvest is hard to determine, as the colour development is complete before the plums are ripe.

Amongst the most important factors affecting consumer acceptability of plums are high total soluble solids (TSS) content, although acidity (TA – titratable malic acid), TSS/TA ratio, and phenolic content are also important as they affect flavour (Crisosto *et al.*, 2001). Consumers want sweet, flavoursome fruit (McGlasson, 2001), and in general, the demand is for more mature fruit. High rates of flesh softening and susceptibility to internal breakdown are the main limitations of the market life of many fruit, including plums (Plich, 1999; Brummel & Harpster, 2001). These problems can be exacerbated if plums are harvested overmature. Growers need to be able to determine the optimum stage of maturity at which to harvest their plums. This is especially difficult in cultivars such as 'Songold' and 'Angeleno' where there is either very little colour development or complete colour development prior to harvest. Consequently, these cultivars are sometimes strip harvested (meaning all the plums in a block are harvested in one picking session, when the majority of the plums are at optimum harvest maturity) or they are harvested according to size. Many plum cultivars have the same skin colour at harvest, but are not the same maturity. This results in a low pack out, with many plums being either immature or overmature.

Plums are climacteric fruit, meaning there is a continuous decrease in respiration rate followed by a sharp increase that is accompanied by autocatalytic ethylene production in the fruit (Sekse, 1988). Recently, plums have been further classified as either climacteric or suppressed climacteric, based on ethylene production. A suppressed climacteric cultivar is one that typically produces 15 – 500 times less ethylene than a climacteric cultivar (Abdi *et al.*, 1998). Preliminary results seem to indicate that suppressed climacteric plums are better able to withstand cold storage. Furthermore, they respire at a slower rate and are therefore easier and cheaper to maintain at optimum temperatures. Classifying plums in this way and relating these classes to ripening patterns could be

a way of determining how new varieties will ripen and react to different storage regimes. Abdi *et al.* (1997b) recommended incorporating the suppressed climacteric character into plum breeding programs to extend storage and shelf life.

Rate of ethylene production and respiration are not the only factors that affect quality in plums. Preharvest factors, e.g. nutrition, irrigation, light management and cultural practices, postharvest factors, such as storage regime and also harvest maturity, determine the final quality of the product.

1.2. Fruit ripening

The main role of ripening is to render fruit attractive and palatable to a variety of seed dispersing organisms (Giovannoni, 2001). As a result, ripening also imparts value to fruit as agricultural commodities, as they become more flavoursome, with improved colour and texture. Changes during ripening generally include modification of cell wall ultrastructure and texture, alteration of membrane condition and function, conversion of starch to sugars, increased susceptibility to post-harvest pathogens, alterations in pigment biosynthesis and accumulation of flavour and aromatic volatiles (Harker & Maindonald, 1994; Giovannoni, 2001). Chlorophyll degrades and anthocyanins and carotenoids increase, resulting in colour development from green to reds and yellows (Tucker, 1993). Plums differ from many other fruits in that conversions from starch to sugar are not associated with ripening. Fructose is the predominant sugar, followed by glucose, sorbitol and sucrose. Malic acid is the most common organic acid in plums (Taylor, 1993d). In general, acids decline during ripening, due to their utilization as respiratory substrates (Tucker, 1993).

During normal ripening, pectin methylesterase (PME) de-esterifies pectin in the cell wall making it a suitable substrate for polygalaturonase (PG). PG depolymerises and solubilises pectin. These pectin modifying enzymes affect the integrity of the middle lamella, which controls cell-to-cell adhesion and thus influences fruit texture (Brummel & Harpster, 2001). This results in a decline in flesh firmness and a change in texture (Harker & Maindonald, 1994). As a result of softening and increased susceptibility to pathogens of fruit, ripening also results in a decrease in shelf life and a subsequent increase in costs for shipping and storing, in order to keep them saleable (Giovannoni, 2001).

1.2.1. Role of ethylene in fruit ripening

In climacteric fruit, ethylene is necessary for the coordination and completion of ripening

(Giovannoni, 2001). Fruit softening is one of the ripening processes that is most sensitive to ethylene (Lelievre *et al.*, 1997a). Plum fruit treated with 15 ppm ethylene during a five week storage period at 0°C produced lower levels of ethylene after storage and softened more slowly than untreated fruit, possibly because of negative feedback (Dong *et al.*, 2001). Colour changes can be either ethylene dependent or independent depending on the type of pigment involved and the fruit species (Lelievre *et al.*, 1997a). Abdi *et al.* (1998) found the development of skin colour in plums to be an ethylene independent phenomenon, while aroma production was either ethylene dependent or independent, depending on the cultivar. The role of ethylene seems to be that of a catalyst, hastening and co-ordinating pigment production and chlorophyll loss. Volatile production either occurs at the same time as the rise in ethylene production, or later in fruit development (Abdi *et al.*, 1997b).

1.2.2. Climacteric vs. Suppressed climacteric

The term suppressed climacteric was first used by Abdi *et al.* (1997b) to describe plums that typically produce 15-500 times less ethylene than climacteric cultivars. Furthermore, the ethylene is produced later than in climacteric types, towards the latter part of the ripening process. However, they are still classified as climacteric as they show an ethylene peak. These plums also have a reduced respiratory climacteric. The suppressed climacteric phenotype is the result of an impaired ability of the fruit to convert 1-amino-cyclopropane-1-carboxylic acid (ACC) to ethylene to co-ordinate ripening sufficiently. Levels of ACC during fruit development are similar between the two classes, though slightly lower in the suppressed climacteric type. This may be the result of higher levels of ethylene production in the climacteric cultivars as the genes for ACC are upregulated by ethylene. ACC may also be more efficiently converted to malonyl or glutamylamino derivatives in the suppressed-climacteric cultivars (Abdi *et al.*, 1998).

On the tree, fruit growth in the suppressed cultivars 'Shiro' and 'Rubyred' ceased before the development of full colour. In climacteric cultivars 'Gulfruby' and 'Beauty', fruit growth continued after full colour development (Abdi *et al.*, 1997b). However, completion of colour development before completion of growth is not always specific to climacteric cultivars.

Suppressed climacteric cultivars seem unable to synthesise new receptors when treated with 1-methylcyclopropene (1-MCP). As these new receptors are needed to overcome the effects of the 1-MCP, the fruit becomes overripe and decays without the production of an ethylene climacteric or a

clear respiratory climacteric. However, treatment with an ethylene analogue such as propylene can overcome this inhibition (Abdi *et al.*, 1998).

1.3. Preharvest factors affecting plum fruit quality

Quality, market life, and internal breakdown are all related to preharvest factors. These factors include mineral nutrition, irrigation and cultural practices, as well as genetic factors.

1.3.1. Genotypic differences

The foremost factor affecting the occurrence of chilling injury on temperate crops is genetic diversity within species (Bramlage, 1982). In a study by Abdi *et al.* (1997a), it was suggested that the development of chilling injury is influenced by the genetic background of a cultivar and that fruit with a long fruit development period are less prone to chilling injury. In cucumbers, cultivars that lose more moisture during storage develop more chilling injury symptoms once placed at higher temperatures (Purvis, 1995). Results indicate that this is true for plums (Paper 4) and therefore the ability of a plum to withstand the dessicating effects of storage could possibly influence the degree of chilling injury that it would sustain. This would be determined by the breeding characteristics of the cultivar, e.g. skin and wax layer thickness.

High incidences of internal breakdown are associated with vigorous trees (Kotzé *et al.*, 1987; Woolridge *et al.*, 1995). While vigour can be controlled by pruning or judicious fertilizer application, the inherent vigour of the tree is determined by the genetic makeup of either the rootstock or the cultivar itself.

1.3.2. Light and temperature

Light may have a twofold effect on quality in plums, as well as other crops. Firstly, the effect of the light itself and secondly, the effect of the heat generated by the intensity of the light.

Temperature and light are two factors that are important for the development of red pigment in fruit (Dussi *et al.* 1995). In red pears (cv. 'Sensation Red Bartlett'), fruit covered with gelatin filters allowing passage of light with different wavelengths consistently yielded a lower skin hue and higher anthocyanin concentrations than the control, with longer wavelengths giving increased anthocyanin content. The amount of light interception affects chlorophyll content of the outer

pericarp of kiwifruit, with lower values measured in shaded fruit (Antognozzi *et al*, 1995). In 'Redhaven' peach fruit, shading the fruit with 40% and 10% full sun screens resulted in less red colour development. The greater the amount of shade, the less red colour developed (Erez & Flore, 1986).

The sink strength of a fruit is influenced by light (Erez & Flore, 1986). Light intensity influences the leaf assimilation rate and modulates both source and sink enzyme activity and synthesis in fruit. Inner fruit and fruit covered with aluminium foil have lower flesh firmness values and soluble solids contents and can thus not be stored for a long period in the case of kiwifruit (Antognozzi *et al*, 1995). TSS and flesh firmness in peaches are lower in fruit covered in foil for 18 days prior to harvest (Erez & Flore, 1986). In plums, shading of the lower parts of the tree results in lower levels of soluble solids and higher levels of gel breakdown because of a lower level of photosynthesis in these areas (Taylor 1993c). 'O'Henry' peach fruit that developed in the shaded, inner canopy position of the tree, developed more internal breakdown than fruit in the outer canopy (Crisosto *et al.*, 1995).

Dry matter production is closely linked to light interception (Palmer, 1993). Differences in light interception have been correlated with differences in yield between systems. A low fruit production per unit light interception could indicate poor partitioning of dry matter into fruit or poor conversion of light into dry matter. In kiwifruit (Antognozzi *et al*, 1995) and 'Redhaven' peaches (Erez & Flore, 1986), fruit weight was not influenced by percentage light intensity.

Light levels in peach trees during the latter half of Stage III (final swell), are the most important for fruit weight and quality, as this is the stage where fruit are the major sink for photosynthates (Myers, 1993). Marini *et al.* (1991) found that light intensities less than 23% that of incident photosynthetic photon flux density (PPFD) can reduce fruit redness and soluble solids concentration, as well as slow down ground colour changes in peach (Myers, 1993). Girdling experiments with peach trees done by Chalmers *et al.* (1975a) and Marini *et al.* (1991) have suggested that photosynthates can be translocated from unshaded areas of the tree to shaded fruit.

Southwick (1990) reported that fresh weight, dry weight, and sugar content of prunes developing at various canopy locations are linearly related to PPFD. Fruits situated near non-shaded leaves were more likely to develop optimum quality than fruit near shaded leaves. Flesh firmness was affected by percent PPFD, regardless of the shade period, with the effect of light being dependent on the stage of coverage. Similar results were found for TSS (Marini *et al.*, 1991).

In a trial conducted on avocados by Woolf *et al.* (2000), exposed fruit had less chilling injury than shaded fruit after storage at 0°C, with the least amount of injury on the exposed side of the exposed fruit. The higher tolerance of exposed fruit to low temperatures was ascribed to the diurnal temperature stress that the fruit experienced causing them to produce heat shock proteins. Before harvest, the temperature of the flesh on the exposed side of the exposed fruit was as much as 15 to 20°C higher than the temperature of the shaded fruit, while the nonexposed side could be 5°C higher. Temperatures in exposed fruit can reach up to 50°C. These temperatures are similar to postharvest treatments (such as hot water treatments) that have been shown to increase fruit tolerance to high and low temperatures, increase shelf life and slow ripening by inducing heat-shock protein synthesis (González-Aguilar *et al.*, 2000; Woolf *et al.*, 2000). Temperature causes a bigger increase in heat shock protein synthesis than ultra violet light. During postharvest ripening at 20°C, exposed fruit showed a 2 to 5 day delay in their ethylene peak compared with shaded fruit. The average firmness of the exposed fruit was higher than the shaded fruit with the exposed side being the firmest. Electrolyte leakage was highest in shaded fruit after storage at 0°C. Levels of polygalacturonase increased in both exposed and shaded fruit but took longer in the exposed fruit that softened more slowly. It was concluded that the exposed fruit ripened slower than the shaded fruit, as could be seen by the ethylene production rates (Woolf *et al.* 2000).

1.3.3. Mineral nutrition

Preharvest fertilization as well as postharvest dips of nutrient solutions impact greatly on the postharvest quality of fruit. Mineral elements are implicated in the development of internal breakdown in plums (Taylor *et al.*, 1993c). Nitrogen plays a very important role in fruit quality. High N levels stimulate vigorous vegetative growth, causing shading of the lower branches. Excessive N delays stone fruit maturity, induces poor visual red colour development and inhibits ground colour change from green to yellow. In contrast, N deficiency leads to small fruit with poor flavour and unproductive trees (Crisosto *et al.*, 1997). Low incidence of internal breakdown in South African plums has been associated with significantly higher Ca, Mg, and Mn content of leaves in October and with high Na and Zn content at the end of January (Kotzé *et al.*, 1989b). High incidences of internal breakdown are associated with low levels of Ca and high levels of K in both fruit and leaves. High levels of P in leaves and low levels in fruit have also been implicated in development of the disorder (Kotzé *et al.*, 1987). Furthermore, low incidences of internal breakdown were associated with significantly lower N content of fruit in October and with high Ca and Mg content at harvest (Kotzé *et al.*, 1989b). High incidence of internal breakdown was also associated with low N/K and high K/Ca ratios in leaves and with low Ca/Mg and high N/P ratios in

fruit (Kotzé *et al.*, 1987). These effects on low chilling susceptibility can also be seen on other crops. The effect of mineral nutrition is, however, not only implicated in chilling injury but in a host of other postharvest processes.

Mineral nutrition of apple fruit can influence the development of low temperature injury (Bramlage, 1982). High rate of nitrogen fertilization both decreased and increased the occurrence of browncore in 'McIntosh' apples. Low fruit phosphorus and calcium concentrations were associated with high levels of low temperature breakdown in 'Cox's Orange Pippin'. In 'O'Henry' peaches, nitrogen application increased the incidence of internal breakdown of fruit stored for 2 weeks at 0°C during ripening, but had no effect on longer stored fruit. Fruit of nitrogen deficient trees had more internal browning than the trees receiving treatment (Crisosto *et al.*, 1995).

Calcium is important in plant cell membranes. When calcium is deficient, deterioration of membranes occurs. Calcium alters the structure of membranes, leading to changes in fluidity and permeability and acts in a large number of physiological activities associated with membranes. It has been hypothesised that Ca triggers the primary events in chilling injury, primarily because of a redistribution of cellular calcium. Calcium has been reported to promote protein kinase action which could trigger senescence (Stanley, 1991). In contrast, the role of calcium in delaying senescence of apple and tomato fruit has been studied (Marangoni *et al.*, 1996). The calcium-calmodulin complex is required for protein phosphorylation, an action necessary for the activation of many key enzymes. Furthermore, calcium has an effect on the stabilization of cell walls and membranes, as mentioned (Eksteen, 1982). It can act to cross-link pectin chains via calcium bridges between carboxyl groups by complexing with the polyuronide backbone of the cell wall (Seymour & Gross, 1996). Calcium sprays are often applied preharvest to fruit crops to increase the calcium levels of the trees and reduce internal disorders. But in a trial conducted by Joubert and Kotzé (1989a), no effect on internal breakdown in plums was found with such sprays.

Plum trees have a high nutritional requirement with respect to boron (Wójcik, 1998). Boron plays a structural role in plants in that it cross links cell wall polymers such as hemicellulosic and pectic polysaccharides. Up to 90% of the cellular boron has been localised in the cell wall fraction (Blevins & Lukaszewski, 1998). The structural role of boron was further proved by Brown and Hu (1997), as boron depletion in plum trees caused no discernible change in mature leaf appearance, membrane integrity or photosynthetic capacity, but resulted in a severe disruption of plant growth and metabolism in young growing tissues. Preharvest boron treatment reduces membrane permeability and improves the ability of fruit tissue to withstand adverse storage conditions such as

chilling and high CO_2 (Xuan *et al.*, 2001). In a trial conducted in 1958 the lower limit, upper limit and mean concentration of leaf boron concentrations on the 31st of January that were associated with high production levels were 30, 45 and 37.3 ppm respectively (Beyers *et al.*, 1968). Foliar boron sprays applied in spring or autumn caused a significant increase in soluble solids content in fruit at harvest time (Wójcik, 1998). Soil boron application did not affect this parameter.

1.3.4. The "tree – effect"

While fruit are still on the tree, there is a strong suppression of the climacteric. This is known as the "tree-effect" (Abdi *et al.*, 1997b). In the cultivar 'Beauty', the start of ethylene production took 14 days longer in fruit left on the tree, than in fruit harvested 28 days after pit hardening. This tree factor was found to not only delay the accumulation of ACC in attached 'Golden Delicious' apples but also to inhibit the conversion of ACC to ethylene (Lau *et al.*, 1986). The effect can be overcome by application of an ethylene analogue, indicating that it is ethylene mediated. Reports suggest that it is common to climacteric fruit, although the mechanism of action is still unknown.

1.3.5. Irrigation

Deprivation of water before harvest can result in a reduction in yield and fruit size, an increase in TSS, and a high incidence of internal breakdown in peaches (Veihmeyer & Hendrickson, 1949). In a trial conducted by Crisosto *et al.* (1997), normal irrigation (100% evapotranspiration, ET), over-irrigation (150% ET) and deficit irrigation (50% ET) had no influence on yield, flesh firmness, acidity, colour or pH at harvest, but gave smaller fruit with a higher soluble solids concentration at 50% ET. Postharvest water stress can also influence the following seasons fruit quality. Moderate postharvest water stress on an early maturing plum (cv. 'Red Beaut') had no detrimental effect on growth, fruit quality or productivity the following season. Severe stress, however, caused extensive defoliation and a subsequent reduction in yield (Johnson *et al.*, 1994).

1.3.6. Cultural practices

Girdling of peaches and nectarines 4-6 weeks before harvest can increase fruit size and advance and synchronize maturity (Crisosto *et al.*, 1997). In some cases, girdling has been known to increase soluble solids concentration and acidity. In plum, rapid fruit softening and severe tree weakening has been noted in girdled trees.

Fruit thinning is a practice that can increase fruit size while reducing yield. Too many fruit left on the tree will result in smaller fruit with lower TSS. The stage of fruit growth and the removal of fruit at harvest are related to changes in carbon requirements that in turn affect the rate of photosynthesis and the total daily photosynthesis of peach trees. When peach fruit are removed from the tree, ^{14}C turnover is substantially reduced, indicating a coupling between supply and demand (Chalmers *et al.*, 1975b). Furthermore, mealiness and flesh browning increased with decreasing crop load in 'O' Henry' peaches (Crisosto *et al.*, 1997).

1.3.7. Canopy position

Taylor *et al.* (1993c) found that fruit from the lower canopy of 'Songold' plums were more mature than fruit in the upper canopy. This could be due to the protracted blossoming period of these trees caused by a lack of chilling units during the winter. Besides the effect of blossoming patterns, the main effect of canopy position is the effect of differing light levels in different parts of the tree canopy. Fruit grown in a high light environment have a longer shelf life and are of a better quality with less internal breakdown than fruit grown in a low light environment (Crisosto *et al.*, 1997). The top and outer canopy tend to receive more light than the inner or lower part of the canopy.

1.4. Effect of harvest maturity on plum fruit quality

Harvest maturity is the most important factor determining consumer acceptability of plums (Abdi *et al.*, 1997b). Harvesting plums at an early stage of maturity may result in a product that has a good appearance, and transports and stores well, though yield and flavour may be sacrificed (Abdi *et al.*, 1997b). Total soluble solids increased with advancement of harvest date in a trial conducted by Singh *et al.* (1990) on cv. 'Kala Amritsar' and 'Kataru Chak', indicating an improvement in flavour. However, fruit harvested later, ripen faster and perish before they are sold. These fruit are also more prone to bruising. Fruit that are harvested after they are considered commercially mature develop severe breakdown (Abdi *et al.* 1997a). Abdi reported that harvesting within a narrow maturity range could reduce the incidence of gel breakdown. Kotzé *et al.*, (1989) found that the advantage gained in terms of internal breakdown by harvesting optimum or pre-optimum was only evident when fruit were stored above –0.5°C (3°C in their case) for the duration of the storage period. In the dual temperature regime (13 days at –0.5°C and 15 days at 7.2°C) as well as during intermittent warming to 20°C fruit of all maturities had low incidence of the disorders.

In propylene treated fruit, the time between harvest and the occurrence of significant levels of ethylene production was related to harvest date - the later the harvest date, the shorter the period before ethylene was produced (Abdi *et al.*, 1997b). These fruit also tended to have higher levels of CO_2 production.

In a trial conducted in India by Singh *et al.* (1990) on the cultivars 'Kala Amritsar' and 'Kataru Chak', it was found that total phenolic content decreased gradually with advanced maturity with a minimum phenolic content at the last picking date. This would explain why less mature fruit tend to develop internal browning while more mature fruit tend to develop gel breakdown. In peaches, Ju *et al.* (2000) found that fruit harvested earlier tended to have more leatheriness (water loss), and fruit harvested later had more mealiness, indicating that these disorders were different and occurred at different maturities. Fruit from the later harvests developed more disorders than those of the earlier harvests.

In 'Songold' plums, Taylor *et al.* (1993c) found that fruit with a firmness of 5.2 kg gave the best overall quality, with more mature fruit giving the most gel breakdown. They also found that fruit harvested last has the lowest levels of N, P, K, Ca and Mg and were least optimal for good fruit quality.

Growers need to be able to determine the precise stage of development of their fruit in order to maximise the effects of advanced maturity on quality whilst minimising its effect on chilling injury (Abdi *et al.*, 1997a).

1.5. Postharvest factors affecting plum fruit quality

1.5.1. Temperature regimes

Temperature is the main factor contributing to quality in fresh produce. Decreasing temperature lowers metabolism and increases shelf life (Marangoni *et al.*, 1996). It can be a limiting factor in the storage of plums since between –0.5°C and 10°C fruit may suffer from chilling injury once ripened. Ice crystal damage to plasma membranes occurs when the extracellular solution freezes. This happens between –0.8°C and –15°C, depending upon solute concentration and supercooling (Abdi *et al.* 1997a ; Stanley, 1991).

1.5.2. Chilling injury

One of the biggest obstacles to successful long-term storage of plums has always been low-temperature (chilling) injury (Smith, 1967). Senescence and chilling injury share similar mechanisms (Marangoni *et al.*, 1996). Chilling injury in stone fruit occurs at temperatures above -0.5°C and below 10°C (Luchsinger & Walsh, 1998). The highest incidence of woolliness and internal breakdown occurs between 2°C and 6°C (Eksteen, 1984). The effect of low temperature in the occurrence of chilling injury is twofold. Firstly it results in the membranes becoming leaky and secondly it disturbs the normal functioning of the pectolytic enzymes governing fruit softening.

Plant membranes exist as fluid bilayers of phospholipids containing embedded proteins and sterols (Marangoni *et al.*, 1996). Functional membranes are fluid in what is called a liquid crystalline state (Stanley, 1991). During chilling, heterogeneous lipid domains in the membranes undergo a phase transition from a liquid-crystalline to a gel-phase (Marangoni *et al.*, 1996). This may result in structures that tend to phase-separate from membranes, causing structural perturbations through which cell fluids can leak (Stanley, 1991). These phase changes are reversible up until the point where lipid degradation and accumulation of lipid degradation products induce irreversible membrane damage (Marangoni *et al.*, 1996). A rise in temperature causes a phase transition to liquid crystalline, increasing the lateral diffusion rate of lipids by at least two orders of magnitude (Stanley, 1991). Chilling tolerant membranes are able to maintain their liquid-crystalline state at lower temperatures than chilling sensitive membranes (Marangoni *et al.*, 1996).

Lipid peroxidation would appear to occur during chilling in cucumbers and tomatoes and may be responsible for the formation of irreversible lateral phase separations. Phospholipid hydrolysis, fatty acid peroxidation and breakdown to hydrocarbons would induce the formation of gel-phase lipids that in turn lead to gel-phase. Antioxidants and antioxidant enzymes seem to be involved in the prevention of chill-induced oxidation of lipids (Marangoni *et al.*, 1996). Antioxidants are a heterogeneous group of compounds that act in one of three ways: (1) free radical terminators interrupt the free radical chain of oxidative reactions by contributing active phenolic hydrogen carbons; (2) reducing agents function as oxygen scavengers via electron transfer; (3) chelating agents act synergistically with other antioxidants by complexing prooxidant metal ions, such as iron and copper (Stanley 1991).

The binding potential of pectic substances is governed by pectolytic enzyme activity (Taylor *et al.*, 1994). Pectinmethylesterase (PME) removes methyl groups from esterified galacturonic acid

polymers. Endo-polygalacturonase catalyses internal hydrolytic cleavage of unesterified α-1,4-D-galacturonan linkages and exo-polygalacturonase hydrolyses terminal galacturonosyl residues from the non-reducing end of the molecule, releasing galacturonic acid as a product (Seymour & Gross, 1996). During normal ripening, PME de-esterifies methylated pectic substances and enables polygalacturonase (PG) to hydrolyse the reaction product, thereby producing soluble pectins (Taylor *et al.*, 1994; Brummel & Harpster, 2001; Giovannoni, 2001). This increase in cell wall-degrading enzyme activity is a characteristic common to most softening fruits. As the fruit ripens, a substantial portion of its cell wall pectins are converted to a water-soluble form and these changes are of considerable importance for normal fruit texture (Luza *et al.*, 1992). Storing fruit at low temperatures stimulates the activity of PME while inhibiting the effect of PG. Low PME activity at the beginning of the storage period, followed by increased activity towards the end of the storage period, leads to the formation of low methoxyl pectins of high molecular weight with a high water binding potential. Cell fluids then bind to the pectic substances in the cell wall area to form gel complexes (Taylor *et al.*, 1994). The gelling power of pectins increases the higher the viscosity (Taylor *et al.* 1993a) and the rate of gelation increases with increasing amounts of PME relative to PG (Zhou *et al.*, 2000). Levels of protopectin are higher in the inner mesocarp of 'Songold', which may explain the higher viscosity of water soluble pectin in this area (Taylor *et al.*, 1993b). As reported by various authors, chilling has been shown to increase membrane permeability in a variety of chill-sensitive species (Furmanski and Buescher, 1979).

In fruit stored at dual temperature (10 days at –0.5°C followed by 18 days at 7.2°C), PG resumes its activity once the fruit have been moved to the higher temperature. At these temperatures protopectin is broken down and the levels of water-soluble pectins increase because of the higher PG activity. Higher temperatures, are associated with increased viscosity of water-soluble pectins, increased internal conductivity and levels of gel breakdown. These higher temperatures also give the membranes a chance to regenerate, decreasing their permeability and thus resulting in a reduced leaking of cell fluids (Taylor *et al.* 1993a). Positive effects of higher temperatures are only seen if storage at low temperatures was not long enough to irreversibly damage the membranes (Taylor *et al.* 1993a).

Plum varieties which possess a higher concentration of sugars may be less susceptible to internal breakdown and could possibly be stored at temperatures lower than -0.5°C (Plich, 1999).

1.5.3. Gel breakdown and internal browning

The two main disorders found in South African plums are gel breakdown (GB) and internal browning (IB). Both are classified as chilling injury and have the same mechanism of action, as described above under "*1.5.2. Chilling injury*". Biochemical and physiological variations between the inner and outer mesocarp, such as pectic and phenolic composition, as well as maturity are responsible for the differences between IB and GB. In 'Songold' plums, acidity was higher in the outer tissue while TSS was lower, indicating that the inside of the fruit matured faster than the outside (Taylor *et al.*, 1993b). The middle lamella of the inner tissue was better developed with thicker cell walls than that of the outer tissue. Internal conductivity and viscosity of water soluble pectins were higher in the inner tissue. High levels of total electrolyte leakage indicated that the inner cell membranes were more permeable than those in the outside. It has been reported that more mature fruit are more likely to suffer from IB or GB during storage. During the early stage of ripening there is less water soluble pectin in the intercellular spaces of the fruit and this may be the reason for the lower incidence of chilling injury (Abdi *et al.* 1997a). Furthermore, environmental and cultural conditions also affect the response of a cultivar to storage. In apple, for example, browncore and internal browning are most extensive after cool, cloudy growing seasons (Bramlage, 1982).

Gel breakdown occurs as a gelatinous breakdown around the stone and is associated with loss of juiciness and a thickening of the cell walls (Taylor *et al.*, 1994). Gel breakdown is not only a chilling injury, as it is sometimes found on the tree in fruit that has been allowed to become very ripe (± 3.5kg) (Eksteen, 1982; Taylor *et al.*, 1994).

Internal browning is a brown discolouration of the flesh, starting under the skin and often occuring through the whole mesocarp. IB occurs after extended storage at low temperatures when viscosity of water soluble pectins is at its highest. The brown discolouration is due to the enzyme polyphenoloxidase that catalyses the oxidation of phenolic compounds. At this stage the enzyme has unrestricted access to the phenols because of the ruptured membranes caused by the low temperature storage (Taylor *et al.* 1993a). For this reason, IB is usually associated with less mature fruit because of their higher levels of phenolics, though IB and GB can occur together in the same fruit.

We propose that the difference between IB and GB could further be due to an additional factor that, to our knowledge, has not yet been studied. In the case of internal browning, phenolics, that are

located in the vacuole, are responsible for the brown discolouration. These phenolics can only be released if the tonoplast becomes more permeable due to chilling temperatures. They are then oxidised by polyphenoloxidase and become brown. It is proposed that dual temperature regimes are still stressful enough to disrupt the cell wall degrading enzymes, but that such a regime would keep the tonoplast intact. In contrast, single temperature regimes could disrupt both the cell wall degrading enzymes and the tonoplast, resulting in internal browning. This is purely speculative and further investigation is needed to test this hypothesis.

1.5.4. Effect of chilling on ethylene synthesis

Chilling may stimulate, inhibit or fail to modify ethylene production in fruit tissues, depending on species, cultivar, developmental stage and duration of the chilling treatment (Lelièvre *et al.*, 1997b). Many fruit species require chilling for a certain period in order to ripen normally. Taylor *et al.* (1993a) reported that low temperature storage prior to ripening is required for 'Songold' plums to ripen normally.

The primary effect of a low temperature stress in apples is a perturbation stimulating the ACC oxidase system followed by an autostimulation of ACC synthase (Jobling *et al.*, 1991). The same results were seen in pears chilled for three months at 0°C (Lelièvre *et al.*, 1997b). Chilling results in a burst of ethylene production in fruit upon rewarming. In these cases, the capacity of converting ACC to ethylene was enhanced, rather than damaged, by chilling (Zhou *et al.*, 2001). The effect of low temperatures can be mimicked at warm temperatures by treating the fruit with C_2H_4 or an analogue such as propylene and acetylene. Both treatments stimulate the expression of ACC oxidase activity (Jobling *et al.*, 1991). Chilling-induced accumulation of ACC synthase and ACC oxidase transcripts is strongly reduced when ethylene action is blocked with 1-MCP during chilling. In these fruit, ACC synthase and ACC oxidase transcripts rapidly disappeared upon rewarming. In non-chilled fruit treated with an ethylene analogue ethylene synthesis, ACC synthase activity and ACC synthase mRNA's remained at low levels, while ACC oxidase levels and ripening increased. This indicates that ACC synthase gene expression is regulated only during, or after chilling treatment, while ACC oxidase gene expression can be induced separately by either chilling or ethylene (Lelièvre *et al.*, 1997b).

1.5.5. CA storage regimes

Storage and shelf life of fruit can be prolonged by changing the ambient gas composition using a

controlled atmosphere (CA), ultra low oxygen (ULO) or modified atmosphere (MA) (Blanke, 1991).

Work done as early as the 1940's indicated a positive effect of CA storage, specifically reduced O_2, on the quality of plums, with Wickson plums held at 5% O_2 producing about 75% less CO_2 than plums held at 50% O_2 (Claypool & Allen, 1951). In nectarines, storing fruit under CA conditions with CO_2 levels as high as 20% and O_2 levels between 8 and 16% resulted in firmer fruit with less woolliness, internal browning and reddish discolouration during ripening (Retamales *et al.*, 1992). 'O'Henry' peaches kept in CA conditions of 17% CO_2 and 6% O_2 had less internal breakdown symptoms, mainly due to the reduction of internal browning (Crisosto *et al.*, 1995). Various CA regimes have been proposed for plums (Kader, 2001). The University of California, Davis, recommends an O_2 level of 1-2% and a CO_2 level of 5-10% (Anon., 1999). However, cultivar responses of plums to CA and MA conditions vary widely in the U.S.A. (Smock, 1979), and there is still debate as to whether CA should be used on South African plums.

The major benefits of CA during storage and shipment are retention of fruit firmness and ground colour (Crisosto *et al.*, 2001). CA reduces losses in acidity in fresh fruit (Smock, 1979; Kader, 1986), delays fruit ripening and softening (Kader 1986), and lowers the rate of volatile emission (Smock, 1979). The effectiveness of CA on plums depends on cultivar, preharvest factors, market life and shipping time (Crisosto *et al.*, 2001). In apples, it is possible to double the storage life through the application of CA, but the same is not necessarily possible for stone fruit (Truter *et al.*, 1994). CA conditions must be established rapidly after harvest in order to conserve storage quality of apples by delaying the development of the fruits' capacity to produce ACC and ethylene (C_2H_4) (Jobling *et al.*, 1991).

Elevated CO_2 and lowered O_2 have different physiological effects in delaying ripening. Burg and Burg (1967) suggested that the inhibition of ethylene biosynthesis by both reduced O_2 and elevated CO_2 is mediated through the receptor site. But recent work (de Wild *et al.*, 1999) has shown that CO_2 must have an influence other than on ethylene perception. This was shown by blocking all ethylene receptors in pears with 1-methylcyclopropene (1-MCP), an ethylene inhibitor. The reduction in ethylene by CO_2 was similar in 1-MCP treated and untreated pears. It was proposed that CO_2 is an antagonist of ethylene action and non-competitively inhibits the formation of ACC and ethylene (Blanke, 1991; de Wild *et al.*, 1999). There are many effects of elevated CO_2 on respiration including reduced activity or synthesis of various enzymes of respiratory metabolism, uncoupling of oxidative phosphorylation and a change in intercellular pH that could influence

respiration. Elevated CO_2 can either stimulate, inhibit, or have no effect on respiration, depending on the commodity and the CO_2 level (de Wild *et al.*, 1999; Kader 1986). Smock (1979) found that, in apples, succinate dehydrogenase is the respiratory enzyme most affected by CO_2. O_2 levels below 8% decrease ethylene production of fresh fruit and vegetables and reduce their sensitivity to ethylene (Kader, 1986). Low O_2 inhibits the formation of ethylene through enzyme kinetics, as ACC oxidase requires O_2 to convert ACC to ethylene (de Wild *et al.*, 1999). The decrease in respiration rate in response to reduced O_2 levels is due to the suppression of the activity of oxidases such as polyphenol oxidase and glycolic acid oxidase. These oxidases have a 5 to 6 times lower affinity for O_2 than cytochrome oxidases (Kader, 1986). However, once O_2 levels drop below 2%, cytochrome oxidases are also affected, retarding respiration.

It must be noted however, that CA can induce disorders in fruit when not applied correctly or when applied to sensitive fruit. In plums, exposure to O_2 levels below or CO_2 levels above the tolerance limits results in various physiological disorders such as impaired ripening (Kader, 1986).

In general, very little work has been done on plums as compared to, for example, apples. However, it is clear that a wide variety of factors, both pre- and postharvest will affect plum fruit quality. Pre-harvest treatments and cultural practices as well as postharvest handling and storage regimes will all contribute to delivering the final product.

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The effect of canopy position and light on the quality of 'Songold'(*Prunus salicina* Lindl.) plums

Abstract

Gel breakdown (GB), a gelatinous breakdown around the pip, is a major problem in 'Songold' plums. Trials were conducted over two years in Tulbagh and Porterville on V- and spindle training systems to see whether open, high density trees have less GB compared to low density trees, due to better light management within the canopy. Quality parameters such as total soluble solids and colour showed that the high density canopies improved overall fruit quality and minimised differences between top and base fruit. There was no significant difference between the amount of gel breakdown in the lower part of the canopy and that in the upper part of the canopy, proving that this type of training system improved fruit quality. When fruit were shaded with 80% shade netting, more GB occurred than in the control, indicating that improved light management was the main reason for the improved fruit quality.

Keywords: flesh firmness, electrical conductivity, internal browning, gel breakdown

2. Introduction

'Songold' is a South African plum cultivar that is exported in large quantities. Browning of the mesocarp (called internal browning or IB) used to be a serious problem in 'Songold' plums exported under single temperature (-0.5°C) storage regimes. Hartmann *et al.* (1988) found that storing plums under a dual temperature regime (-0.5°C for 10 days followed by 7.5°C for 18 days) as described by Boyes and De Villiers (1949), prevented internal browning. However, at this time another internal disorder, known as gel breakdown, became apparent (Taylor *et al.*, 1994). Gel breakdown (GB) is a gelatinous breakdown occurring in the mesocarp tissue surrounding the stone in plums. It was thought that IB had previously masked the symptoms of GB.

There are many factors that contribute to the formation of GB, such as harvest maturity, storage regimes and canopy position in the tree (Taylor *et al.*, 1993). Different positions in the tree canopy

receive different light levels and it is generally accepted that the lower parts of the canopy receive less light due to shading by the upper parts. Taylor *et al.* (1993) conducted trials in a low density (4.5 m × 2.7 m) 'Songold' orchard trained to a palmette system and reported a higher incidence of gel breakdown in the lower parts of the canopy. This was attributed to more shading in the bottom fruit, as is commonly found in trees trained to a palmette system. Similarly, Crisosto *et al.* (1995) found that 'O'Henry' peach fruit that developed in the shaded, inner canopy position, developed more internal breakdown than fruit in the outer canopy. In addition to the effect on internal disorders, light has a direct effect on fruit quality characteristics such as colour, TSS and flesh firmness (Gerard & Bruchou, 1992).

The new trend in plum orchard training systems is to produce trees with a more or less pyramidal shape, i.e. a wide base with a softer top. These orchards are high density orchards with in-row spacings ranging from 0.75 to 1.5 m and between-row spacings of 3.5 to 4 m (Cook & Strydom, 1997). Besides giving earlier returns on investments to growers by giving maximum growth in the first year from planting, these training systems result in better light distribution within the canopy due to an improved tree structure. Advantages of reducing shading in the tree are more uniform maturity, more accurate assesment of optimum maturity for harvest, easier selection of optimum maturity fruit by pickers, fewer picks through an orchard and better fruit quality (Taylor, 1996).

The main aim of our study was to determine whether a higher density planting would produce the same problem of gel breakdown in the lower parts of the canopy. The hypothesis was that higher density trees with a more open canopy would result in less GB as a consequence of better light distribution. Other quality parameters such as colour and TSS were also evaluated. A second trial was set up where we artificially shaded fruit in the tree to test our hypothesis that shaded fruit would have an inferior quality (especially more gel breakdown) compared to fruit exposed to the sun.

2. Materials and methods

2.1. Training system experiment

2.1.1. Plant material, sampling and analysis

1998 Tulbagh spindle system. In 1998, 'Songold' plums where harvested at commercial maturity from a farm in Tulbagh, Western Cape, South Africa (33° 48'S , 19° 0'E). The orchard was planted in a north-south row orientation and trained to a spindle system with a tree spacing of 1 m by 4 m (2500 trees ha^{-1}).

1998 Tulbagh V-system. In 1998, 'Songold' plums where harvested at commercial maturity from the same farm in Tulbagh. The orchard was planted in a north-south row orientation and trained to V - system with a tree spacing of 1 m by 4 m (2500 trees ha^{-1}).

In both the 1998 experiments, fruit were harvested from four positions in the tree namely top east, base east, top west and base west. Six trees were selected to give six replicates. Forty fruits were picked in each position and replicated six times, once per tree. Consequently six replicates of ten fruit each could be analyzed on each of the four dates during the dual temperature storage regime (i.e. at harvest, after storage at –0.5°C, after storage at 7.5°C and after shelf life).

1999 Tulbagh spindle system. 'Songold' plums were harvested from an orchard trained to a spindle system from the same farm in Tulbagh on 2 February 1999. This orchard had received summer pruning. The spacing of the spindle system was 1 m by 4 m (2500 trees ha^{-1}). The row orientation was north-south.

1999 Tulbagh V-system. On the same day, 'Songold' plums were harvested from the same Tulbagh farm from an orchard trained to a V–system. The spacing of the V-system was 0.5 m by 4 m (5000 trees ha^{-1}), giving an effective spacing of 1 m between tree canopies. The row orientation was north-south.

1999 Porterville spindle system (pruned). 'Songold' plums were harvested on 1 February 1999 from an orchard in Porterville, Western Cape, South Africa (33° 0'S , 19° 0'E). This orchard had received summer pruning. The spacing of the spindle system was 1 m by 4 m (2500 trees ha^{-1}). The row orientation was north-south.

1999 Porterville spindle system (unpruned). 'Songold' plums were harvested on 1 February 1999 form the same farm in Porterville. This orchard had not received summer pruning. The spacing of the system was 1 m by 4 m (2500 trees ha^{-1}). The row orientation was north-south.

In all the 1999 experiments, fruits were only sampled from the top and the base, making no distinction between east and west. Six trees per system were selected and 20 fruits were picked per tree in each position so that six replicates of ten fruit each could be analyzed on each harvest date. Fruit were only analyzed at harvest, and again after 35 days of cold storage and shelf life (i.e. after 10 days at –0.5°, plus 18 days at 7.5°C plus 7 days at 10°C).

2.1.2. Fruit storage and analyses

Fruit were stored with the dual temperature regime at -0.5°C for 10 days, 7.5°C for 18 days and 10°C for 7 days (simulating shelf life) giving a total storage period of 35 days. This regime eliminates internal browning but promotes development of gel breakdown (Taylor *et al.*, 1993).

In both years, fruit skin colour on two sides of each fruit was analysed using a colorimeter (Nippon Denshoku, Handy colorimeter, NR – 3000, Tokyo, Japan) to measure the chroma (C - intensity), hue angle (H - colour) and lightness (L - value). Hue angle was considered the most important measure of colour, as this gives the actual ground colour change from green to yellow, with a higher bigger hue angle meaning a greener fruit. Firmness was measured on one side of each fruit using a hand-held penetrometer (Southtrade pressure tester, model FT 327, Alphonsine, Italy) fitted with an 11 mm tip. Total soluble solids (% TSS) was measured on a pooled juice sample of each replicate using a hand-held refractometer (TSS 0-32%, Model N1, Atago, Tokyo, Japan). Titratable malic acid was measured on the same juice sample by titrating 10 g of juice with 0.1 N NaOH to a pH of 8.2 using an automated system (Tritino 7195 and sample changer 674, Metrohm Ltd., Herisau, Switzerland) . These titrations were done by a commercial laboratory. Each fruit was cut open through the equatorial axis and visually checked for percentage internal disorders such as aerated flesh (AF - little "bubbles" in the flesh), internal browning (IB - brown discolouration of the mesocarp) and gel breakdown (GB - gelatinous breakdown of the inner mesocarp around the stone). In 1999 only, fruit mass was measured in grams.

2.2. Shading experiment

2.2.1. Plant material and sampling.

Ten 'Songold' plum trees were selected from the Welgevallen Experimental Farm in Stellenbosch, South Africa (33° 48'S , 19° 0'E). These trees were planted as cross pollinators (every tenth tree) in a young, high density 'Laetitia' orchard with no inherent shading. Black shade netting (80%) was used to cover about one third of the branches of each tree at random positions from top to bottom, ensuring that the whole branch and all the fruit on the branch were covered. The fruit were covered on 19 November and remained covered until mature, when they were harvested (21 February 2001). Uncovered branches served as the control. Two trees were blocked to give one replicate, with fifteen fruit per treatment per tree being harvested, giving a total of ten fruit per replicate, per treatment for each of the three sampling dates (at harvest, after cold storage and after shelf life). Fruit were harvested from both the shaded branches (shade fruit) and the unshaded branches (exposed fruit). The fruit were stored for 10 days at -0.5°C, followed by 18 days at 7.5°C (a dual temperature storage regime). The fruit were then transferred to 15°C for five days to simulate shelf life, giving a total of 33 days.

Maturity indexing (colour, firmness, total soluble solids and titratable acidity) was done as described for the previous experiment at harvest, after dual temperature storage and after shelf life. In addition to this, percentage fruit with a green ground colour was rated following shelf life. Electrical conductivity measurements were taken in the inner and outer mesocarp of each fruit, one reading per fruit, using a conductivity bridge with 7 mm platinum electrodes spaced 5 mm apart and with a 1 cm^{-1} cell constant (Consort, C925). This measurement was taken on the equatorial axes on the opposite cheek to which the firmness measurement had been taken.

In all experiments, results were statistically analysed using the SAS System (SAS Institute Inc., Cary, North Carolina, U.S.A..). Disorder data was transformed using a logit equation. Significance levels for all maturity indices and internal disorders are given in Tables 1 – 7 and indicate significance at the 5% level.

3. Results

3.1. Training system experiments

1998 Tulbagh spindle system. Hue angle of fruit skin colour at harvest was significantly higher (greener) in the base fruit than in the top fruit (Table 1). After each step in the storage regime and

after shelf life there was no significant difference in hue angle between base and top fruit. The only exception was fruit on the base west that had the highest hue angles after shelf life.

In general, fruit from the top of the tree tended to be firmer compared to fruit from the base of the tree (Table 1). TSS concentration tended to be higher in the base than in the top fruit (Table 1). After shelf life, the eastern base fruit had the highest TSS concentration and the western base fruit had the lowest TSS. No GB was recorded in any position for any of the four sampling dates (Table 1).

1998 Tulbagh V-system. Hue angle before storage and after each step in the storage regime was higher (greener) in base fruit than in top fruit (Table 2). Fruit in the top of the tree were significantly firmer than those in the base at each sampling date (Table 2). However, after cold storage, only base east fruit were softer and all other positions had similar firmnesses. TSS was higher in the base than in the top fruit at all sampling dates, except at harvest where there was no significant difference (Table 2). No GB was recorded in any position until the final sampling date, after shelf life. Although it was not significant, top fruit had higher levels of GB than base fruit (which had none).

1999 Tulbagh spindle system. There was no significant difference in hue angles between top and base fruit at harvest (Table 3). After storage fruit in the base were significantly greener than top fruit. Top fruit had a higher TSS concentration than base fruit at harvest and after shelf life (Table 3). This was significant at harvest, but not after shelf life. There was no significant difference in firmness, fresh mass, TA, AF or GB between top and base fruit, either at harvest or after shelf life.

1999 Tulbagh V-system. Top fruit had a higher mass than bottom fruit, both at harvest and after shelf life. However, this difference was only significant after shelf life. There was no significant difference in hue angle between top and base fruit before storage (Table 4). After storage, fruits in the base were significantly greener than top fruit. Top fruit had a significantly higher TSS concentration than base fruit both before and after storage (Table 4). After shelf life, top fruit had 1.5% higher TSS than base fruit, compared to 1.0 % at harvest. TA was highest in the base fruit at harvest and after shelf life. This was significant at harvest, but not after shelf life (Table 4). There was no significant difference in firmness (only measured after shelf –life), GB or AF either at harvest or after shelf life.

1999 Porterville spindle system (pruned). Fruit were significantly greener in the base fruit than in the top fruit at harvest and after storage (Table 5). Although all fruit coloured up after shelf life, base fruit were greener relative to top fruit than at harvest. Top fruit had a significantly higher TSS concentration than base fruit at harvest and after shelf life (Table 5). There were no significant differences in mass, flesh firmness, TA, AF or GB either after storage or after shelf life.

1999 Porterville spindle system (unpruned). Fruit were significantly greener in the base than in the top at harvest and after shelf life (Table 6). Top fruit were significantly firmer than base fruit at harvest (Table 6). After shelf life, no significant differences were found. There were no significant differences in TSS concentration at harvest but after shelf life top fruit had a significantly higher TSS concentration than base fruit (Table 6). There were no significant differences in fresh mass, TA, GB or AF either at harvest or after shelf life, although more GB developed in the top fruit after shelf life.

3.2. Shading trial

Shaded fruit were not significantly greener than exposed fruit at harvest, but were significantly greener than exposed fruit after storage and after shelf life (Table 7). Furthermore, after shelf life the shaded fruit had a higher percentage green ground colour remaining than the exposed fruit, with 100% of the exposed fruit achieving full colour development as opposed to the 10% of the shaded fruit (data not shown).

At harvest, there was no difference in flesh firmness between shaded and exposed fruit. After storage as well as shelf life, shaded fruit were significantly firmer than exposed fruit (Table 7). TSS was not significantly different at harvest or after storage, however, after shelf life the exposed fruit had a higher TSS than shaded fruit (Table 7). TA was significantly higher in exposed fruit than in shaded fruit at harvest but after storage and shelf life there was no significant difference in TA (Table 7). Although there were no significant differences in internal disorders between shaded and exposed fruit either at harvest or after shelf life, the difference in the incidence of these disorders will be discussed. After shelf life, shaded fruit had 10% more GB compared to the exposed fruit (Table 7). GB was already evident in the shaded fruit after storage, but no GB was recorded in the exposed fruit at this time. After shelf life, the exposed fruit had 20% more overripe fruit than the shaded fruit.

4. Discussion and conclusions

4.1. Training system experiments

The higher fresh mass of fruit found in the top of the canopy in all training systems and in both areas is consistent with the findings by Dann and Jerie (1988) that the dry weight of fruit is higher in the top of the tree compared to the base. Fruit in the top of the tree tend to be bigger because they receive more photosynthates from leaves than fruits in the lower positions (Gerard & Bruchou, 1992). Murray (2001) found that exposed 'Laetitia' and 'Songold' plums had higher fresh fruit masses than those shaded with 20-80% shading. However, in most instances, the difference in mass between top and base fruits was not significant, indicating that improved light management in the canopy resulted in more uniform sized fruit.

At most sampling dates, both training systems, areas and seasons resulted in fruit with higher hue angles (greener fruit) from the base of the tree compared to the top of the tree. This is in direct contradiction to the findings by Taylor *et al.* (1993) on a Palmette system, that top fruit are greener than base fruit. He attributed this difference to the higher maturity levels of the base fruit due to earlier blossoming and not to any effect of light. Since the more effective use of restbreaking agents has reduced protracted blossoming (Theron, 2001), the differences in maturity between fruits on the tree in this experiments should be less than in the trial conducted by Taylor *et al.* (1993). Furthermore, even when differences in hue angle were significant, the differences were small and would probably not be observed by the average person. Improved light penetration to the base fruit, will result in better colour development (Marini *et al.*, 1991), and this seems to be the case in these training systems.

At some sampling dates, fruit from the top of the tree were firmer than those from the base, regardless of the training system, area and year. Gerard and Bruchou (1992) attributed this difference between top and base fruit to a decrease in cell wall pectolytic enzyme activity in the top fruit due to higher temperatures. These enzymes are associated with fruit ripening and softening, and a decrease in their activity would result in firmer fruit. Woolf *et al.* (2000) found that during postharvest ripening of avocados at 20°C, exposed fruit showed a 2 to 5 day delay in their ethylene peak compared with shaded fruit. The average firmness of the exposed fruit was higher than the shaded fruit with the exposed side being the firmest. Electrolyte leakage was highest in shaded fruit

after storage at 0°C. Levels of polygalacturonase increased in both exposed and shaded fruit, but took longer in the exposed fruit that softened more slowly. It was concluded that the exposed fruit ripened more slowly than the shaded fruit as could be seen by the ethylene production rates. This was attributed to high temperatures in the exposed fruit causing the production of heat shock proteins. Temperature was found to cause a bigger increase in heat shock protein synthesis than ultraviolet light. Therefore, top fruit would probably still reach higher temperatures than base fruit, even if the base fruit are receiving more light due to the open canopy.

The higher TSS in the base of the trees in the 1998 experiments could be due to higher temperatures in the top of the trees inhibiting enzymes such as sucrose synthetase (Gerard & Bruchou, 1992). The higher TSS in the top fruit in the 1999 experiments is consistent with findings by Dann and Jerie (1988) that there is a gradient in sugar levels from the base to the top of the tree, and Gerard and Bruchou (1992) who reported lower levels of TSS in base fruit. A further reason could be the higher levels of photoassimilates in the top fruit. While the 1999 results contradicted those of 1998, warmer average temperatures in 1998 may have overridden the effect of photoassimilate accumulation through decreased sugar production by sucrose synthetase.

Gerard and Bruchou (1992) reported higher acidity levels in top fruit and attributed it to a greater allocation of assimilates to these fruit. In our trial, differences between top and base fruit in terms of TA were generally not significant and will therefore not be discussed further.

Taylor *et al.* (1993) reported a 15% higher incidence of gel breakdown in base fruit when compared to top fruit and ascribed it to shading effects within the tree. In our trial, top fruit had more GB but in all cases GB was relatively low. A possible reason why this trial delivered such a low percentage of gel breakdown and why differences between top and base were not significant is the overall good quality of the fruit. This can be attributed to better light management in the high density trees. The trees are smaller with an improved canopy structure and therefore there is less shading within the tree. Overall quality of the bottom fruit was also good, with high TSS and good colour development.

4.2. Shading trial

The greener, shaded fruit found in this experiment is consistent with the finding by Murray *et al.* (2001) that shaded 'Laetitia' and 'Songold' are greener than exposed control fruit. Better colour development will occur in fruit that is exposed to sunlight (Marini *et al.*, 1991). Furthermore, as discussed later, shaded fruit were less mature than exposed fruit, which could also explain why these fruit were greener.

Exposed fruit were less firm after both storage and shelf life than shaded fruit. The reason for this could be similar to that given by Gerard and Bruchou (1992) and Woolf *et al.* (2000) for the difference between top and base fruit as explained under the training systems experiment. The activity of those enzymes that are associated with fruit ripening and softening could be inhibited by high temperatures under the shade netting and a decrease in their activity would result in firmer fruit. Although these fruit were not exposed to sunlight, the black shade netting could make the temperature of these fruit higher than the exposed fruit. Sunburn symptoms were seen on the fruit that were in contact with the shade netting, indicating high temperatures in this area. However, only fruit that did not show such symptoms were used and these fruit were probably at a lower temperature than the exposed fruit. Another explanation for the firmer, shaded fruit could be delayed maturity in these fruit compared to exposed fruit.

The higher TSS levels in the exposed fruit were possibly due to higher levels of photoassimilates in these fruit. Southwick (1990) reported that sugar content of prunes developing at various canopy locations are linearly related to photosynthetic photon flux density (PPFD). Since leaves in the shaded treatment were also shaded, photosynthesis and the supply of photosynthates to the fruit was reduced. In fact, by harvest most leaves on the shaded branches had died due to too little light. A further explanation could be the delayed maturity of the shaded fruit as explained under firmness. The higher TA in the exposed fruit of the shading trial points to assimilates as the reason for higher TA levels in these fruit and not the effect of the advanced maturity. The higher TSS/TA for the exposed fruit indicates better tasting fruit in the exposed fruit.

Exposed fruit had a lower incidence of GB compared to shaded fruit. In a trial conducted on avocados by Woolf *et al.* (2000), exposed fruit had less chilling injury than shaded fruit after storage at 0°C, with the least amount of injury on the exposed side of the sun fruit. The higher tolerance of exposed fruit to low temperatures was ascribed to the diurnal temperature stress that the fruit experienced causing them to produce heat shock proteins. Before harvest, the temperature of

the flesh on the exposed side of the sun fruit was as much as 15 to 20°C higher than the temperature of the shaded fruit, while the shaded side of the exposed fruit was as much as 5°C higher. Temperatures in exposed fruit can reach up to 50°C. These temperatures are similar to postharvest treatments (such as hot water treatments) that have been shown to increase fruit tolerance to high and low temperatures, increase shelf life and slow ripening by inducing heat-shock protein synthesis (González-Aguilar *et al.*, 2000).

The high levels of OR in the exposed fruit indicate that these fruit were physiologically riper than the shaded fruit. This is further substantiated by the higher TSS and better colour development in the exposed fruit. The exposed fruit were also less firm than the shaded fruit. As mentioned, pectolytic enzymes, responsible for fruit ripening and softening, may have been inhibited in the shaded fruit, causing these fruit to be ripen at a slower rate.

One cannot rule out the possibility that the temperatures may have been higher in the shaded fruit, as they were not measured. However, the high TSS combined with the high TA in the exposed fruit tend to dismiss this as the primary cause of the differences between exposed and shaded fruit. The higher level of GB in shaded fruit shows that there was no production of heat shock proteins that could have protected the fruit against chilling injury, as would be expected had the temperatures under the shade netting been much higher than those of the exposed fruit. Maturity of shaded fruit appears to have been delayed by the reduction in light.

To conclude, the training system experiments have shown that there is a small difference, if any, in quality between top and base fruit throughout the tree in these high density systems. The findings by Taylor *et al.* (1993) regarding GB formation in the lower canopy due to shading were not seen in these systems, but were noted in fruit that had been shaded during the shading trial, confirming that shading was the main cause of GB. High density plantings which allow better light penetration to the base fruit because of improved tree architecture and therefore light management may be the answer to producing better quality plums with less gel breakdown problems. Whether this improved fruit quality is due to photosynthates, transpiration, calcium movement, maturity or another factor is still under investigation. Possibly a combination of these factors is responsible. The effect of shading the fruit has made it clear that light penetration is essential in maintaining quality fruit with good flavour and colour as well as storage ability.

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Table 1.

Hue angle (H), firmness (F), total soluble solids (TSS) and gel breakdown (GB) of 'Songold' plums harvested from a spindle training system in Tulbagh (1998), measured at harvest, after dual temperature storage and after shelf life.

		H (°)	Firmness (kg)	TSS (%)	GB (%)
t harvest					
Top	**East**	107 b	9.0 a	14.2 b	0
	West	107 b	9.3 a	14.2 b	0
Base	**East**	109 b	8.3 b	15.4 a	0
	West	113 a	8.8 ab	14.2 b	0
P > F		0.0003	0.0482	0.0103	NS
After 10 days at -0.5°C					
Top	**East**	105	8.4 ab	13.9	0
	West	108	8.6 a	14.1	0
Base	**East**	99	7.6 c	14.1	0
	West	111	8.0 bc	13.4	0
P > F		NS	0.0026	NS	NS
After 10 days at -0.5°C and 18 days at 7.5°C					
Top	**East**	92	5.8 a	13.7 b	0
	West	90	5.6 a	13.8 b	0
Base	**East**	90	5.6 a	14.3 a	0
	West	90	5.1 b	14.3 a	0
P > F		NS	0.0025	0.004	NS
After 28 days cold storage and 7 days at 10°C					
Top	**East**	81 b	4.4 b	14.0 b	0
	West	82 b	4.7 b	14.1 ab	0
Base	**East**	81 b	4.3 b	14.7 ab	0
	West	90 a	5.4 a	13.3 c	0
P > F		0.0001	0.0039	0.0019	NS

Table 2.

Hue angle (H), firmness (F), total soluble solids (TSS) and gel breakdown (GB) of 'Songold' plums harvested from a V- training system in Tulbagh (1998), measured at harvest, after dual temperature storage and after shelf life.

		H (°)	Firmness (kg)	TSS (%)	GB (%)
At harvest					
Top	**East**	104 bc	9.3 a	14.6	0
	West	102 c	8.2 b	14.9	0
Base	**East**	107 a	7.5 c	15.3	0
	West	106 ab	7.4 c	16.4	0
P > F		0.0265	0.0001	NS	NS
After 10 days at -0.5°C					
Top	**East**	99 b	8.1 a	15.0 bc	0
	West	101 b	7.5 b	14.6 c	0
Base	**East**	104 a	6.7 c	15.3 ab	0
	West	104 a	6.8 c	15.9 a	0
P > F		0.0001	0.0001	0.00019	NS
After 10 days at -0.5°C and 18 days at 7.5°C					
Top	**East**	86 b	4.8 a	14.1 bc	0
	West	89 a	4.8 a	13.9 c	0
Base	**East**	90 a	4.1 b	14.5 ab	0
	West	89 a	4.8 a	14.9 a	0
P > F		0.0029	0.0101	0.0069	NS
After 28 days cold storage and 7 days at 10°C					
Top	**East**	82	3.6 a	13.5 c	3
	West	83	3.3 ab	14.4 bc	7
Base	**East**	88	2.7 c	15.0 bc	0
	West	84	3.0 bc	16.0 a	0
P > F		NS	0.0151	0.0001	NS

Table 3.

Hue angle (H), flesh firmness (F), total soluble solids (TSS), titratable malic acid (TA), aerated flesh (AF) and gel breakdown (GB) of 'Songold' plums harvested from a spindle training system in Tulbagh (1999), measured at harvest, and after dual temperature storage (10 days at –0.5°C, 18 days at 7.5°C) and shelf life (7 days at 10°C).

	Mass (g)	H (°)	Firmness (kg)	TSS (%)	TA (%)	AF (%)	GB (%)
At harvest							
Top	114	110	9.2	13.6	1.6	0	0
Base	109	110	9.6	12.9	1.6	0	0
P > F	NS	NS	NS	0.0216	NS	NS	NS
After storage and shelf life							
Top	114	88	3.8	13.5	1.3	7	0
Base	109	92	3.6	13.0	1.3	5	3
P > F	NS	0.0011	NS	NS	NS	NS	NS

Table 4.

Hue angle (H), flesh firmness (F), total soluble solids (TSS), titratable malic acid (TA), aerated flesh (AF) and gel breakdown (GB) of 'Songold' plums harvested from a V training system in Tulbagh (1999), measured at harvest, and after dual temperature storage (10 days at –0.5°C, 18 days at 7.5°C) and shelf life (7 days at 10°C).

	Mass (g)	H (°)	Firmness (kg)	TSS (%)	TA (%)	AF (%)	GB (%)
At harvest							
Top	108	110	-	12.1	1.3	0	0
Base	99	111	-	11.1	1.4	0	0
P > F	NS	NS	-	0.004	0.0214	NS	NS
After storage and shelf life							
Top	102	88	2.8	12.2	1.0	40	10
Base	92	95	2.7	10.7	1.1	23	8
P > F	0.0068	0.0083	NS	0.0001	NS	NS	NS

Table 5.

Hue angle (H), firmness (F), total soluble solids (TSS), titratable malic acid (TA), aerated flesh (AF) and gel breakdown (GB) of 'Songold' plums harvested from a pruned spindle training system in Porterville (1999), measured at harvest, and after dual temperature storage (10 days at –0.5°C, 18 days at 7.5°C) and shelf life (7 days at 10°C).

	Mass (g)	H (°)	Firmness (kg)	TSS (%)	TA (%)	AF (%)	GB (%)
At harvest							
Top	78	104	8.2	16.5	1.2	0	0
Base	75	110	9.5	15.5	1.2	0	0
P > F	NS	0.0098	NS	0.0268	NS	NS	NS
After storage and shelf life							
Top	82	74	3.1	15.7	1.0	22.0	2
Base	76	85	3.1	14.6	1.0	12.0	2
P > F	NS	0.0007	NS	0.0010	NS	NS	NS

Table 6.

Hue angle (H), flesh firmness (F), total soluble solids (TSS), titratable malic acid (TA), aerated flesh (AF) and gel breakdown (GB) of 'Songold' plums harvested from a unpruned spindle system in Porterville (1999), measured at harvest, and after dual temperature storage (10 days at –0.5°C, 18 days at 7.5°C) and shelf life (7 days at 10°C).

	Mass (g)	H (°)	Firmness (kg)	TSS (%)	TA (%)	AF (%)	GB (%)
At harvest							
Top	69	104	10.3	17.0	1.3	0	0
Base	65	108	6.7	16.5	1.7	0	0
P > F	NS	0.0060	0.0021	NS	NS	NS	NS
After storage and shelf life							
Top	73	68	2.4	15.8	1.0	28.0	12
Base	68	77	2.8	15.5	0.9	10.0	8
P > F	NS	0.0007	NS	0.0010	NS	NS	NS

Table 7.

Hue angle (H), fresh firmness (F), electrical conductivity of inner (EC In) and outer (EC Out) mesocarp, total soluble solids (TSS), titratable acidity (TA), gel breakdown (GB), internal browning (IB) and overripeness (OR) of exposed and shaded 'Songold' plums measured at harvest, after dual temperature storage and after shelf life.

		H (°)	Firm. (kg)	EC In (mS/m)	EC Out (mS/m)	TSS (%)	TA (%)	GB (%)	IB (%)	OR (%)
Harvest	**- Exposed**	100.6	6.4	3.0	2.0	12.6	1.48	0	0	0
	- Shaded	103.9	6.4	3.1	2.2	12.2	1.32	0	0	0
P > F		NS	NS	NS	NS	NS	0.0347	NS	NS	NS
Storage	**- Exposed**	71.9	2.9	3.5	1.9	12.6	1.15	0	2	0
	- Shaded	86.1	3.9	3.2	2.2	12.1	1.15	10	0	0
P > F		0.0052	0.0027	NS	0.0148	NS	NS	NS	NS	NS
Shelf life	**- Exposed**	35.7	2.0	3.2	2.2	12.6	1.11	4	0	22
	- Shaded	58.7	3.1	2.8	1.8	11.9	1.08	14	0	2
P > F		0.0109	0.0354	0.0126	0.0018	0.0263	NS	NS	NS	NS

Effect of harvest time on postharvest quality and ripening patterns of four plum (*Prunus salicina* Lindl.) cultivars

Abstract

Many growers are concerned about harvesting later in the harvesting period, as later harvested plums tend to become overripe, have a higher incidence of internal disorders, and are difficult to transport. We harvested optimum maturity 'Pioneer', 'Sapphire', 'Songold' and 'Angeleno' plums five times each, beginning at or just prior to, and extending later than the commercial harvesting period. Fruit were stored for 0, 1, 2, 3, 4 or 5 weeks at –0.5°C. Maturity parameters such as colour, firmness, total soluble solids and titratable malic acid were measured on removal from storage, and again after 1 week at 15°C. Later harvested plums did not develop more internal disorders but did have improved TSS and colour development, indicating the importance of harvesting at optimum maturity. Ethylene production was used to classify 'Pioneer' and 'Sapphire' as climacteric and 'Songold' and 'Angeleno' as suppressed climacteric. These climacteric classes were related to changes in the ripening patterns of the plums.

Keywords: gel breakdown, internal browning, electrical conductivity, Pioneer, Sapphire, Songold, Angeleno, suppressed climacteric

1. Introduction

Many factors affect consumer acceptability of plums. Amongst the most important is high total soluble solids content, although acidity, TSS/TA ratio, and phenolic content are also important as they affect flavour (Crisosto *et al.*, 2001). Consumers want sweet, flavoursome fruit (McGlasson, 2001) and there is a demand for more mature, 'tree ripe' fruit.

Harvest date is the most important factor determining consumer acceptability of plums (Abdi *et al.*, 1997b), as it affects taste, colour and firmness. Harvesting plums at an early stage of maturity may result in a product that has a good appearance, and transports and stores well, though yield and flavour may be sacrificed (Abdi *et al.*, 1997a; 1997b). Fruit that are harvested later, ripen quickly and may perish before they are sold. Although these fruit are also more prone to bruising, plums are less susceptible to bruising than most peach and nectarine cultivars of comparable firmness

(Crisosto *et al.*, 2001). In propylene treated fruit, the time between harvest and the occurrence of significant levels of ethylene production was related to harvest date, with the later harvests having a shorter period before ethylene was produced. These fruit had higher rates of respiration (Abdi *et al.*, 1997b).

In a concurrent study, we found that subjecting plums to a cold storage period at -0.5°C prior to ripening resulted in higher levels of ethylene production compared to fruit that had not received cold and that the longer the cold storage period, the greater the effect. While cold had no effect on ethylene production in 'Pioneer', this effect was seen in 'Sapphire' and to a greater extent in 'Songold' and' Angeleno' (Paper 3). Plum cultivars react differently to high temperatures during delay periods prior to packing and cold storage (De Kock, 2001). 'Sapphire' is temperature sensitive and delays at high temperatures (20°C) before packing have a bigger effect on softening and shelf life in this cultivar than in 'Songold'.

Insufficient winter chilling is often a problem in the Western Cape Province of South Africa, and results in protracted blossoming. Consequently some fruit on the tree ripen much later than other fruit. In some cultivars, such as 'Songold', it is difficult to judge maturity at harvest. For this reason, these cultivars are sometimes strip harvested, i.e. all fruit on the tree are harvested at one time, when the majority of the fruit is at optimum harvest maturity. This results in a low pack-out, as many fruit are either overmature or immature.

The aim of this study was to determine the effect of harvest time on fruit quality. Although this has been determined before (Taylor *et al.*, 1993c; Abdi *et al.*, 1997a; Plich, 1999), previous studies have focused on using more mature fruit, i.e. post-optimum, as harvest time progresses. Our study differed in that at each harvest date, only fruit that were considered optimum for that day (i.e. fruit which were within the optimum picking window recommended for export) were harvested. Our first hypothesis was that fruit harvested later, yet still at optimum maturity, would not be inferior in quality than earlier harvested fruit.

Furthermore, we wanted to classify the four cultivars studied into climacteric or suppressed climacteric classes and to relate these class differences to the differences in ripening patterns of these cultivars. Plums are climacteric fruit, meaning that ripening is associated with an increase in ethylene production. Abdi *et al.* (1997b) have further classified plums into climacteric and suppressed climacteric classes based on ethylene production. A suppressed climacteric plum typically produces 15 to 500 times less ethylene than a climacteric plum. The second hypothesis

was that ethylene production rate, and therefore climacteric class, would affect the ripening pattern of a plum.

2. Methods

2.1. Plant material and sampling

Fruit were harvested from a commercial farm in Paarl, South Africa (33° 48'S , 19° 0'E). The four cultivars were chosen to represent the earliest to the latest cultivars of the plum season. It is important to note that only optimum maturity fruit were harvested on each harvest date. Overmature fruit or fruit that were not yet mature were not harvested.

The first harvest date of 'Pioneer' coincided with the first commercial harvest date for the particular block. The same block was used for the duration of the trial, with fruit being selected for uniformity from a bin into which fruit had been harvested. Optimum maturity (as determined by the producer) was firstly determined by firmness of a sample and then a percentage blush development was assigned to that maturity. Therefore, fruit were ultimately harvested by colour. The last harvest date coincided with the last commercial harvest date. Between the 1st and 2nd harvest dates, there was a spell of cold, rainy weather lasting for about two days. The total harvesting period was 11 days, with five harvest dates (15, 19, 21, 23, 25 November).

The first harvest date for 'Sapphire' coincided with the first commercial harvest date for the block. The first four harvests were selected for uniformity and optimum maturity from fruit harvested at commercial harvest from the same block, with the fourth harvest coinciding with the last commercial harvest. Fruit were selected by percentage red colour development as done in 'Pioneer'. The first four harvests were selected from bins. Twenty trees were left for fruit to hang longer and these fruit were picked on the fifth harvest date. These fruit were selected from the tree by determining the optimum for that specific day. The total harvesting period was 11 days with five harvest dates (6, 8, 11, 13, 16 December).

'Songold''s first harvest date was three days earlier than the commercial harvest date for the particular block. Fruit were harvested directly from a row of trees assigned to the experiment. These fruit were selected by determining the optimum for each specific day by firmness only and relating this firmness to ground colour. The last harvest date was 12 days after the commercial harvest date (only one pick). The total harvesting period was 14 days, with five harvest dates (6, 9, 12, 15, 19

February).

The first harvest date for 'Angeleno' was five days before the first commercial harvest date. Fruit were picked from trees left in a row for the trial. These fruit were selected by determining the optimum for each harvest date by flesh firmness only (specific to each harvest date), as full colour development occurs in 'Angeleno' before fruit are ready for harvesting. 'Angeleno' is harvested by size, but as this was impractical for the experiment, harvesting was done by gently feeling whether fruit was at the desired firmness. Although it was felt that fruit could be left on the tree for longer, the risk did exist that the fruit could be stolen, as it was the last remaining fruit of the plum season. The last harvest date was approximately one week after the second, and final, commercial pick. The total harvesting period was 15 days, with five harvest dates (16, 20, 23, 26 February and 1 March).

At each harvest date, 480 fruit were harvested. After harvest, fruit were placed in storage at -0.5°C for a total of five weeks. Two batches of four replicates of ten fruit each were removed at weekly intervals. One batch was immediately placed at room temperature (± 23°C) and then analyzed for colour, firmness, TSS, electrical conductivity, TA, and internal disorders once fruit were at room temperature. The other batch was placed at 15°C for seven days to simulate shelf life. Upon removal, these fruit were analyzed for ethylene production. After the fruit had reached room temperature, the same indices were measured as at harvest.

2.2 Measurement of ethylene production

A closed system was used to determine the ethylene production over time of all four cultivars. In the static (or closed) system, four replicates of ten fruit each were placed into 5000 ml plastic jars, one replicate per jar. The jars were sealed for an hour, whereafter 2 cm^3 of gas was extracted with a gas tight syringe through a rubber septum in the side of the jar for analysis by gas chromatography.

Samples were injected into a gas chromatograph (Varian GC 3300, Walnut Creek, California, U.S.A.) and ethylene was measured by comparing the output area of the sample to the area of a 1.1 ppm ethylene standard. Equation (i) was used to determine ethylene production.

$$\text{ethylene in } \mu L.kg^{-1}h^{-1} = \frac{C_2H_4 \text{ of sample in ppm} * \text{free space in bucket}}{\text{fruit mass (kg)} * 1000} \qquad \text{(i)}$$

2.3. Maturity Indices

2.3.1. Colour

Colour was measured as lightness (L), chroma (C) and hue angle (H) using a hand held colorimeter (Nippon Denshoku, Handy colorimeter, NR – 3000, Tokyo, Japan). In 'Pioneer', colour at harvest was measured on the cheek with the most colour (blush) development. In 'Sapphire', ground colour data at harvest is missing. In 'Songold' and 'Angeleno' at harvest, as well as in all cultivars after shelf life, colour was measured on the area with most colour development (where discernible). In 'Pioneer' and 'Songold', ground colour at harvest was also measured using a Unifruco Research Services apple and pear colour chart where 0.5 is dark green and 5 is deep yellow. The colour chart values give an indication of the change from green to yellow in those plum cultivars that are harvested based on ground colour change but otherwise show little colour development at harvest. These values were only measured at harvest, as this would be the time when growers would generally use it. The subsequent colour changes were measured with a colorimeter as lightness (L), chroma (C) and hue angle (H). However, only hue angle will be discussed as it indicates the actual colour change from green to yellow, red or purple. In 'Songold', plums were rated for the remains of a green ground colour following shelf life.

2.3.2. Firmness

Four replicates of five fruit each were used to take the firmness measurements. Once fruit had reached room temperature (±20°C), firmness was measured using a hand held penetrometer (Southtrade fruit pressure tester, FT 327, Alphonsine, Italy) fitted with an 11 mm tip and mounted on a drill stand. In the case of 'Pioneer' and 'Sapphire', measurements were taken on two opposite sides of the fruit, one side just below and the other side just above the equator. In 'Songold' and 'Angeleno', measurements were taken on two opposite cheeks on the equator, giving a total of ten readings per replicate for all cultivars.

2.3.3. Total Soluble Solids

TSS were measured on a pooled juice sample (ten fruit per replicate) extracted by using a commercial juicer. TSS (%) was measured with a hand held refractometer (TSS 0-32%, Model N1, Atago, Tokyo, Japan) giving a total of four readings, one per replicate.

2.3.4. Titratable Malic Acid

Titratable malic acid was measured on the same pooled juice sample as used for the TSS measurements by titrating 10 ml of juice with 0.1 N NaOH to a pH of 8.2 using an automated system (Tritino 7195 and sample changer 674, Metrohm Ltd., Herisau, Switzerland). Measurements are given in percentage (g malic acid / 100 g juice). Titrations were done by a commercial laboratory.

2.4. Internal disorders

2.4.1. Electrical Conductivity

Electrical conductivity (EC) was measured as an indicator of membrane permeability according to the method described by Furmanski and Buescher (1979). This method is rapid, nondestructive and sensitive. A conductivity bridge (Consort, C925) with a cell constant of 1 cm^{-1} consisting of two 7 mm long platinum needles spaced 5 mm apart in a rubber stopper and inserted into the flesh to a depth of 7 mm was used. Fruit were cut open on the equatorial axis and four readings were taken, two in the inner (ECIn) and two in the outer (ECOut) mesocarp. Four replicates of five fruit each were used. Thus, a total of ten readings were taken at each position per replicate.

2.4.2. Internal disorders

Internal disorders were measured by cutting through the equatorial axes of the fruit and rating for visual symptoms of gel breakdown (GB - gelatinous breakdown around the pip), internal browning (IB - brown discolouration throughout the mesocarp) and overripeness (OR - gelatinous breakdown under the skin). 'Angeleno' was also rated for aerated flesh (AF), manifested as little "bubbles" that occur throughout the mesocarp (Truter, 2001).

Results were statistically analysed using the SAS System (SAS Institute Inc., Cary, North Carolina, U.S.A..). Disorder data was transformed using a logit equation. Significance levels for all maturity indices, ethylene production and internal disorders are given in Tables 1 – 4 and indicate significance at the 5% level.

2. Results and discussion

3.1. 'Pioneer'

3.1.1. Ethylene production

'Pioneer' reached a maximum of c.125 $\mu L.kg^{-1}.h^{-1}$ ethylene at shelf life after one week storage at -0.5°C for fruit from harvest 2 (Fig. 1). For the first two weeks of shelf life, ethylene production increased and thereafter, as storage period increased, the production of ethylene measured after shelf life decreased. At the final sampling date, ethylene production was lower than at the beginning of the storage period. Although there was a statistically significant effect of harvest date on ethylene production, no clear trend could be seen except in fruit from harvest 2 that had the highest level of ethylene production for most of the storage period.

In 'Pioneer', the higher rate of ethylene production of harvest 2 was ascribed to the cold weather preceding this harvest. Low temperature induction of ethylene in pears has been observed before or after detachment from the tree (Jobling, 1991). Possibly a similar effect on plums could have caused an increased production of ethylene in the second harvest once these fruit had been harvested.

No trend in the effect of harvest time on ethylene production could be determined (Fig. 1). In 'Pioneer' after zero storage and one week shelf life there was a difference of about 90 $\mu L.kg^{-1}.h^{-1}$ between the lowest (harvest 1) and the highest (harvest 2) ethylene values. Towards the end of storage the higher values decreased and the lower values increased so that the difference at the final sampling date was only about 40 $\mu L.kg^{-1}.h^{-1}$

3.1.2. Skin colour

The change in ground colour of the skin from green to yellow (as measured by the colour chart), as harvest time progressed was not very clear in 'Pioneer' (data not shown). Values for the five harvests were 3.20, 3.35, 3.30, 3.00, and 3.35. As harvest maturity in 'Pioneer' could be assessed by looking at the development of a red blush on the plum, in this season, ground colour was not an important harvesting parameter. Although the colour difference at harvest was not easy to see, the hue angle values were significantly different between harvest dates (Fig. 3), with the earlier harvested fruit being greener than later harvested fruit.

Hue angle values decreased gradually during storage at –0.5°C, indicating a change from green to

yellow. In fruit from the second harvest, rapid yellowing occurred after three weeks of storage. This difference was attributed to the cold, wet weather preceding the second harvest that may have hastened ripening of these fruit.

When fruit were placed at 15°C (shelf life), hue angle decreased rapidly indicating a change from green to dark red/purple. After one week at 15°C (shelf life), there was no difference in hue angle between harvests, except for fruit from the 1st harvest that were transferred to 15°C immediately after harvest, which had a higher hue angle (i.e. greener fruit). This indicates that earlier harvested fruit are slower to ripen than later harvested fruit. After two weeks of storage, hue angle of fruit from the second harvest was similar to that of fruit from the other harvests after shelf life.

3.1.3. Firmness

The difference in flesh firmness of fruit between harvest times (± 2 kg) was not as great as expected (Fig. 5). Flesh firmness dropped during storage at -0.5°C. This decrease was preceded by a slight increase in firmness. Once again, as with colour, the effect of the cold weather on fruit from harvest 2 of 'Pioneer' can be seen by the greater decrease in fresh firmness after three weeks as compared to the other harvest dates, probably due to enhanced ripening. There was a rapid drop in firmness of fruit that were held for one week at 15°C immediately after harvest with fruit from harvest 1 being the firmest (5.4 kg) and fruit from harvest 5 being the least firm (1.6 kg). As storage time increased, flesh firmness continued to decrease and the magnitude of difference in flesh firmness between fruit from different harvest times after shelf life decreased.

3.1.4. Titratable acidity

There was a slight increase in TA over storage time for fruit from harvests one and four (Fig. 6), but in general TA decreased over both storage time and shelf life. This is because acids are used as a respiratory substrate and therefore provide energy for respiration during storage (Tucker, 1993). With the exception of fruit from harvest 1 that had the highest TA at storage, no other effect of harvest time could be seen clearly. As storage time progressed, the reduction in TA was constant for all except fruit from harvests one and four. The decrease in TA after shelf life already occurred at the first sampling date (thus no cold storage), indicating that no cold storage was required to induce further ripening. As could be expected from the reduction in acidity, the pH increased over time during both storage and shelf life (data not shown). Unlike TA, pH in 'Pioneer' was much less variable between sampling dates.

3.1.5. Total Soluble Solids

There was a slight increase in percentage total soluble solids with longer time at both storage and shelf life (Fig. 7). TSS tended to increase after shelf life. Fruit from harvest 1 had the highest TSS at harvest and increased to the greatest extent after shelf life. Other than harvest 1 fruit, no other effect of harvest time on TSS could be seen. The decrease in TSS of fruit at harvest 2 and 3 and the increase in TSS of fruit at harvest 4 and 5 is a clear indication of the diluting effect that the rain had on TSS and the subsequent concentration of TSS as photosynthates were again transported to the fruit.

When comparing TSS/TA, a ratio that is used as an indication of flavour in some fruit such as apricots (higher value means better flavour), one can clearly see the effect of storage on flavour development (data not shown). 'Pioneer' developed virtually full flavour after shelf life even after zero storage at -0.5°C. At the end of storage, fruit from harvest 2 and 5 of 'Pioneer' had the best flavour once ripened. The fact that harvest one had the least flavour, indicates that the increase in flavour of harvest 2 is possibly due to these fruit ripening quicker because of the cold weather that preceded their harvesting.

3.1.6. EC of the inner mesocarp

With increasing storage time, ECIn increased reaching a peak after five weeks storage in fruit from all five harvest dates (Fig. 8). This increase was preceded by a slight decrease in ECIn after the commencement of storage. After shelf life, ECIn was higher than after storage. The exception was fruit of harvest 4 that was lower after shelf life than after storage and remained low at each sampling date after shelf life. During storage, harvest 3 fruit had the highest ECIn and after shelf life harvest 2 fruit had the highest ECIn. There was no significant effect of storage time on ECIn after shelf life. Total internal disorders (GB plus IB) correlated well with the magnitude of the electrolyte leakage.

3.1.7. EC of the outer mesocarp

The electrical conductivity of the outer mesocarp (ECOut) was lower than ECIn after both storage and shelf life (Fig. 9). After storage, the changes in ECOut were similar to that of ECIn, but the increase in ECOut during storage was smaller and occurred later than in ECIn. ECOut of harvest 1 fruit after shelf life was the lowest of all harvests, while fruit of harvest 2 and 3 was the highest. In

'Pioneer' after shelf life, fruit of both harvests 2 and 3 showed an increase in ECOut after two and zero weeks storage respectively, but after four and three weeks, ECOut dropped down to the same level as the other harvests. The increase in ECOut of fruit of harvests 2 and 3 of 'Pioneer' after shelf could be the result of the cold weather that occurred prior to these harvests. This increase is also consistent with the low GB and high IB found in fruit of these harvests after shelf life at the end of the storage period.

3.1.8. Internal disorders

With increasing storage time, there was an increase in GB after both storage and shelf life. The maximum percentage of GB for 'Pioneer' after storage was 30% (Fig. 10). This value was reached after four weeks of cold storage. The maximum GB reached after shelf life was 70%. This value was reached after 3 weeks of storage, whereafter there seemed to be a slight decrease in GB for fruit of all harvests except harvest 1 that continued to increase till the final sampling date. Fruit of harvest 1 of 'Pioneer' had the highest level of GB after storage of all four cultivars, possibly due to the low levels of IB, making GB easier to see than in those harvests where high levels of IB were found. There was no clear effect of harvest time on incidence of GB.

IB increased as storage time increased (Fig. 11). The highest level of IB after shelf life was 70%, after five weeks of storage. IB after shelf life started developing after three weeks of storage. There is no clear effect of harvest time on the incidence of IB. Harvest 1 fruit gave the lowest incidence of IB while harvest 2 fruit gave the highest incidence of IB, both after storage and shelf life.

OR increased in the first part of storage and then decreased in the latter part in 'Pioneer' (Fig. 12). As could be expected, no OR was found directly after storage. Fruit from the earlier harvests had the lowest incidence of OR.

3.2. 'Sapphire'

2.2.1. Ethylene production

Ethylene production rate in 'Sapphire' increased as storage time increased (Fig. 1). After no cold storage and one week shelf life, ethylene levels were low, with a maximum of 15 $\mu L.kg^{-1}.h^{-1}$ for harvest 1 fruit. After one week of storage this increased to a maximum of 48 $\mu L.kg^{-1}.h^{-1}$ for harvest 1 fruit and after this a constant level of ethylene was produced for the duration of the storage period

for fruit of all five harvest dates. Fruit of harvest 1 consistently had the highest ethylene production. For fruit of all other harvest dates there was no clear effect of harvest time on ethylene production. The higher values of harvest 1 fruit indicate that these harvests may be more difficult to control during storage than subsequent harvests. The higher ethylene production in fruit of harvest 1 could be due to the fact that the first harvest of a particular cultivar contains those fruit which could have been harvested earlier, but were left on the tree until enough fruit had ripened to make harvesting economically viable. If this is the case, then strip harvesting (i.e. picking all the fruit of a particular block in one harvesting session) will result in a large percentage of fruit that will be overripe after shelf life and therefore be unmarketable.

3.2.2. Colour

Ground colour chart values were not used for 'Sapphire'. At harvest, fruit had a green ground colour with a third to three quarters of the skin showing a deep red blush – the later the harvest, the greater the area of skin that had developed a blush. Hue angle after shelf life was about 10° for fruit from all harvest dates and all storage times (Fig. 3). However, hue angle was only measured on the red part of the fruit and is therefore not an indication of total colour development. In general, the shorter the storage period, the smaller the extent of red colour development was following shelf life. This effect was more pronounced in the earlier harvested fruit i.e., later harvested fruit showed better colour development both at harvest and after storage and shelf life.

3.2.3. Flesh firmness

In 'Sapphire', the decrease in flesh firmness between harvest times was not as great as expected (Fig. 5). The difference in flesh firmness at harvest between the first and last harvest dates was ±3 kg. Flesh firmness decreased during storage. After zero storage and one week shelf life the firmest fruit (harvest 2) was 7.7 kg and the softest fruit (harvest 5) was 1.1 kg. As storage time at -0.5°C increased, firmness after shelf life decreased so that at the final sampling date, the difference in firmness between the firmest and softest fruit was only ±2 kg.

3.2.4. Titratable acidity

There was a reduction in titratable acidity over time for both storage and shelf life for fruit of all five harvests (Fig. 6). Although TA decreased substantially after shelf life as compared to harvest time, this reduction in TA had already occurred to a great extent in storage due to the acids being a

respiratory substrate. As storage time progressed, the reduction in TA was constant for all harvest dates. No clear effect of harvest time on TA could be seen. No cold storage was required to reduce TA after shelf life. pH increased over time at both storage and shelf life (data not shown).

3.2.5. Total Soluble Solids

There was a slight decrease in TSS during both storage and shelf life of 'Sapphire'. Fruit from the earlier harvests had the highest TSS at harvest as well as during storage and shelf life. In 'Sapphire', according to the TSS/TA values, flavour did develop after zero storage and one week shelf life, but flavour improved as storage time increased (data not shown). Generally, fruit from the last harvests of 'Sapphire' had good flavour, indicating that leaving the fruit on the tree will improve flavour development.

3.2.6. EC of inner mesocarp

With increasing storage time, ECIn at storage increased to a maximum of 3.89 μS/m for harvest 2 fruit (Fig. 8). This increase occurred after 2 weeks of storage and was preceded by a slight decrease in ECIn after the commencement of storage. After shelf life ECIn was higher than after storage. No correlation was found between harvest time and ECIn during storage or after shelf life. Total internal disorders (GB plus IB) correlated well with the magnitude of the electrolyte leakage.

3.2.7. EC of the outer mesocarp

The EC of the outer mesocarp of 'Sapphire' was lower than ECIn after both storage and shelf life (Fig. 9). After storage, the changes in ECOut were similar to that of ECIn, but the rise in ECOut after storage was smaller and occurred later than in ECIn. After shelf life, harvest 1 fruit had the highest ECOut for the duration of the storage period, but no other effect of harvest time on ECOut could be seen.

3.2.8. Internal disorders

In 'Sapphire' there was an increase in GB after both storage and shelf life with increasing storage time (Fig. 10). The maximum percentage GB after shelf life was 70% (for harvest 5) and occurred after three weeks of cold storage, whereafter there seemed to be a slight decrease in GB for fruit of all harvests except harvest 2 fruit that continued to increase. There was no clear effect of harvest

date on incidence of GB at both storage or shelf life.

'Sapphire' reached a maximum percentage IB of about 70% after five weeks storage both after storage and after shelf life. Increasing storage period resulted in increased incidence of IB after storage and shelf life. IB after shelf life started developing after one week of storage. Harvest 1 fruit had the highest incidence of IB, both after storage and after shelf life, but there was no other clear effect of harvest time on IB.

In 'Sapphire', OR increased in the first part of storage and then decreased towards the end of storage (Fig.12) . No OR was found directly after storage. Fruit from the later harvests had the least amount of OR.

3.3. 'Songold'

3.3.1. Ethylene production

In 'Songold', an increase in storage period at -0.5°C prior to shelf life led to an increase in ethylene production after shelf life with a maximum value of only 22 $\mu L.kg^{-1}.h^{-1}$ being reached after five weeks storage (Fig. 1). Although harvest 4 fruit had the highest rate of ethylene production after zero storage and one week shelf life, harvest 1 fruit had the highest rate of ethylene production for most of the storage period. This could be due to the presence of overmature fruit in the first harvest as explained in 'Sapphire'. Although fruit were harvested directly from the tree, overmature fruit are more likely to be included in this harvest than in subsequent harvests. For fruit from the other harvest dates, differences in ethylene production rate were small. No ethylene was produced during storage.

3.3.2. Colour

The change in ground colour from green to yellow as harvest time progressed was clear in 'Songold' from the increasing colour chart value (Fig. 2). With the exception of fruit from the fifth harvest date that decreased, there was a general increase in colour value from 3.68 (harvest 1) to 4.43 (harvest 4). In 'Songold' there is no discernible blush on the fruit at harvest, and therefore ground colour changes are an important parameter used for harvesting.

Although statistically significant, the change in hue angle from green to yellow as harvest time

progressed was not clearly seen (Fig. 3). Increasing storage time resulted in a lower hue angle, indicating that the fruit were becoming more yellow in storage at -0.5°C. After shelf life, hue angle of harvest 1 decreased more than those of the other harvest times. This quicker colour development in fruit of the first harvest could be due to the first harvest having more overripe fruit than subsequent harvests.

Fig. 4 shows the number of fruit that had a green tinged ground colour after shelf life. As storage time increased, the number of green tinged fruit after shelf life decreased. For the first three sampling dates, fruit that were harvested later had better colour development than earlier harvested fruit, but this difference decreased as storage time increased.

3.3.3. Flesh firmness

In 'Songold', the decrease in flesh firmness between harvest times was not as great as expected (Fig. 5). At harvest, the difference in flesh firmness between the first and last harvest date was ±2 kg and this difference stayed constant for the entire storage and shelf life period. Flesh firmness dropped during storage and this decrease was preceded by a slight increase in flesh firmness. There was virtually no drop in flesh firmness after the zero storage and shelf life period. As storage time at -0.5°C increased, flesh firmness after shelf life decreased gradually. After three weeks storage, flesh firmness after shelf life stayed more or less constant for the remainder of the storage period. Although statistically significant, the effect of harvest date could not be ascertained as there was no clear trend.

3.3.4. Titratable acidity

There was a reduction in titratable acidity over time in 'Songold' both in storage and after shelf life, though the greatest reduction in TA was already seen in storage. As storage time progressed, the reduction in TA was constant for all harvest dates. TA only dropped gradually after shelf life as storage time progressed, with no change in TA after zero week's storage and one week shelf life. This is similar to the results seen for firmness and colour and indicates that 'Songold' requires cold storage prior to shelf life in order to ripen normally. No clear trend could be seen in the effect of harvest date on TA. Where any effect could be seen, fruit from the earlier harvests had higher TA values than fruit from the later harvests. pH of 'Songold' increased over time during both storage and shelf life (data not shown).

3.3.5. Total Soluble Solids

Fruit from the later harvests had the highest TSS values at harvest and fruit from the earlier harvests had the lowest. TSS of harvest 5 increased during storage and after shelf life and that of harvest 1 increased after shelf life but remained unchanged during storage. The remaining harvests decreased slightly during storage but remained unchanged after shelf life. According to the TSS/TA values (data not shown), 'Songold' developed little flavour without cold storage and flavour developed more as storage time at -0.5°C increased. Generally, fruit from the last harvests of 'Songold' had good flavour, indicating that leaving the fruit on the tree will improve flavour development.

3.3.6. EC of inner mesocarp

With increasing storage time, ECIn after storage increased (Fig. 8). Although the effect of harvest time on ECIn could not be seen after storage, after shelf life fruit from the earlier harvests tended to have higher ECIn values than fruit from the later harvests. During storage, harvest 3 fruit showed a sharp increase at the end of the storage period when compared to fruit from other harvest times. In 'Songold', the increase in ECIn correlated well with the onset of GB and IB after storage. Total internal disorders (GB plus IB) correlated well with the magnitude of the electrolyte leakage.

3.3.7. EC of the outer mesocarp

In 'Songold', the ECOut was lower than ECIn after both storage and shelf life (Fig. 9). After storage, the changes in ECOut were similar to that of ECIn, but the rise in ECOut after storage was smaller and occurred later than in ECIn. There was a clear effect of harvest time on ECOut after shelf life, with fruit from the earlier harvests having the highest ECOut values and fruit from the later harvests having the lowest values. In 'Songold', the high ECOut found after shelf life correlated well with the relatively low percentage GB, as few ions would be bound. After shelf life, both harvests 1 and 2 fruit showed a similar increase after one week storage that peaked at two weeks and then declined. There was no statistically significant effect of harvest time on ECOut after storage.

3.3.8. Internal disorders

There was an increase in GB at both storage and shelf life with increasing storage time (Fig. 10). The maximum percentage of GB for 'Songold' after shelf life was 70%. This value was only

reached after five weeks of cold storage. The highest level of GB reached after storage was 90% after five weeks of storage and this value was higher than was measured after shelf life. This could be due to the masking of GB by IB. At the last sampling date at shelf life, harvest 1 fruit had the lowest incidence of GB and in general fruit from the earlier harvests had the lowest levels of GB, though this effect was not clear, possibly due to only optimum maturity fruit being harvested.

The highest incidence of IB after shelf life that was found in 'Songold' was 88% (Fig. 11). IB was observed after two weeks of storage when evaluated after shelf life, but only developed after four weeks when evaluated after storage. Increased storage at -0.5°C resulted in increased incidence of IB both after storage and after shelf life. Fruit from the earlier harvests had the highest levels of IB after storage and shelf life. The higher levels of IB found in the earlier harvested fruit is concurrent with what one would expect. Earlier harvested fruit would probably be less ripe and therefore have higher levels of phenolics that cause the browning effect when the cell membranes become leaky due to chilling. In a trial conducted in India by Singh *et al.* (1990) on the cultivars 'Kala Amritsar' and 'Kataru Chak', it was found that total phenolic content decreased gradually with increasing maturity with a minimum at the last picking date. This would result in the formation of GB rather than IB in the later harvested fruit. As with GB, the lack of a clear effect of harvest time on IB in most instances indicates that harvesting fruit at optimum maturity will result in more uniform fruit quality.

In 'Songold', OR increased in the first part of storage and then decreased towards the end of storage (Fig. 12). The only exception to this was fruit from the first harvest of 'Songold' in which OR increased towards the end of storage and was generally higher than any other harvest. No other effect of harvest time on OR could be seen.

3.4. 'Angeleno'

3.4.1. Ethylene production

An increase in storage period at -0.5°C prior to shelf life led to an increase in ethylene production with a maximum value of 1.36 $\mu L.kg^{-1}h^{-1}$. (harvest 3 fruit) only being reached after five weeks storage (Fig. 1). After four weeks storage and one week shelf life, fruit from the later harvests had the highest rate of ethylene production. Prior to this, differences between harvest dates were negligible.

3.4.2. Colour

At harvest, there were significant differences between hue angles of fruit from the five harvests, with harvest 2 fruit having the highest hue angle. There was a slight increase in hue angle over storage time and after shelf life for fruit from all harvest times (Fig. 3). However, even though all these differences were statistically significant, they were difficult to distinguish with the naked eye and colour could not be used to determine whether fruit were ready to be harvested. Instead, flesh firmness was used.

3.4.3. Flesh firmness

The decrease in flesh firmness at harvest between harvest times was not as great as expected (Fig. 5). The difference in flesh firmness between the first and last harvest date was ±2 kg. Throughout storage and shelf life this difference remained constant. During storage, flesh firmness increased slightly and after shelf life flesh firmness decreased slightly to a minimum of 6.1 kg. In general, earlier harvested fruit were firmer than later harvested fruit, both after storage and after shelf life, although this trend was not always clear.

3.4.4. Titratable acidity

There was a slight reduction in TA over time in 'Angeleno' after both storage and shelf life. Fruit harvested earlier tended to have higher TA values than those harvested later. After shelf life, the TA values of fruits from those harvests with the highest initial TA seemed to decrease faster than those with the lower initial TA. pH of 'Angeleno' increased over time in both storage and shelf life, though the increase was relatively small (data not shown).

3.4.5. Total Soluble Solids

In 'Angeleno', there was a slight increase in TSS over time during both storage and shelf life. Although there were statistically significant differences between harvest dates with regards to TSS, the differences were so small that they would probably not be noticed in a taste test when considered on its own. No effect of cold could be seen on flavour development, as there was no effect on TSS or TA.

3.4.6. EC of inner mesocarp

With increasing storage time, ECIn of 'Angeleno' decreased (Fig. 8). This decrease occurred during storage and did not change when measured after shelf life indicating that this cultivar can probably withstand cold temperatures for a longer time before damage to the membranes occurs. No particular trend could be seen with respect to the effect of harvest date on ECIn, either after storage or after shelf life.

3.4.7. EC of the outer mesocarp

The absence of any disorders in 'Angeleno' can be seen in the relatively unchanged ECOut. The electrical conductivity of the outer mesocarp of 'Angeleno' was lower than ECIn after both storage and shelf life (Fig. 9). As with ECIn, ECOut of 'Angeleno' generally decreased over storage time for both storage and shelf life. The only exception was an increase after five weeks storage and one week shelf life for harvest four fruit. No effect of harvest time on ECOut could be seen.

3.4.8. Internal disorders

The only internal disorder that was noted in 'Angeleno' was aerated flesh (AF). No GB, IB or OR was found in 'Angeleno' at any time during storage or shelf life (Fig. 11). At harvest, the earlier harvests had lower incidences of AF than the later harvest (Fig. 13). The increased AF in later harvested fruit could indicate a possible drawback of allowing this cultivar to remain on the tree for an extended period. However, as storage time increased, this effect of harvest time became less apparent. Storage had no effect on AF before shelf life, but there was an increase in AF after shelf life after 2 weeks of storage and the highest incidence of AF was found after five weeks of storage and 1 week shelf life. The initial effect of harvest time on AF was not maintained during storage.

4. Overall discussion and conclusion

Ethylene production rates were used to classify the cultivars into the climacteric classes as described by Abdi *et al.* (1997), where a suppressed climacteric cultivar is one that typically produces 15-500 times less ethylene than a climacteric cultivar and where ethylene production is delayed. Based on the ethylene production rate of the four cultivars studied, we classified 'Pioneer' as climacteric (max. 125.0 $\mu L.kg^{-1}h^{-1}$) and 'Songold' and 'Angeleno' as suppressed climacteric (max. 22.0 and max. 1.6 $\mu L.kg^{-1}h^{-1}$, respectively). 'Sapphire' (max. 48.0 $\mu L.kg^{-1}h^{-1}$) was more

difficult to classify as the fruit from the earlier harvests behaved more like a suppressed climacteric cultivar and the fruit from the later harvests behaved like a climacteric cultivar, but based on ethylene production and general ripening patterns, we have classified it as climacteric. Although there is, as yet, no specific "cut off" value by which to classify the climacteric and suppressed climacteric classes, the ethylene evolution and ripening patterns of the four cultivars studied gave a good indication of where they should be placed.

When hue angle as well as percentage green fruit are considered together to represent colour development, two trends become apparent. Firstly, fruit that are harvested later tend to have better colour development than fruit harvested earlier in the harvesting period. The second trend that can be seen is the effect of cold temperature storage on colour development. The longer the fruit is kept at -0.5°, the more colour develops once fruit is placed at ripening temperatures. In 'Songold', a suppressed climacteric plum, this trend was seen very clearly as storage time increased. In 'Pioneer' and 'Sapphire', the two climacteric cultivars, the trend was not as clear. This seems to indicate that climacteric cultivars do not need cold in order to develop full colour. However, though not evident from the hue angle data, 'Sapphire' did not develop full colour after shelf life unless it was stored at -0.5°C prior to ripening. In the beginning of the storage period, the extent of colour development after shelf life was greater than in 'Songold' but less than in 'Pioneer'. As storage time increased, colour development after shelf life increased and a shorter storage period was needed for full colour development in 'Sapphire' than in 'Songold'.

It would seem that both climacteric and suppressed climacteric cultivars develop better colour with later harvesting. Earlier harvests of climacteric cultivars can, nevertheless, develop full colour without cold, while those of suppressed climacteric cultivars require cold.

In all four cultivars, the decrease in flesh firmness between harvest times was not as great as expected, indicating that leaving fruit on the tree to increase in size and accumulate sugars will not necessarily result in fruit that is too soft at harvest. In our experiments, flesh firmness readings were higher than those of fruit harvested by the grower, even though fruit had been left on the tree for a longer period. This indicates the importance and efficacy of harvesting at optimum maturity. Furthermore, fruit was cooled immediately after harvest without delay, indicating the importance of cooling fruit as soon as possible after harvest to retain flesh firmness and extend shelf life. Depending on the cultivar, placing fruit in a cold store before packing and only packing when sufficient quantities of fruit are available will result in softer fruit with more internal breakdown and is undesirable (Combrink & Visagie, 1997). Where fruit were softer, such differences tended to be

negated after storage and shelf life.

The different effect of a cold storage period on climacteric or suppressed climacteric plums at -0.5°C can be seen. This is especially clear in the suppressed climacteric cultivar, 'Songold'. When there was no storage at -0.5°C, there was no drop in firmness after shelf life. The longer the storage period at -0.5°C, the greater the decrease in firmness once fruit was placed at ripening temperatures. A similar result was seen in fruit of harvest 1 to 4 of 'Sapphire'. In this cultivar, only firmness of harvest 5 fruit decreased rapidly without the need of a cold storage period. This indicates that cold is needed to stimulate ripening and therefore softening in suppressed climacteric cultivars but that cultivars with higher levels of ethylene production may only need cold for those fruit that have been harvested early or are not sufficiently mature. 'Pioneer', a climacteric cultivar, did not require cold to induce ripening in fruit from any of the five harvests.

Total soluble solids increased with advancement of harvest date in a trial conducted by Singh *et al.* (1990) on cv. 'Kala Amritsar' and 'Kataru Chak'. In our trial, trends between harvest dates and TSS levels at harvest were not consistent. This was aggravated by the diluting effect of the rain during the harvest of 'Pioneer'. One would expect there to be a clear increase in TSS from one harvest date to the next. The fact that we consistently harvested fruit at optimum maturity and not overripe fruit, and that enough fruit were left on the tree to negate the effect of thinning could explain why this increase in TSS is not always seen.

There was little change in TSS after shelf life when compared to storage for all four cultivars. Of the four principal sugars in 'Songold' plums, sucrose and fructose tend to increase with single or dual temperature storage, while glucose decreases. Sorbitol increases and decreases with single and dual temperature storage respectively (Taylor *et al.*, 1993d).

An increase in electrical conductivity indicates an increase in electrolyte leakage. The increased leakage of electrolytes as storage time progressed is an indication that cell membranes were becoming damaged due to chilling injury. The increase in ECIn after shelf life is consistent with findings that internal conductivity in peaches increased when fruits were transferred to 21°C (Furmanski and Buescher, 1979). This is probably due to the cell contents becoming more fluid at higher temperatures. However, the increase in ECIn after shelf life was smaller than one would expect when comparing it to the incidence of internal disorders seen after shelf life. This was probably due to binding of electrolytes into gel complexes together with the bound water as GB forms. Similar results have been found on peaches (Furmanski and Buescher, 1979). Conductivity

was enhanced in fruits chilled for 1 and 2 weeks but declined in longer stored fruit when transferred to 21°C. This decline coincided with the first symptoms of woolliness. Free ions are increasingly bound with increasing time of chilling. The first stage may indicate an alteration in membrane permeability and the subsequent leakage of cell fluids. The second stage is an indication of cations being bound to the enhanced levels of demethylated pectin which then forms rigid gel complexes. This would explain why 'Songold', that had the highest level of GB, also had the lowest ECIn after shelf life.

The lower ECOut of all four cultivars after both storage and shelf life when compared to ECIn is probably due, in part, to changes in cell morphology between the inner and outer mesocarp as described by Taylor *et al.* (1993b). Inner mesocarp tissue generally consists of bigger cells than the outer mesocarp and therefore there will be relatively more free electrolytes in any one volume of area (in this case the volume comprised by the conductivity bridge needles). For the same reason, the rise in ECOut when internal disorders become evident will be smaller than that of the inner mesocarp. The fact that this rise on ECOut occurs later than in ECIn indicates that the outer mesocarp may withstand cold storage for longer than the inner mesocarp. This may explain why GB (found in the inner mesocarp) still occurs in dual temperature storage, but that IB (mainly found in the outer mesocarp) can be controlled by dual temperature storage.

With increasing storage time, there was an increase in GB and IB after both storage and shelf life for all four cultivars. Prolonged storage at low temperatures results in chilling injury that is manifested as GB or IB. Taylor (1993a) found a similar increase in GB and IB after 30 days storage at -0.5°C and found that it was associated with the increase in electrolyte leakage and internal conductivity at a time when the viscosity of water soluble pectin was at its highest. Extractable juice decreased, indicating that cell fluids had bound to pectic substances in the cell wall (Taylor *et al.* 1993a). Limited availability of cell fluids combined with the reduced ability of pectins to bind fluids may have resulted in the development of OR as opposed to GB in the outer mesocarp (Taylor *et al.*, 1993b). The reduction in GB in 'Pioneer' and 'Sapphire' after shelf life towards the end of the storage period could be due to the increased level of IB that could mask the GB symptoms. One would expect lower levels of GB for the earlier harvests and this is the case for 'Sapphire' and 'Songold'. However, the lack of a clear trend in incidence of GB with relation to harvest date is significant as the general perception is that delaying harvesting results in more internal disorders. In peaches, Ju *et al.* (2000) found that fruit harvested earlier tended to have more leatheriness and fruit harvested later had more mealiness, indicating that these disorders were different and occurred at different maturities. Fruit from the later harvests developed more disorders than those of the earlier

harvest. Abdi *et al.* (1997a) reported that more mature plums are more likely to suffer internal problems during storage. It was suggested that during the early stage of ripening there was less soluble pectin in the intercellular spaces of the fruit and that this may be the reason for the lower incidence of chilling injury (Abdi *et al.* 1997a). However, this does not seem to present a problem if the fruit are harvested at the optimum maturity.

As found in 'Pioneer, 'Sapphire' and 'Songold' in this trial, Taylor *et al.* (1993a) found that OR in 'Songold' plums was inhibited by storage at -0.5°C, but developed during ripening if stored for less than 30 days. The reduction in OR towards the end of the storage period is a common phenomenon and could be due to three reasons: Firstly, the reduction in levels of OR could be due to the binding of cell fluids to form rigid gel complexes (Taylor *et al.* 1993a, 1993c). Abdi *et al.* (1997a) reported an increase in firmness at this stage of development in 'Shiro' and 'Gulfruby' and connected it to the conversion of soluble pectins to insoluble forms. Secondly, IB and severe GB could mask the presence of OR. Thirdly, acetaldehyde that is formed during the formation of IB has been known to inhibit ripening in some fruit and may therefore have reduced the levels of OR (Ritenour *et al.*, 1997). The high level of OR in the first harvest of 'Songold' is significant as it indicates that this harvest could contain many overripe fruit that could have been harvested earlier as previously explained. Once again this indicates one of the negative aspects of strip harvesting.

In general, harvest time did not have as big an impact on fruit quality as expected. If anything, later harvested fruit seemed to be less prone to chilling injury and have better colour and flavour development. This shows that harvesting later does not negatively influence fruit quality as long as fruit are still harvested at optimum maturity. Strip harvesting will result in fruit being rejected due to too many overripe and immature fruit. Many growers are concerned about leaving fruit on the tree for too long in case of a sudden drop in flesh firmness. Therefore growers need to be able to determine the precise stage of development of their fruit in order to maximise the effect of enhanced maturity on quality whilst minimising its effect on chilling injury and overripeness (Abdi *et al.*, 1997a). The cost of an increased number of harvests should also be considered.

The influence of the climacteric class on fruit ripening pattern can clearly be seen when looking at the effect of cold storage prior to ripening. The effect of increased ethylene production due to increased cold storage period can be seen in colour development, softening (firmness) and flavour changes. 'Pioneer' coloured and softened without the need of a cold storage period. In 'Sapphire', early harvested fruit that had only been stored for one week or less at -0.5°C, showed an abnormal ripening pattern after shelf life, with the inner mesocarp still green and astringent and the outer

mesocarp showing signs of ripening such as colour change and softening. Later harvested fruit, however, ripened fully, even without cold storage. 'Songold' did not ripen at all without cold storage, irrespective of the harvest date. Suppressed climacteric plums appear to require a cold storage period to ripen, whereas climacteric fruit do not. This need for cold can be overcome in those fruit that may require cold storage to ripen by harvesting at a more advanced maturity, provided the natural rate of ethylene production of the fruit is high enough, as in 'Sapphire'.

The effect of the climacteric class on chilling injury susceptibility is less clear. In a study by Abdi *et al.* (1997a), it was suggested that the genetic background of cultivars influences the development of chilling injury and that fruit with a long fruit development period (FDP) are less prone to chilling. Although the cultivar in this study with the longest FDP, 'Angeleno', had the least amount of chilling injury, 'Songold', a suppressed climacteric cultivar, had more chilling injury than the climacteric cultivars 'Pioneer' and 'Sapphire' (which have shorter FDP's than 'Songold'). It may be useful to further classify plums into even more classes. It is clear that a plum like 'Angeleno' should belong to a totally different class from any of the other plums and that this genotype would be very useful in plum breeding programs. By incorporating the suppressed climacteric genotype into a breeding program it may be possible to prolong the storage period and shelf life.

Kotzé *et al.* (1989) found that the advantage gained in terms of internal breakdown by harvesting optimum or pre-optimum was only evident when fruit were stored above -0.5°C (3°C in their case) for the duration of the storage period. In dual temperature regimes, as well as during intermittent warming to 20°C, fruit of all maturities had less disorders. It will therefore be necessary to repeat these experiments in a dual temperature regime to determine the effect of harvest date on quality and ripening patterns when fruit are stored in this way.

To conclude, we have shown that allowing fruit to remain on the tree and accumulate sugars and increase in size will not result in an inferior quality fruit if harvested at optimum maturity. Secondly, the climacteric class of a plum, based on ethylene production rate, will affect the ripening pattern of a plum and can be used to determine how a specific cultivar will react during storage and assist in determining storage regimes for new plum cultivars.

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Table 1.

Significance values of the effect of harvest time (HT), storage time (STT) and harvest – storage interaction for ethylene production rate (C_2H_4), hue angle (H) , firmness (F), titratable malic acid (TA), total soluble solids (TSS), inner (ECIn) and outer (ECOut) electrical conductivity, gel breakdown (GB), internal browning (IB) and overripeness (OR) of 'Pioneer'.

	After storage			After shelf life		
	STT	**HT**	**STT*HT**	**STT**	**HT**	**STT*HT**
C_2H_4	.	.	.	0.0001	0.0047	0.0004
H	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
F	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TA	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TSS	0.0001	0.0001	0.0008	0.0001	0.0001	0.0001
EC In	0.0001	0.0041	NS	NS	0.0001	0.0012
EC Out	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
GB	0.0001	0.0001	0.0001	0.0001	NS	0.0001
IB	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
OR	.	.	.	0.0001	0.0001	0.0001

Table 2.

Significance values of the effect of harvest time (HT), storage time (STT) and harvest – storage interaction for ethylene production rate (C_2H_4), hue angle (H) , firmness (F), titratable malic acid (TA), total soluble solids (TSS), inner (ECIn) and outer (ECOut) electrical conductivity, gel breakdown (GB), internal browning (IB) and overripeness (OR) of 'Sapphire'.

	After storage			After shelf life		
	STT	**HT**	**STT*HT**	**STT**	**HT**	**STT*HT**
C_2H_4	.	.	.	0.0001	0.0001	0.0001
H	.	.	.	0.0400	0.0001	NS
F	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TA	0.0001	0.0129	0.0106	0.0001	0.0001	0.0001
TSS	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001
EC In	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
EC Out	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
GB	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
IB	0.0001	0.0281	NS	0.0001	0.0001	0.0001
OR	.	.	.	0.0001	0.0001	0.0001

Table 3.

Significance values of the effect of harvest time (HT), storage time (STT) and harvest – storage interaction for ethylene production rate (C_2H_4), hue angle (H) , firmness (F), titratable malic acid (TA), total soluble solids (TSS), inner (ECIn) and outer (ECOut) electrical conductivity, gel breakdown (GB), internal browning (IB) and overripeness (OR) of 'Songold'.

	After storage			After shelf life		
	STT	**HT**	**STT*HT**	**STT**	**HT**	**STT*HT**
C_2H_4	.	.	.	0.0001	0.0150	0.0001
H	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
F	0.0001	0.0012	0.0001	0.0001	0.0001	0.0001
TA	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
TSS	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
EC In	0.0001	0.0001	0.0001	0.0001	0.0350	0.0237
EC Out	0.0003	NS	0.0001	0.0001	0.0001	0.0001
GB	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
IB	0.0001	0.0004	0.0001	0.0001	0.0001	0.0001
OR	.	.	.	0.0001	0.0001	0.0001

Table 4.

Significance values of the effect of harvest time (HT), storage time (STT) and harvest – storage interaction for ethylene production rate (C_2H_4), hue angle (H) , firmness (F), titratable malic acid (TA), total soluble solids (TSS), inner (ECIn) and outer (ECOut) electrical conductivity and aerated flesh (AF) of 'Angeleno'.

	After storage			After shelf life		
	STT	**HT**	**STT*HT**	**STT**	**HT**	**STT*HT**
C_2H_4	.	.	.	0.0001	0.0001	0.0001
H	NS	NS	NS	0.0001	0.0043	0.0001
F	0.0219	0.0003	0.0100	0.0367	0.0002	0.0023
TA	0.0188	0.0001	0.0244	0.0001	0.0001	0.0001
TSS	0.0002	0.0003	0.0001	0.0001	0.0001	0.0001
EC In	0.0001	0.0104	0.0026	0.0001	0.0121	0.1377
EC Out	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
AF	NS	0.0001	0.0001	0.0001	0.0001	0.0001

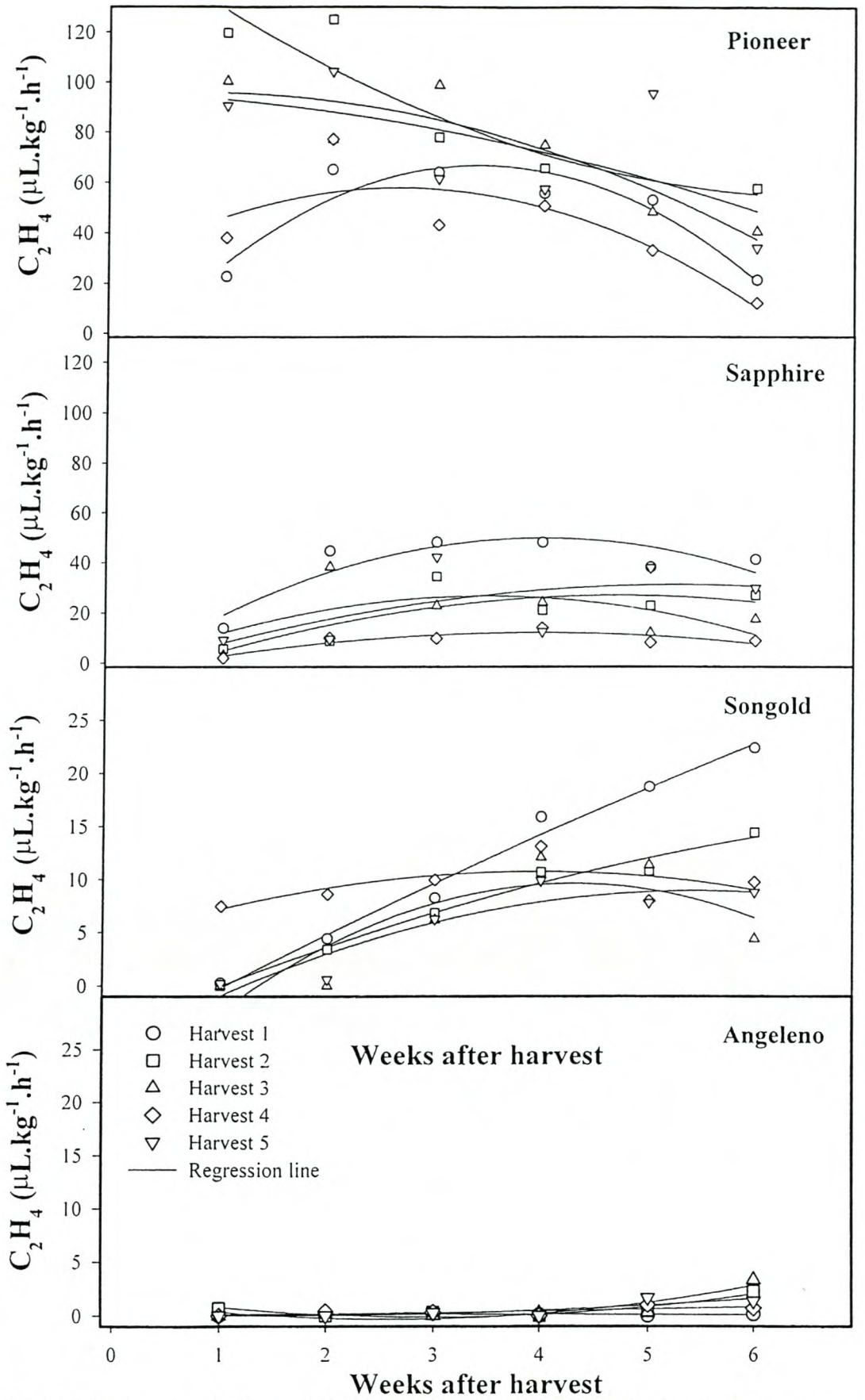

Fig. 1 Ethylene evolution of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks followed by one week at 15°C (shelf life). (Note y-axis scales differ).

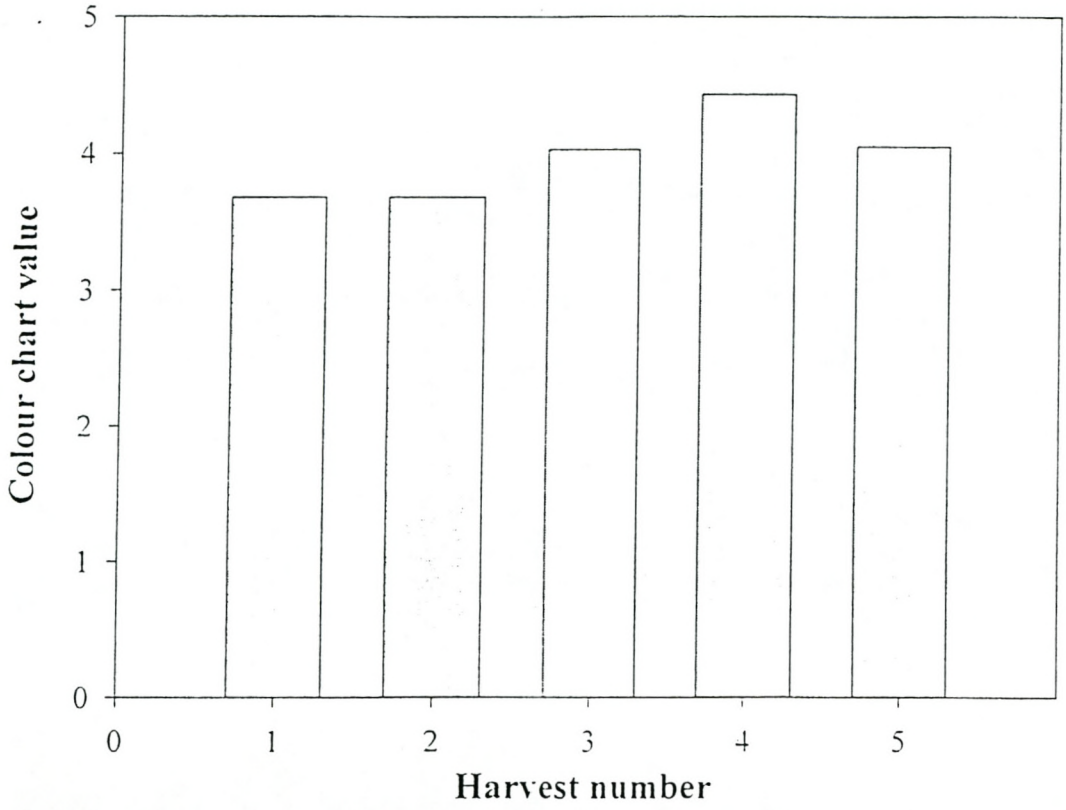

Fig. 2 Effect of harvest date on skin ground colour (measured with a colour chart where 0.5 = dark green and 5 = deep yellow) of 'Songold' plums at harvest.

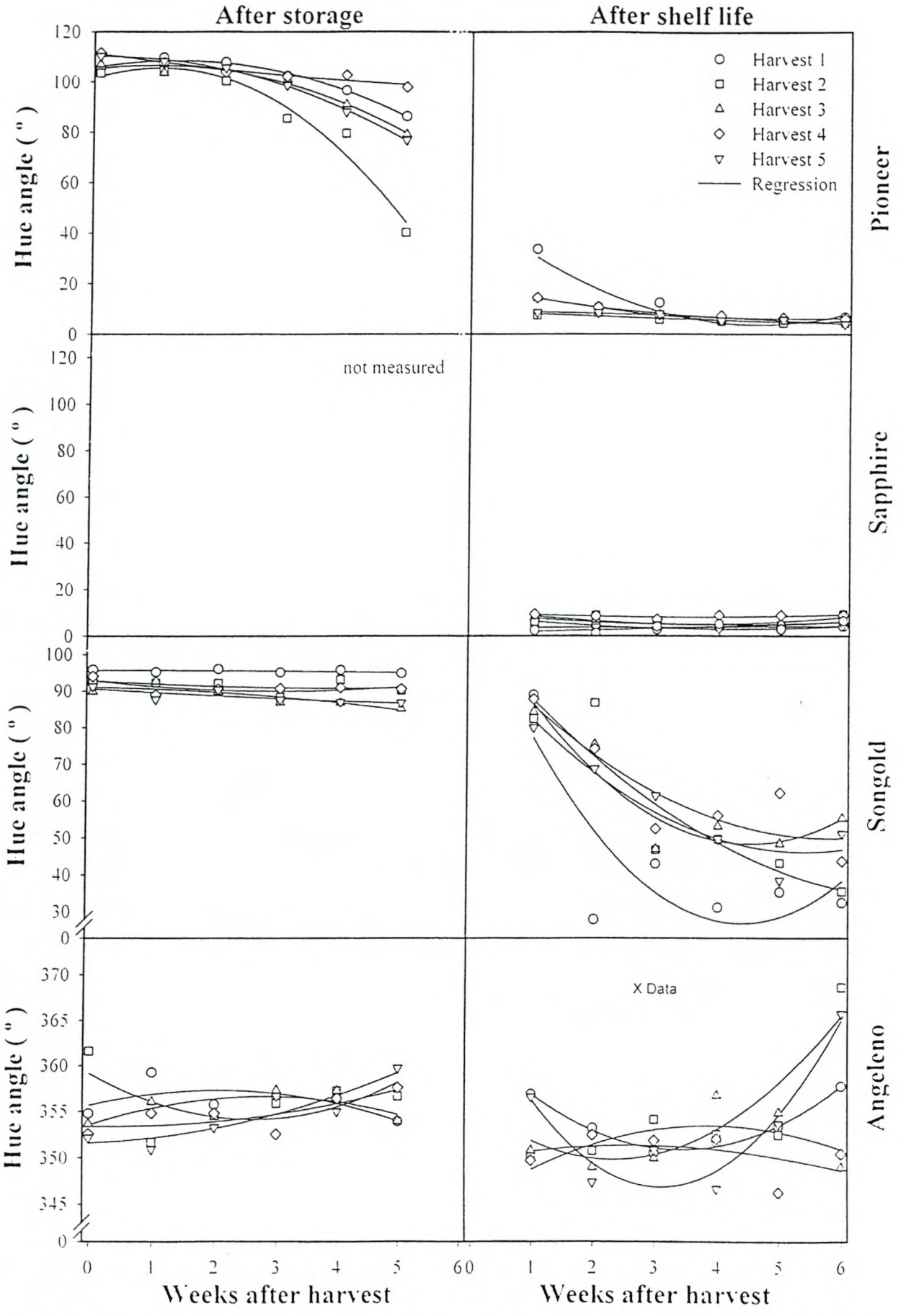

Fig. 3 Hue angle of four plum cultivars harvested five times and measured weekly after storage at –0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

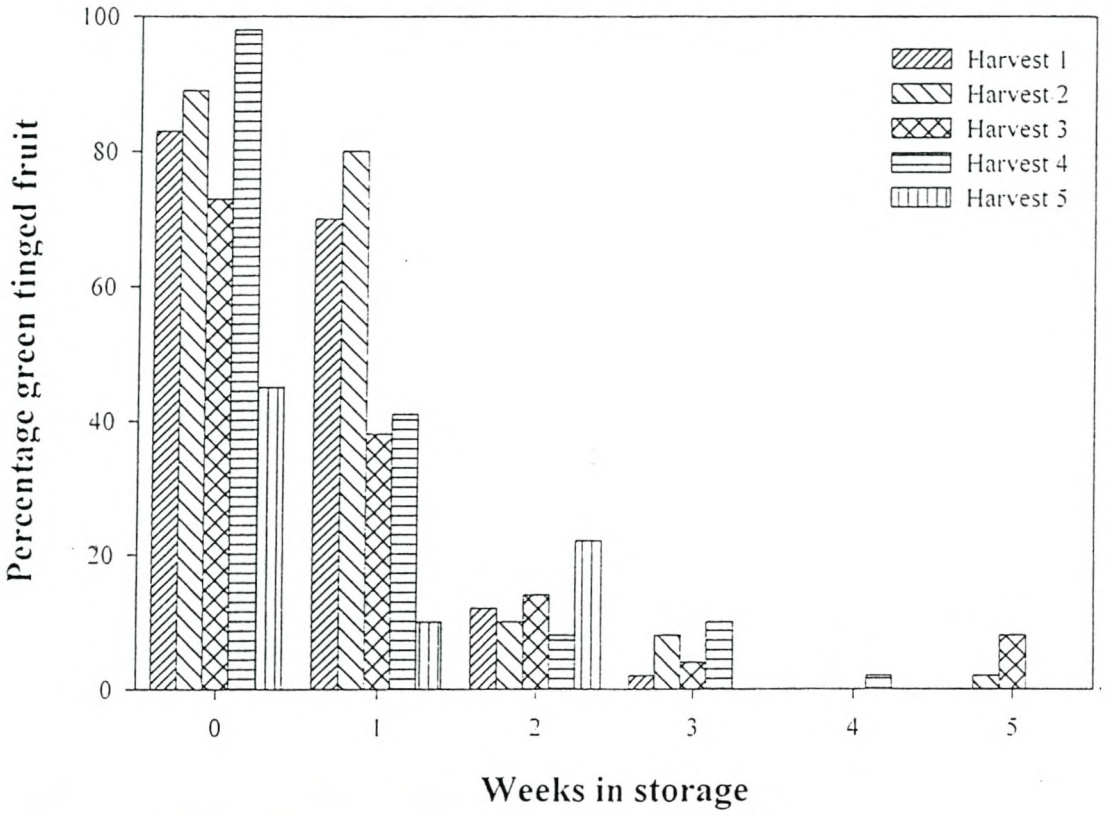

Fig. 4 Percentage green tinged fruit of 'Songold' plums harvested five times and measured weekly after storage -0.5°C for 0, 1, 2, 3, 4, and 5 weeks followed by one week shelf life at 15°C.

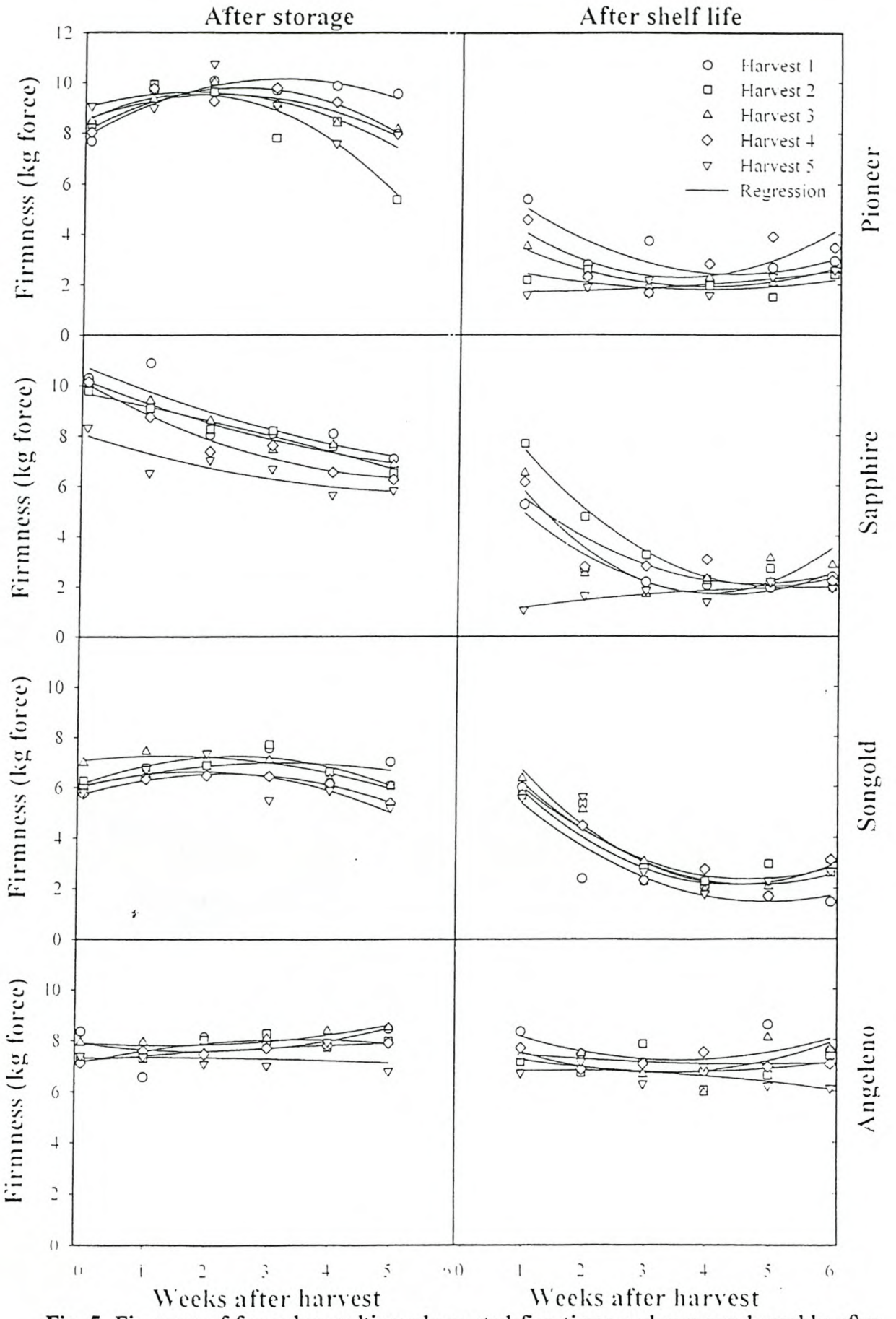

Fig. 5 Firmness of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

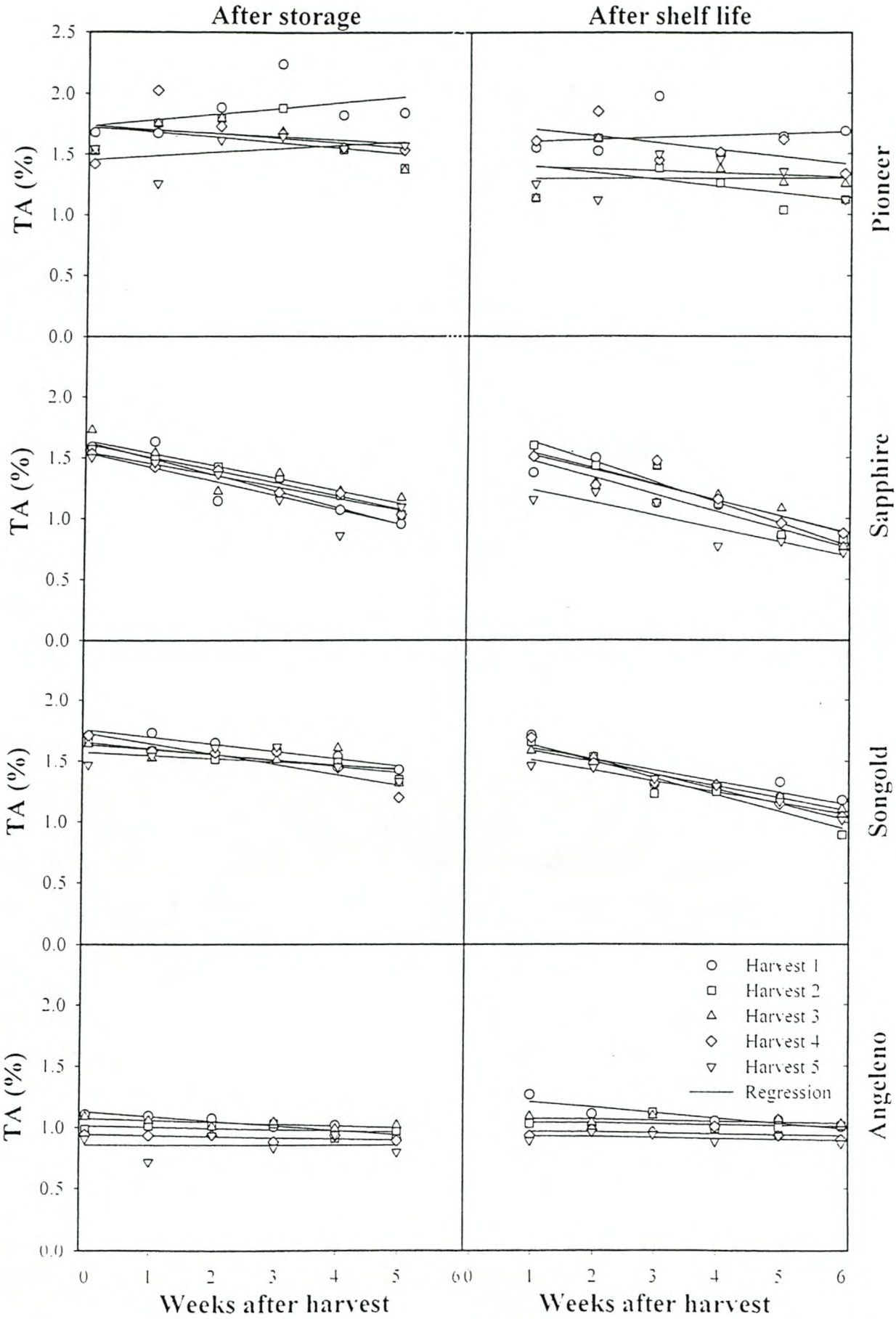

Fig. 6 Percentage titratable malic acid of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

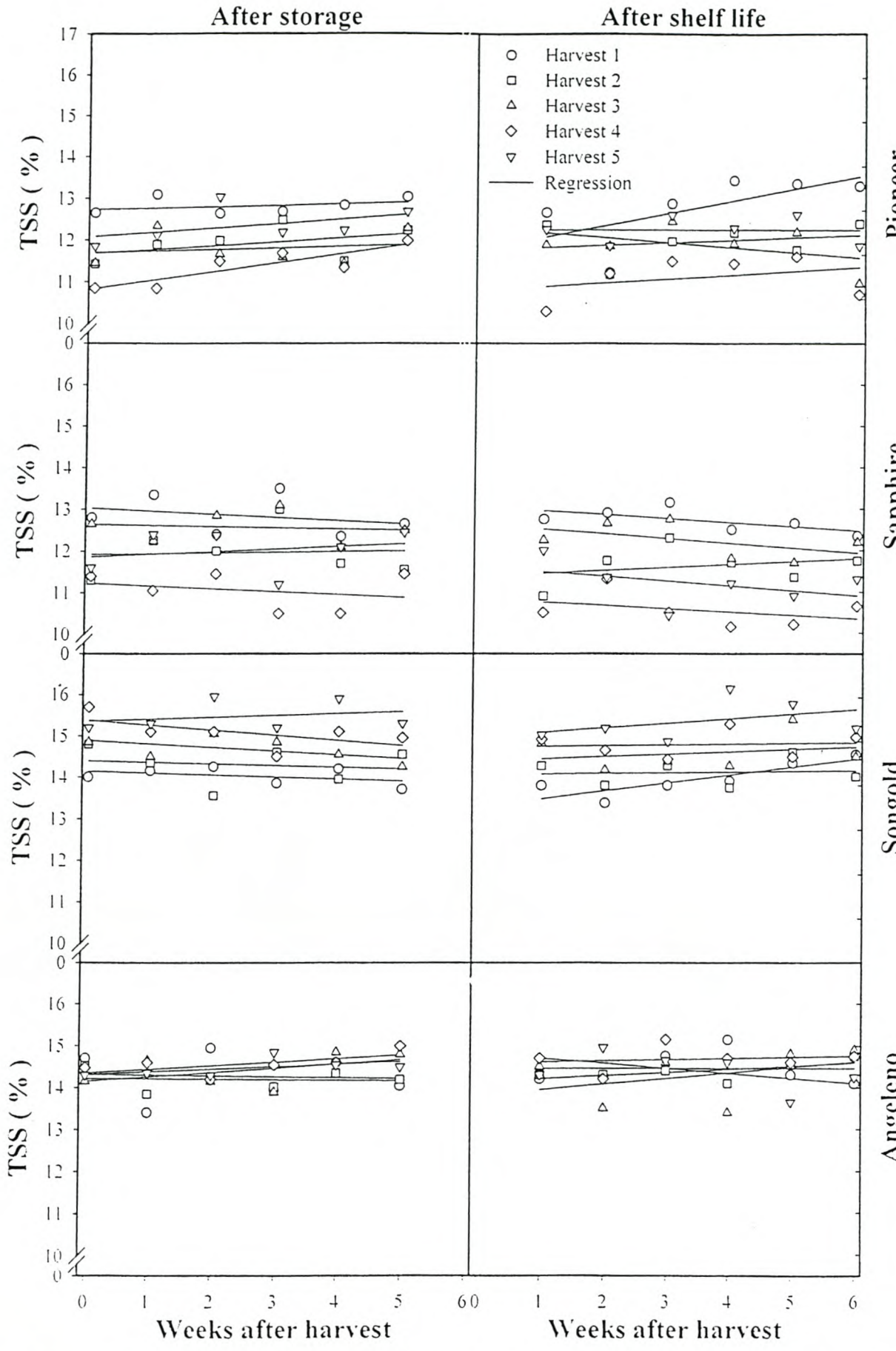

Fig. 7 Total soluble solids (TSS) of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

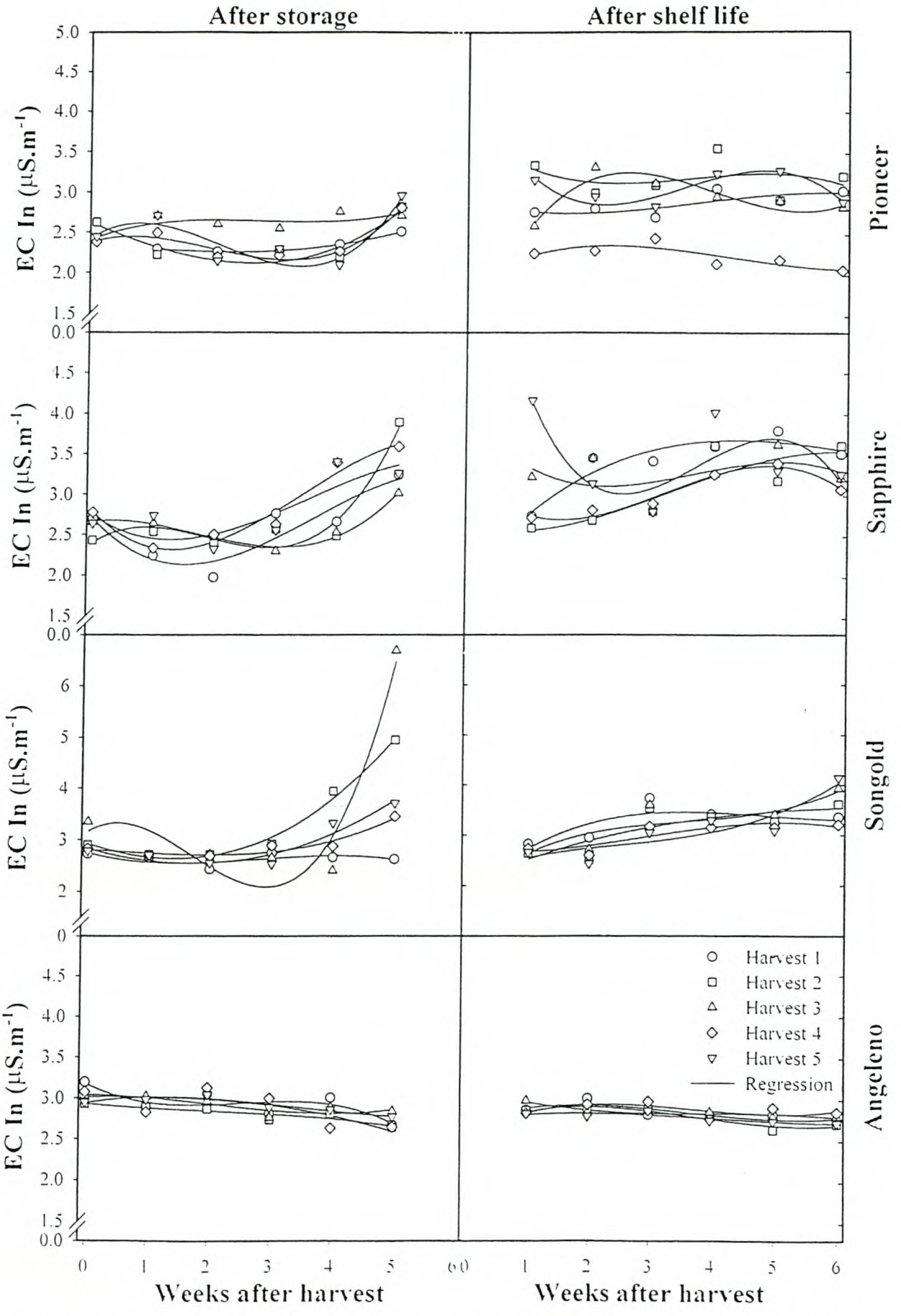

Fig. 8 Electrical conductivity of the inner mesocarp of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

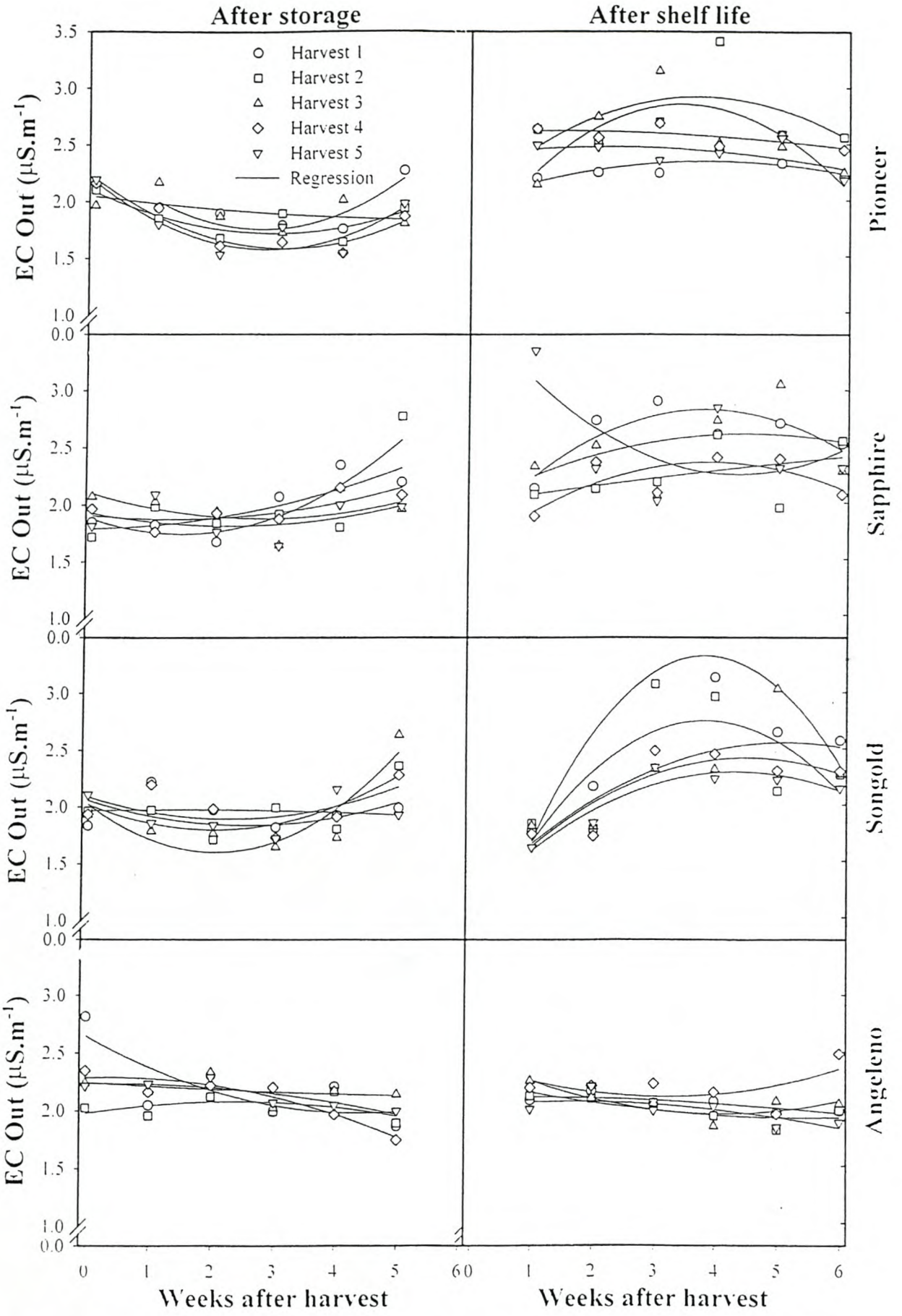

Fig. 9 Electrical conductivity of the outer mesocarp of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

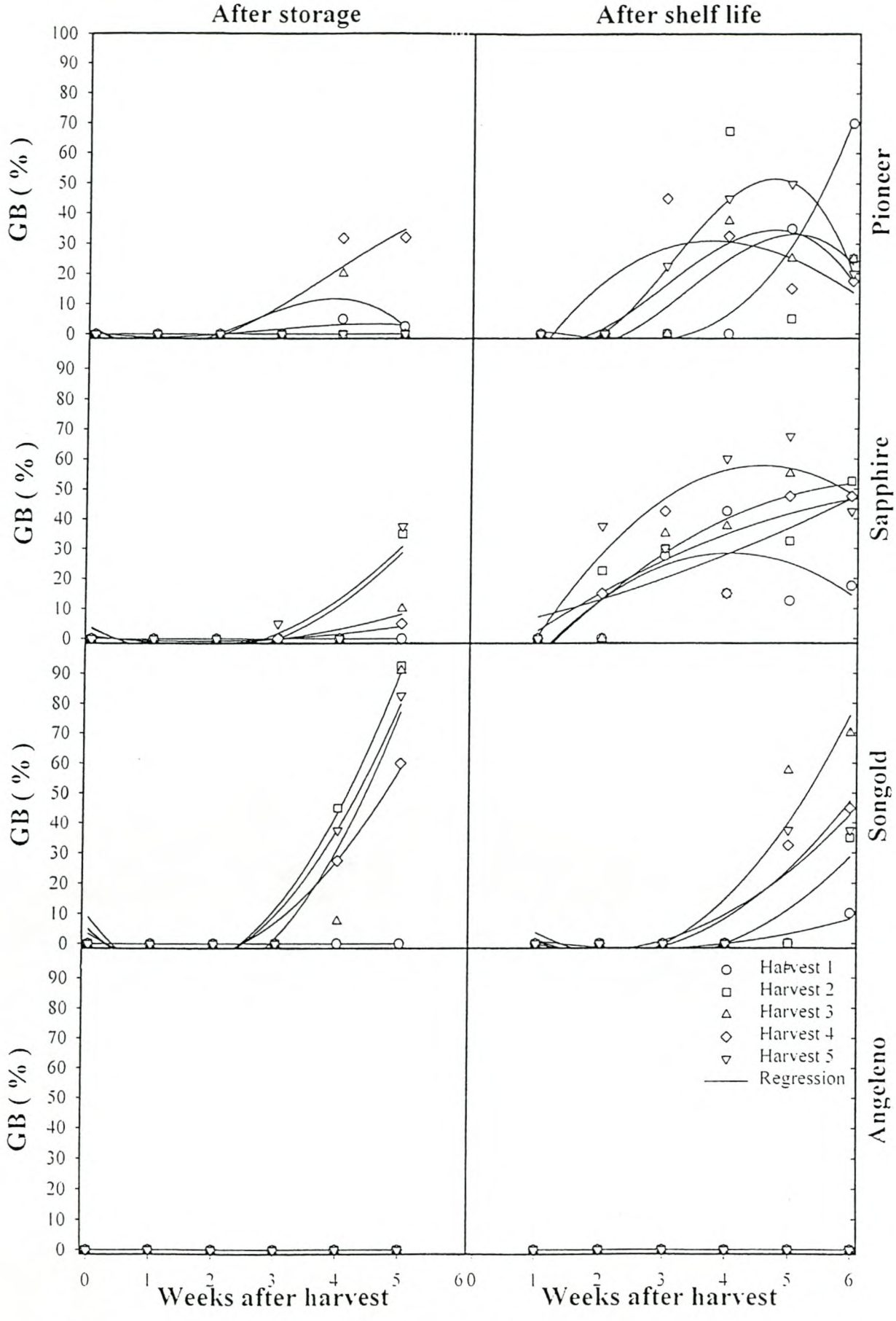

Fig. 10 Percentage gel breakdown (GB) of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

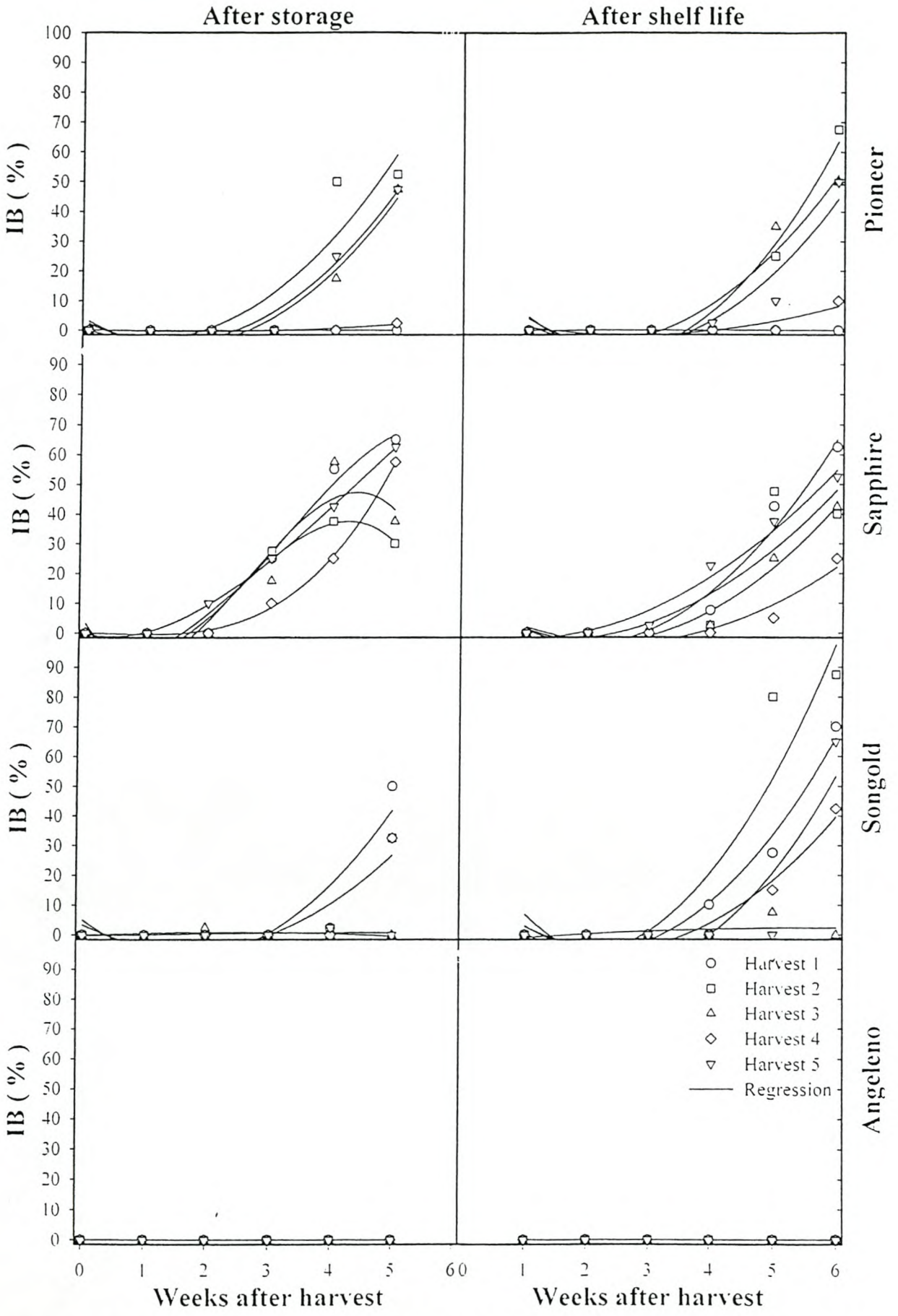

Fig. 11 Percentage internal browning (IB) of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

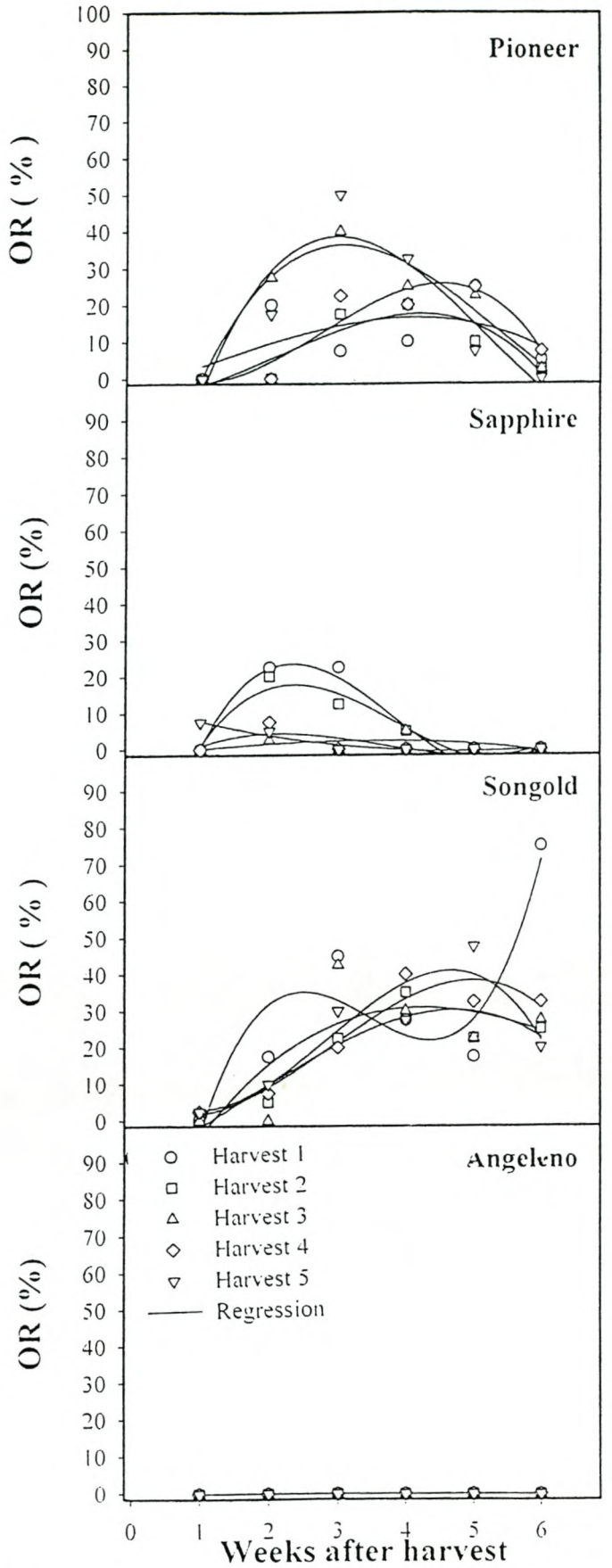

Fig. 12 Percentage overripeness (OR) of four plum cultivars harvested five times and measured weekly after storage at -0.5°C for 0, 1, 2, 3, 4, and 5 weeks plus one week at 15°C (shelf life).

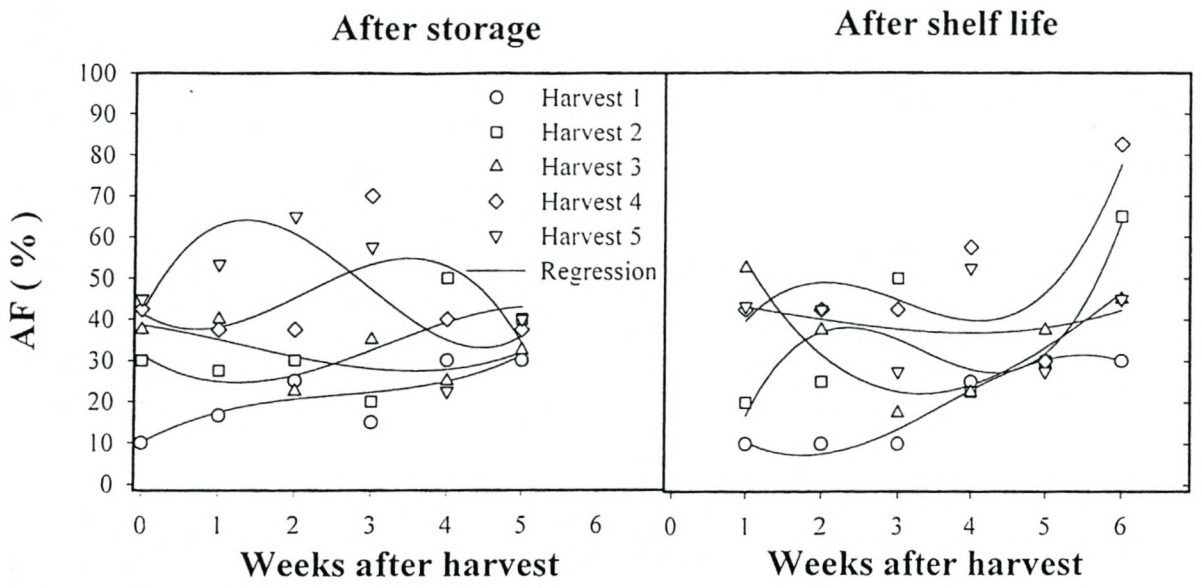

Fig. 13 Percentage aerated flesh (AF) of Angeleno plums harvested 5 times and measured weekly after storage at –0.5°C for 0, 1, 2, 3, 4, and 5 weeks and again after one week at 15°C (shelf life).

Ethylene production and respiration rates of four plum (*Prunus salicina* Lindl.) cultivars

Abstract

Plums, a climacteric fruit, can further be classified as climacteric or suppressed climacteric based on ethylene production. Although both were classified as climacteric, the respiration rates and ethylene production of 'Pioneer' plums during storage at –0.5°C and 7.5°C were higher than those measured for 'Sapphire'. Respiration rates measured for 'Songold' and 'Angeleno', both suppressed climacteric plums, were considerably lower than for the climacteric cultivars. 'Songold' and 'Angeleno' were also stored at 15°C to measure ethylene production. The suppressed climacteric plums responded to a period of cold at -0.5°C storage prior to transfer to 15°C, by higher rates of respiration and ethylene production. Preliminary results indicate that suppressed climacteric plums need a cold storage period in order to ripen normally, while climacteric cultivars do not.

Keywords: ripening, 1-amino-cyclopropane-1-carboxylic acid, temperature, suppressed climacteric, Pioneer, Sapphire, Songold, Angeleno

1. Introduction

Plums are climacteric fruit, meaning there is a continuous decrease in respiration rate followed by a sharp increase that is accompanied by autocatalytic ethylene production in the fruit (Sekse, 1988). Abdi *et al.* (1997) have further classified different plum cultivars as either climacteric or suppressed climacteric based on their rate of ethylene production. Suppressed climacteric plums typically produce a 15-500 fold lower level of ethylene than climacteric cultivars. However, they are still classified as climacteric as they show an ethylene peak. Furthermore, the ethylene is produced later than in climacteric types, towards the latter part of the ripening period. They also have a reduced respiratory climacteric (Abdi *et al.*, 1998).

The suppressed climacteric phenotype is the result of an impaired ability of the fruit to convert 1-amino-cyclopropane-1-carboxylic acid (ACC) to ethylene to co-ordinate ripening sufficiently. Levels of ACC during fruit development are similar between the two classes, though slightly lower in the suppressed climacteric type. This may be the result of higher levels of ethylene production in the climacteric cultivars as the genes for ACC are upregulated by ethylene (Abdi *et al.*, 1998). ACC

may also be more efficiently converted to malonyl or glutamylamino derivatives in the suppressed-climacteric cultivars.

High rates of flesh softening and susceptibility to internal breakdown are the main limitations of the market life of plum fruit (Plich, 1999). Climacteric classification may be a way of determining the ripening rate of a particular cultivar, length of shelf life and susceptibility to chilling injury. In a concurrent study, the four cultivars examined in this study were classified as climacteric ('Pioneer' and 'Sapphire') or suppressed climacteric ('Songold' and 'Angeleno'). The aim of this study was to further determine the differences in ethylene evolution and CO_2 production (i.e. respiration) of these four cultivars over time and at different temperatures. Measurements were taken at –0.5°C as well as at 7.5°C as these are the temperatures used in the South African dual temperature regime for plums. Measurements were also taken at 15°C as an average shelf life temperature.

The second part of this study focused on the effect of a cold storage period on ethylene production in 'Songold' and 'Angeleno'. It is known that 'Songold' plums will not ripen normally without receiving a cold storage period at -0.5°C. Untreated fruit turn "leathery" and fail to ripen. The primary effect of a low temperature stress in apples is a perturbation stimulating the ACC oxidase system followed by an autostimulation of ACC synthase (Jobling *et al.*, 1991). Therefore the capacity of converting ACC to ethylene is enhanced rather than damaged by chilling (Zhou *et al.*, 2001). This results in higher levels of ethylene in cold treated fruit. In slow ripening cultivars, exogenous application of ethylene (100 ppm for 1-3 days at 20°C) is needed for even ripening (Crisosto *et al.*, 2001). Therefore our hypothesis was that a cold storage period prior to ripening would affect ethylene evolution and CO_2 production once fruit is placed at higher temperatures.

2. Materials and methods

2.1. Plant material

Four different plum (*Prunus salicina* L.) cultivars ('Pioneer', 'Sapphire', 'Songold' and 'Angeleno') were harvested from a farm in Paarl, South Africa (33° 48'S , 19° 0'E) at commercial maturity. The initial flesh firmness and total soluble solids of the four plum cultivars was 8.5 kg and 12% for 'Pioneer', 10.0 kg and 12% for 'Sapphire', 6.5 kg and 15% for 'Songold' and 8.0 kg and 14.5% for 'Angeleno'.

2.2. System set-up

A dynamic or "flow through" system was used for determination of both the ethylene evolution and respiration. After harvest, six replicates of ten fruit each were placed into 5 litre buckets, one replicate per bucket. A flow board with needle valves was connected to the bottom of the bucket through an inlet valve to pump air in the bottom and out the top by means of an outlet valve connected to rubber tubing. Airflow rates were kept at a constant 400 $mL.min^{-1}$.

2.3. Sampling and analysis

An infra red gas analyser (IRGA – 5151, Kingston, Ontario) was connected to the outflow pipe to measure CO_2 production. Gas samples of 2 cm^3 were extracted from the outlet pipe for ethylene (C_2H_4) determination by gas chromatography (Varian GC 3300, Walnut Creek, California). The outlet pipe was long enough to ensure that no outside air would be pulled into the syringe. Measurements for both CO_2 and C_2H_4 were taken every two to three days.

Since 'Angeleno' and 'Songold' had very low levels of ethylene production at -0.5°C and 7.5°C, and since it is known that 'Songold' will not ripen normally without a cold storage period, we examined the effect of a cold shock on the respiration rate and ethylene production of these two suppressed climacteric cultivars. The storage regimes for both experiments and for each cultivar were as follows. The asterisk (*) indicates times when CO_2 and ethylene were not measured.

1. Ethylene production and respiration rates of the four cultivars:

'Pioneer' : -0.5°C for 37 days
7.5°C for 37 days
'Sapphire' : -0.5°C for 35 days
7.5°C for 35 days
'Songold' : -0.5°C for 10 days
7.5°C for 37 days
15°C for 35 days
'Angeleno' : -0.5°C for 35 days
7.5°C for 35 days
15°C for 35 days

2. Effect of cold shock on ethylene production and respiration of 'Songold' and 'Angeleno':

'Songold': 7.5°C for 35 days (same data as in part 1)
15°C for 35 days (same data as in part 1)
-0.5°C for 3 days* followed by 35 days at 7.5°C
-0.5°C for 3 days* followed by 35 days at 15°C
-0.5°C for 10 days* followed by 25 days at 15°C

'Angeleno' : 7.5°C for 35 days (same data as in part 1)
15°C for 35 days (same data as in part 1)
-0.5°C for 10 days* followed by 31 days at 7.5°C
-0.5°C for 10 days* followed by 35 days at 15°C

C_2H_4 was measured by comparing the output area of the sample to the area of a 1.1 ppm ethylene standard. Equation (i) was used.

$$\text{ethylene in } \mu L.kg^{-1}.h^{-1} = \frac{C_2H_4 \text{ of sample in ppm} * \text{air flow rate in } mL.h^{-1}}{\text{fruit mass measured in kg} * 1000} \quad \text{(i)}$$

CO_2 production was measured in ppm. The respiration rates were determined by equation (ii).

$$CO_2 \text{ production} = \frac{CO_2 \text{ concentration (in ppm)} * 1/10\,000}{100 * \text{flow rate in } mL.h^{-1} / \text{mass (in kg)}} \quad \text{(ii)}$$

3. Results

3.1. Ethylene production and respiration rates of the four cultivars:

3.1.1. Ethylene evolution

In 'Pioneer', no C_2H_4 was measured at -0.5°C at any time (Fig.1). At 7.5°C the highest level of ethylene production measured was 110.0 $\mu L.kg^{-1}.h^{-1}$ at the final sampling date (day 37). C_2H_4 evolution steadily increased with increasing storage time, but showed no climacteric peak.

'Sapphire' produced a maximum of 25.0 $\mu L.kg^{-1}.h^{-1}$ C_2H_4 after 21 days at 7.5°C. This value seemed to indicate a climacteric peak in C_2H_4 evolution. No C_2H_4 was measured at -0.5°C for the duration of the storage period (Fig.1).

Since ethylene evolution was low in 'Pioneer' and 'Sapphire' at 7.5°C, we also included 15°C for 'Songold' and 'Angeleno'. At 7.5°C, 'Songold' produced a maximum of 2.6 $\mu L.kg^{-1}.h^{-1}$ C_2H_4 at the final sampling date (day 37) (Fig. 1). At 15°C the maximum reached was 2.8 $\mu L.kg^{-1}.h^{-1}$ at day 35, the final sampling date. No C_2H_4 was measured at -0.5°C.

'Angeleno' produced no C_2H_4 at -0.5°C or 7.5°C at any time during the storage period. Maximum C_2H_4 production at 15°C was 22.0 $\mu L.kg^{-1}.h^{-1}$ at the end of the storage period (Fig.1).

3.1.2. CO_2 production

'Pioneer' produced a maximum CO_2 of 10 $mg.kg^{-1}.h^{-1}$ after 31 days in storage at -0.5°C (Fig. 2). At 7.5°C 'Pioneer' produced the highest level of CO_2 (38 $mg.kg^{-1}.h^{-1}$) after 28 days of storage, whereafter it decreased to approximately 22 $mg.kg^{-1}.h^{-1}$ for the remaining storage period. This seemed to indicate a respiration climacteric.

'Sapphire' produced a maximum CO_2 level of 7 $mg.kg^{-1}.h^{-1}$ after 10 days at -0.5°C and then decreased slightly (Fig. 2). A maximum CO_2 of 28 $mg.kg^{-1}.h^{-1}$ was reached after 10 days at 7.5°C whereafter it decreased to 15 $mg.kg^{-1}.h^{-1}$. At day 19 it showed a smaller peak CO_2 of 18 $mg.kg^{-1}.h^{-1}$.

Respiration in 'Songold' was only measured for 10 days at -0.5°C and in this period a maximum CO_2 of 5 $mg.kg^{-1}.h^{-1}$ was produced (Fig. 2). At 7.5°C the maximum was 17 $mg.kg^{-1}.h^{-1}$ at the last sampling date, day 37 and at 15°C it was 35 $mg.kg^{-1}.h^{-1}$ after 16 days. This value seemed to indicate a respiratory climacteric.

At 15°C, CO_2 production in 'Angeleno' steadily increased to a maximum of 43 $mg.kg^{-1}.h^{-1}$ at the final sampling date, day 37 (Fig. 2). At -0.5° and 7.5°C the maximum CO_2 was 16 and 7 $mg.kg^{-1}.h^{-1}$ respectively. No clear climacteric could be seen at any temperature.

3.2. Effect of cold shock on ethylene production and respiration of 'Songold' and 'Angeleno'

3.2.1.Ethylene production

The effect of the cold storage treatment on C_2H_4 production can clearly be seen at 7.5°C as well as at 15°C for both 'Songold' and 'Angeleno'. In 'Songold' (Fig. 4), fruit that received a 10 day cold storage period prior to being placed at 15°C produced more C_2H_4 than fruit that received a 0 or 3 day cold storage period. This maximum C_2H_4 of 4.5 $\mu L.kg^{-1}h^{-1}$ was reached after only 22 days of storage. In fruit stored for 3 days at -0.5°C, the maximum C_2H_4 of 2 $\mu L.kg^{-1}h^{-1}$ was reached after 31 days. C_2H_4 levels of fruit that received no cold storage remained low and only increased at the end of the storage period. In fruit stored at 7.5°C (Fig. 3) after the cold storage period similar results were found, but in this case the maximum C_2H_4 of 3.6 $\mu L.kg^{-1}h^{-1}$ for fruit stored for 3 days was only reached after 28 days at 7.5°C.

In 'Angeleno' the maximum rate of C_2H_4 production at 15°C was 14.0 $\mu L.kg^{-1}h^{-1}$ after 25 days for fruit cold stored for 0 days (Fig. 6). Fruit that had received cold storage for 10 days reached a maximum level of C_2H_4 production of 5.5 $\mu L.kg^{-1}h^{-1}$ at the end of the storage period. At 7.5°C no C_2H_4 was produced in either treated or untreated fruit (Fig. 5).

3.2.2. CO_2 production

No clear effect of the cold storage period on CO_2 production could be seen on either cultivar (Fig. 3, 4, 5 & 6). However, the effect of temperature on respiration rate is clear, with higher temperatures resulting in higher respiration rates.

4. Discussion and conclusions

'Pioneer' was the plum cultivar that produced the highest amount of C_2H_4, followed by 'Sapphire', 'Songold' and 'Angeleno' (Fig. 1). 'Pioneer' and 'Sapphire' have been classified as climacteric and 'Songold' and 'Angeleno' as suppressed climacteric based on the classification by Abdi *et al.* (1998) (Paper 2). As discussed in Paper 2, 'Sapphire' was intermediate between climacteric and suppressed climacteric with regards to ethylene production, but based on ripening patterns it was classified as climacteric. As found by Abdi *et al.* (1998), the production of CO_2 seemed to correlate with the C_2H_4 production class, with climacteric plums producing more CO_2 than suppressed climacteric plums.

Heat production of a commodity is calculated by multiplying ml $CO_2.kg.h^{-1}$ by 122 to get kcal.metric $ton^{-1}.day^{-1}$ (Crisosto *et al.*, 2001). Classifying plums as either climacteric or suppressed climacteric could assist in determining shipping temperature regimes as plums with a high

respiration rate will also generate more heat, resulting in higher costs to keep the fruit at optimum temperature. Furthermore, the respiration curve can be used as an objective criterion for determining the physiological status, i.e. the stage of maturity of a fruit. By correlating factors such as TSS, colour, flesh firmness etc. with this respiration curve, it would be possible to determine criteria for harvesting optimum maturity fruit (de Swardt & Redelinghuys, 1968).

Storing plums at -0.5°C prior to transfer to 7.5°C or 15°C seemed to hasten the onset of ripening once transferred to these higher temperatures. Rates of C_2H_4 evolution were higher and earlier for those 'Songold' plums that received the most cold storage prior to ripening (Fig. 3 & 4). It has been found that 'Songold' and 'Angeleno' plums that have not received a cold storage period prior to ripening fail to soften or develop colour, but that 'Pioneer' will ripen without any cold storage (Paper 2).

Storing plums at -0.5°C prior to storage clearly has an effect on certain cultivars. This effect seems to be more pronounced in cultivars that produce less C_2H_4 (i.e. suppressed climacteric). 'Pioneer' did not need any cold storage prior to ripening to produce maximum levels of C_2H_4 (Paper 2). 'Sapphire' increased its C_2H_4 production after only one week of cold storage and the ethylene production of both 'Songold' and 'Angeleno' increased with increasing storage time. It therefore seems that classifying plums as climacteric or suppressed climacteric could also indicate which cultivars require cold to ripen normally. This would affect the dual temperature regime currently in use in South Africa, as the storage period at -0.5°C prior to being placed at 7.5°C will induce ripening in some cultivars but will have no effect on the ripening of others. Furthermore, the true suppressed climacteric cultivars, e.g. 'Angeleno', could be shipped at -0.5°C without the danger of chilling injury. It may, however, be necessary to supply ethylene (100 ppm for 1-3 days at 20°C) to co-ordinate ripening of these cultivars (Crisosto et al., 2001).

The C_2H_4 evolution and respiration patterns of the four cultivars studied were well correlated to the climacteric classes into which they had been placed. By incorporating the suppressed climacteric character into a breeding program it may be possible to produce slower ripening plums with lower rates of respiration and ethylene production as well as lower heat production. The effect of chilling on C_2H_4 production provides another parameter by which to determine optimum shipping regimes for plums.

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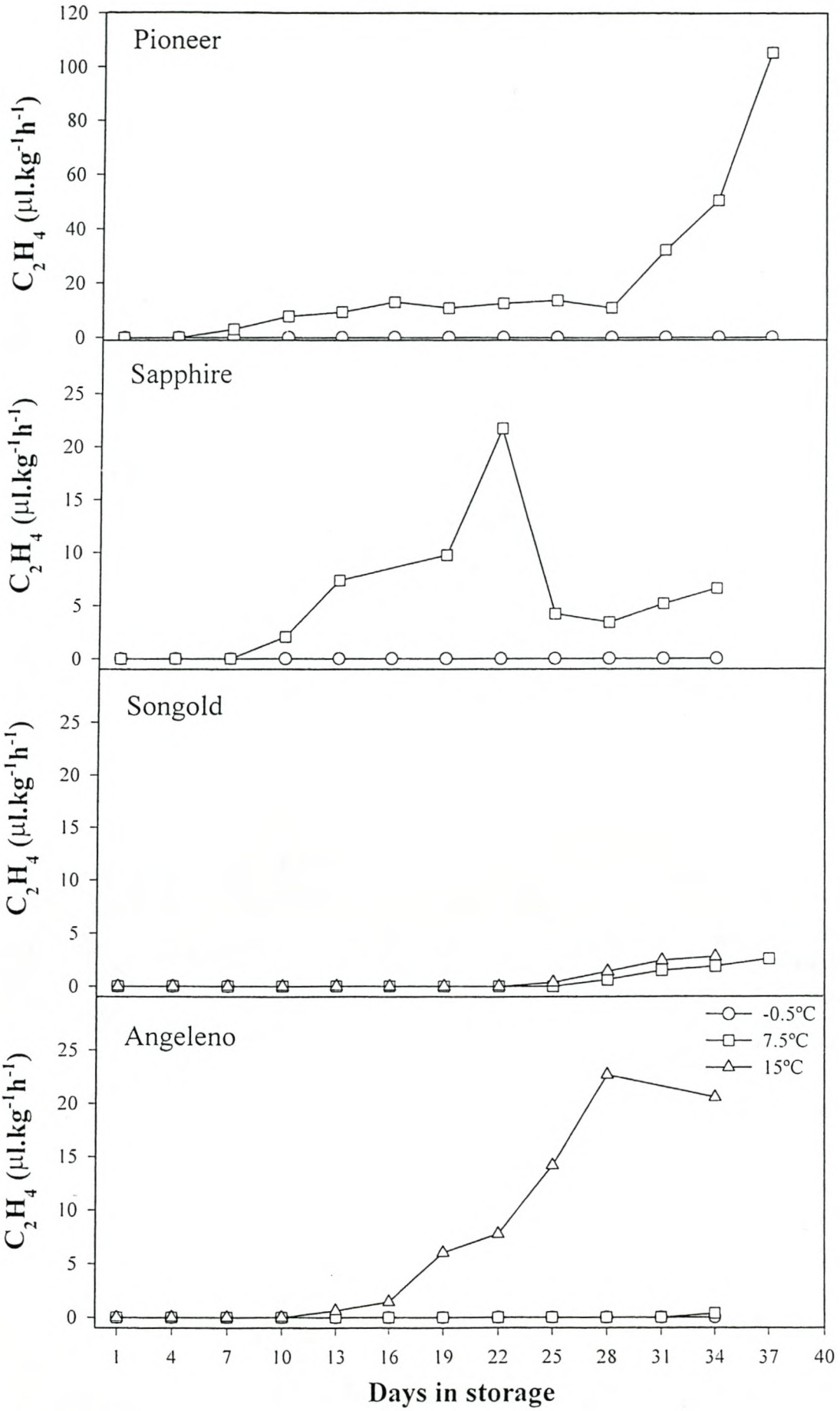

Fig. 1 Ethylene production rates of four plum cultivars at three temperatures measured every three days from harvest. (Note y-axis scales differ).

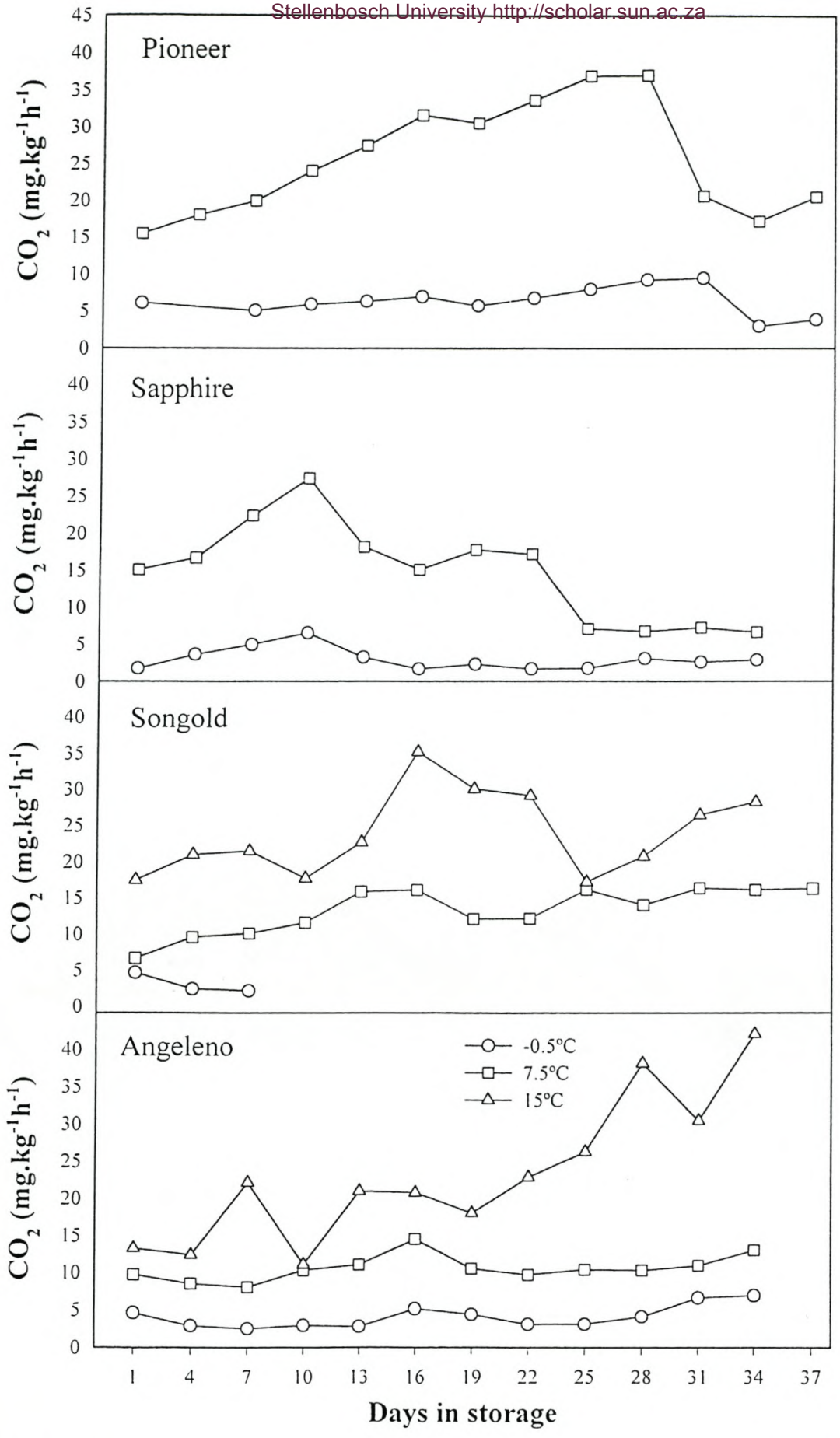

Fig. 2 Respiration rates of four plum cultivars at three temperatures measured every three days from harvest.

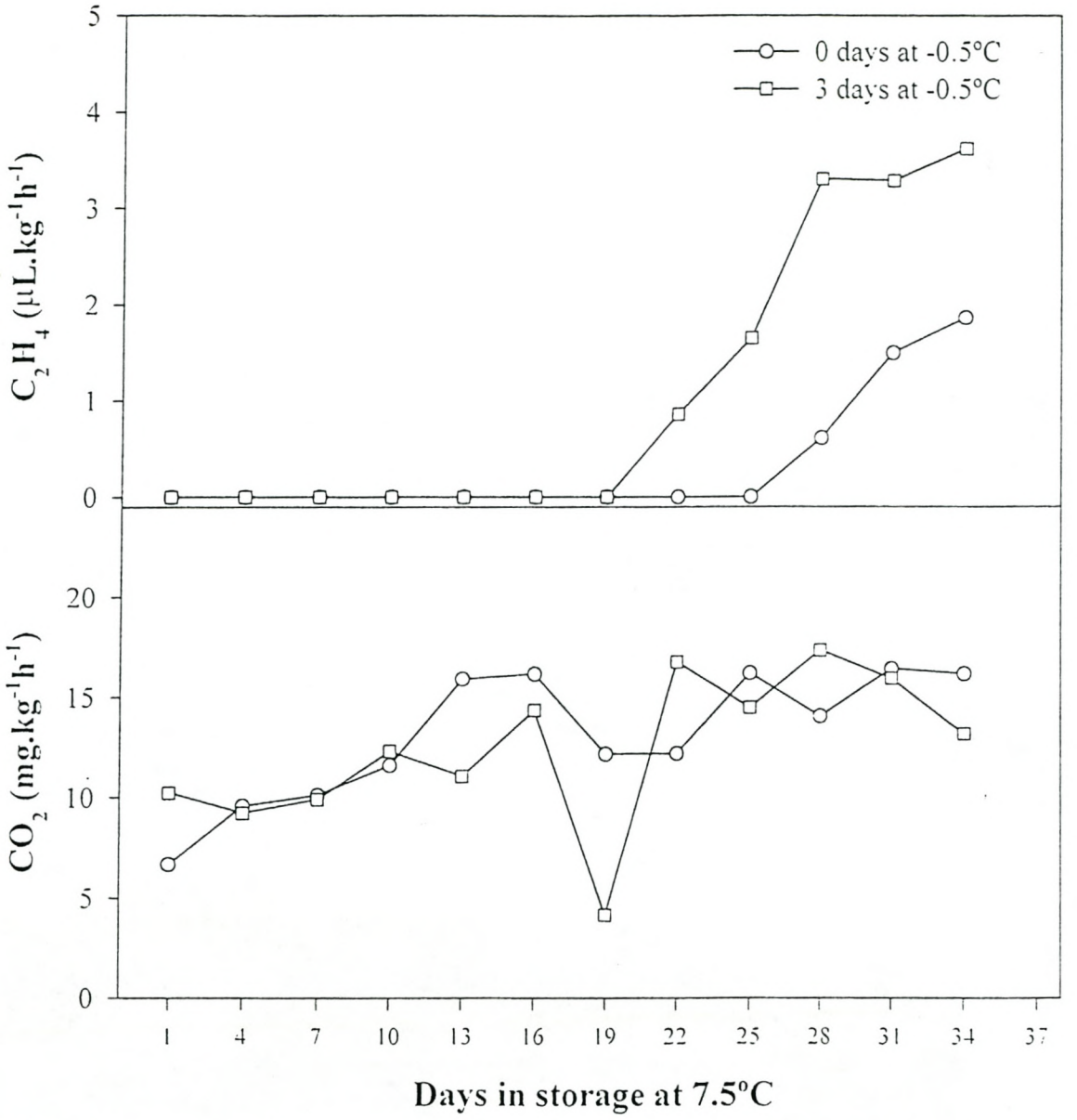

Fig. 3 Respiration and ethylene production of 'Songold' plums measured every three days at 7.5°C following cold storage treatment at -0.5°C for 0 and 3 days.

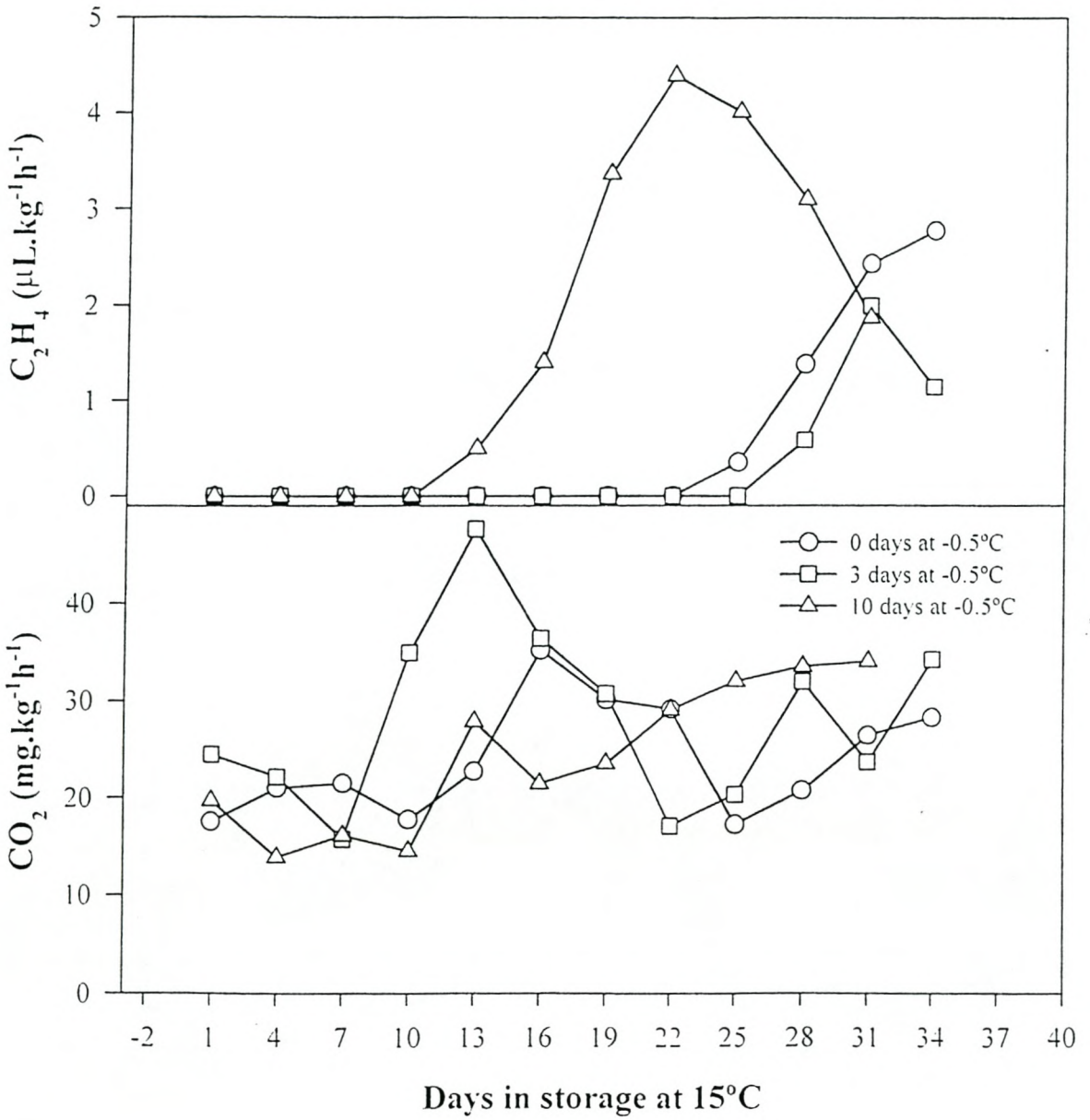

Fig. 4 Respiration and ethylene production of 'Songold' plums measured every three days at 15°C following cold storage treatment at -0.5°C for 0 , 3 and 10 days.

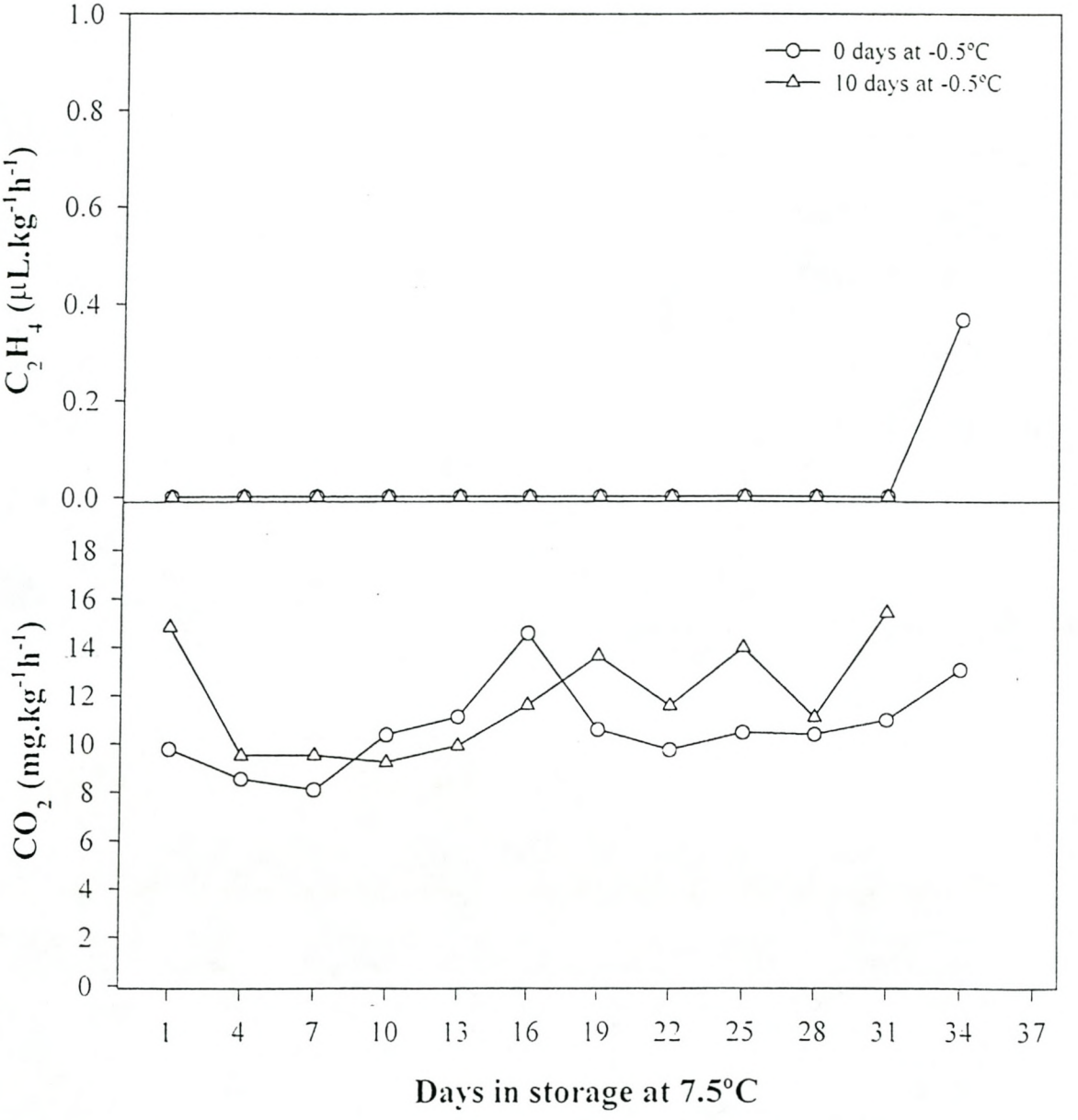

Fig. 5 Respiration and ethylene production of 'Angeleno plums measured every three days at 7.5°C following cold storage treatment at -0.5°C for 0 and 10 days.

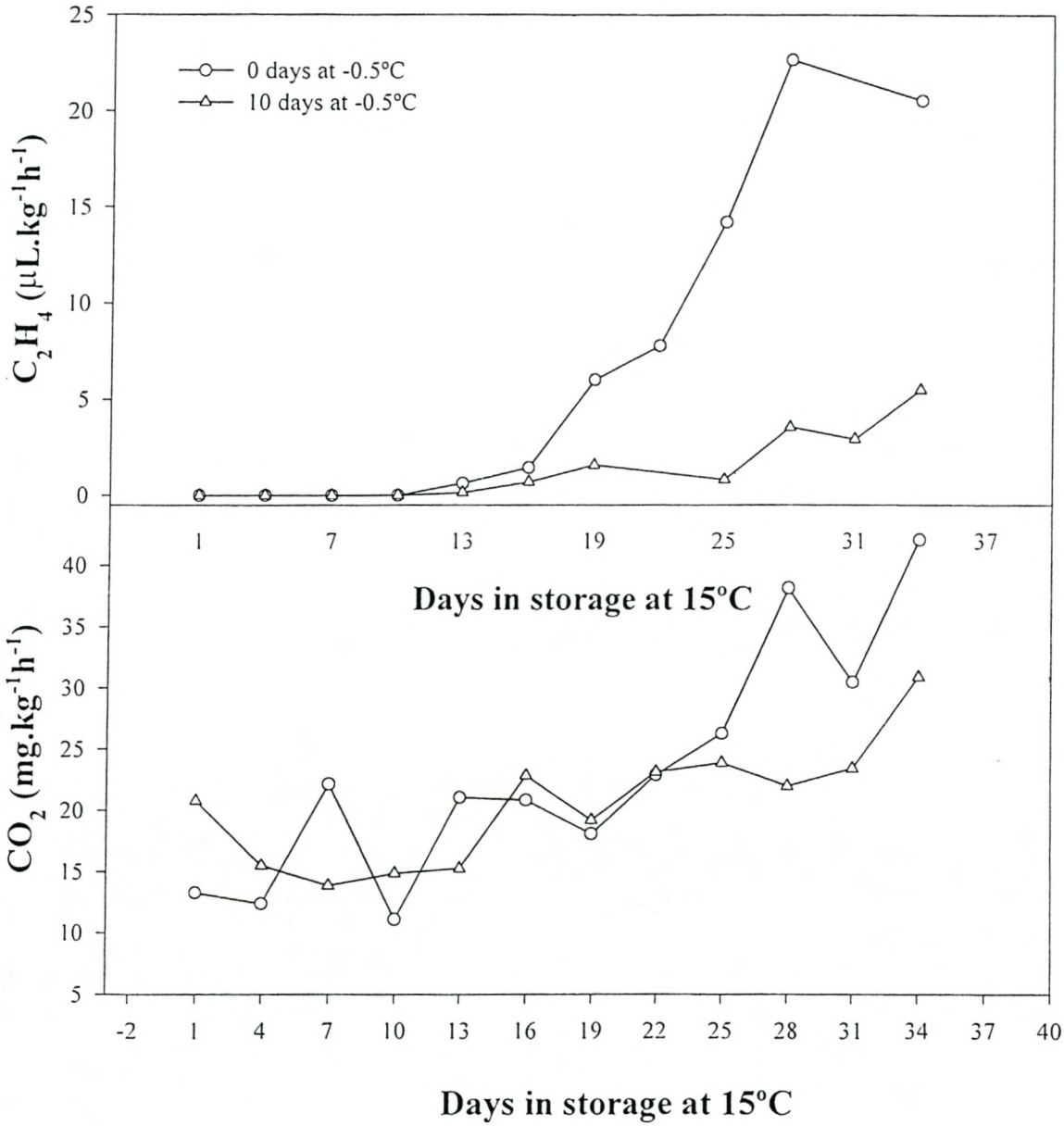

Fig. 6 Respiration and ethylene production of 'Angeleno' plums measured every three days at 15°C following cold storage treatments for 0 and 10 days at –0.5°C.

Effect of a postharvest boron dip on internal quality of 'Songold' plums (*Prunus salicina* Lindl.)

Abstract

Gel breakdown (GB), a result of chilling injury, is a problem in 'Songold' and other plum cultivars. Since boron plays a structural role in cell walls and cell membranes, we wanted to test the effect of a postharvest boron dip (1.06% for 10 minutes) on postharvest quality of 'Songold' plums, and in particular on the incidence of gel breakdown. Control and treated fruit were analysed after the treatment, again after 4 weeks of storage at -0.5°C, and finally after a further 7 days at 15°C. The boron dip resulted in high levels of shrivel which could have accounted for the higher levels of GB and internal browning found in treated fruit. However, flesh firmness, total soluble solids and electrical conductivity readings indicate that there may have been other effects of the boron treatment on the cell walls and membranes and this should be investigated further.

Keywords: electrical conductivity, pectin, polygalaturonase, pectin-methylesterase, gel breakdown, flesh firmness, TSS

1. Introduction

Plum trees have a high nutritional requirement with respect to boron (Wójcik, 1998). Up to 90% of cellular boron has been localized in the cell wall fraction (Blevins & Lukaszewski, 1998). Boron plays a structural role in plants in that it cross-links cell wall polymers such as hemicellulosic and pectic polysaccharides (Blevins & Lukaszewski, 1998), thus strengthening the cell walls. Lower levels of boron appear to result in higher levels of internal breakdown. According to Kotzé *et al.* (1989), the optimum level of boron in leaves of plum trees in January must be between 32 and 46 $mg.kg^{-1}$ to restrict the level of internal breakdown to below 5%.

During normal ripening, pectin-methylesterase (PME) de-esterifies methylated pectic substances and enables polygalacturonase (PG) to hydrolyse the reaction product, thereby producing soluble pectins (Taylor *et al.*, 1994). This increase in cell wall-degrading enzyme activity is a characteristic common to most softening fruits (Luza *et al.*, 1992). As the fruit ripens, a substantial portion of its cell wall pectins is converted to a water-soluble form and these changes are of considerable

importance for normal fruit texture (Luza *et al.*, 1992). Storing fruit at low temperatures stimulates the activity of PME while inhibiting the effect of PG (Taylor *et al.*, 1994). Low PME activity at the beginning of the storage period, followed by increased activity towards the end of the storage period, leads to the formation of low methoxyl pectins of high molecular weight with a high water binding potential (Taylor *et al.*, 1994). As PG is inhibited, these pectins cannot be broken down into water soluble molecules. When membranes become "leaky" due to increased permeability, cell fluids then bind to the pectic substances in the cell wall area to form gel complexes (Taylor *et al.*, 1994). Possibly, cross-linking in the cell wall structure by boron will lessen the fraction of pectins available for gelling. Furthermore, preharvest boron treatment reduces membrane permeability, thus reducing the amount of cell fluids that can bind to the pectins in the cell walls. B seems to improve the ability of fruit tissue to withstand adverse storage conditions such as chilling and high CO_2 (Xuan *et al.*, 2001).

The structural role of boron was further proved by Brown and Hu (1997) as boron depletion in plum trees caused no discernible change in mature leaf appearance, membrane integrity or photosynthetic capacity, but resulted in a severe disruption of plant growth and metabolism in young growing tissues. Calcium is also known to be taken up by developing tissues only. However, postharvest application of Ca has been shown to strengthen cell wall structure, improve membrane integrity and reduce the amount of electrolyte leakage in cold stored cucumbers (Kwon *et al.*, 1999). We hypothesised that a postharvest boron dip would have affect plum quality, specifically by reducing the incidence of internal breakdown i.e. gel breakdown and internal browning.

2. Materials and methods

2.1 Plant material and treatment

Commercially mature 'Songold' plums (flesh firmness of 6 kg) were selected for uniformity from an orchard in Paarl, South Africa (33°48'S ; 19°0'E). The fruit were immediately cooled to room temperature (±25°C). Treated fruit each received a 6% H_3BO_3 dip for ten minutes, giving a B concentration of 1.06%, whereafter treated and control fruit were placed at -0.5°C for four weeks to induce chilling injury, reserving 100 fruit for the initial analyses. These fruit were placed at 15°C for 24 hours before maturity indexing was done (harvest). After cold storage, five replicates of ten fruit of both control and treated fruit were analyzed for colour, firmness, TSS, TA, electrical conductivity, and internal disorders. The remaining fruit were placed at 15°C for five days to simulate shelf life before the same parameters were measured.

2.2. Maturity Indexing

Colour was measured as lightness (L), chroma (C) and hue angle (H) using a colorimeter (Nippon Denshoku, Handy colorimeter, NR – 3000, Tokyo, Japan). One reading per fruit was taken on the cheek. After shelf life, the area with the most blush was measured.

Once fruit had reached room temperature (±25°C), flesh firmness was measured using a hand held penetrometer (Southtrade pressure tester, model FT 327, Alphonsine, Italy) fitted with an 11 mm tip and mounted on a stand. Measurements were taken on one cheek on the equator, giving a total of ten readings per replicate.

Total soluble solids were measured on the pooled juice of all ten plums in a replicate, extracted using a commercial juicer. TSS was measured with a hand held refractometer (TSS 0-32%, Model N1, Atago, Tokyo, Japan).

Titratable malic acid was measured on the same pooled juice sample as used for the TSS measurements. Titratable malic acid was measured by titrating 10 g of juice with 0.1 N NaOH to a pH of 8.2 using an automated system (Tritino 7195 and sample changer 674, Metrohm Ltd., Herisau, Switzerland) . These titrations were done by a commercial laboratory (Hortec).

2.3 Internal disorders

Electrical conductivity was used as a measure of membrane integrity and measured according to the method described by Furmanski and Buescher (1979). This method is rapid, nondestructive and sensitive. Electrical conductivity measurements were taken in the inner and outer mesocarp of each fruit, one reading per fruit, using a conductivity bridge with two 7 mm platinum electrodes spaced 5 mm apart and a 1 cm^{-1} cell constant (Consort, C925). This measurement was taken on the equatorial axes on the opposite cheek to which the flesh firmness measurement had been taken.

Internal disorders were rated by cutting through the equatorial axes of the fruit and rating for visual symptoms of gel breakdown (gelatinous breakdown around the pip), internal browning (brown discolouration throughout the mesocarp) and overripeness (gelatinous breakdown under the skin). Fruit were also rated visually for shrivel.

Results were statistically analysed using the SAS System (SAS Institute Inc., Cary, North Carolina, U.S.A..). Disorder data was transformed using a logit equation. Significance levels for all maturity indices and internal disorders are given in Table 1 and indicate significance at the 5% level.

3. Results

Fruit that had received a boron dip suffered cuticular damage that could be seen as a brown discolouration of the skin. Since this brown discolouration masked any changes in skin colour, colour measurements after storage and shelf life were discarded. The hue angle of the fruit at harvest was ± 93°, indicating green fruit (data not shown).

There was no effect on flesh firmness at the initial sampling date (Table 1) or after shelf life. After cold storage, control fruit were significantly less firm than the treated fruit.

TSS were significantly higher in treated fruit after both cold storage and shelf life, despite being lower at harvest. There was no significant difference in TA at harvest, after storage or after shelf life.

There was no change in electrical conductivity in either the inner (ECIn) or the outer (ECOut) mesocarp from harvest till the end of storage time. After shelf life both ECIn and ECOut were higher in the control fruit than in the treated fruit, and significantly more so for the outer EC.

Although there were no significant differences between control and treated fruit for either GB, IB or OR, treated fruit had 6% more GB and IB than control fruit after shelf life. These fruit also had severe shrivel, indicating moisture loss. The control fruit had 10% more overripeness after shelf life than the treated fruit.

4. Discussion and conclusions

The boron treated fruit were firmer after 4 weeks storage at -0.5°C, indicating that the boron did in fact have a strengthening effect on the cell walls. As no shrivel was noted at this time, it is unlikely that the increase in flesh firmness is due to the "leathery" quality due to moisture loss that some plums display when shrivelled. Although it could be argued that the boron treatment may have inhibited ripening of the treated fruit, resulting in firmer fruit, this effect was not seen after shelf

life. Furthermore, the lower TA values of the treated fruit after storage indicated that they were riper than the untreated fruit.

The higher TSS levels found in the boron treated fruit are in accordance with previous findings that foliar boron sprays applied in spring or autumn cause a significant increase in soluble solids content of fruit at harvest time (Wójcik, 1998). Soil boron application does not affect this parameter. The higher TSS could also be a secondary effect of shrivel. As the water content of the fruit decreased, the TSS would become more concentrated and therefore give a higher reading. A similar effect would occur after storage, even though visual symptoms of shrivel were not yet present.

The higher levels of EC in both the inner and outer mesocarp of control fruit after shelf life indicate that more electrolyte leakage had occurred in these fruit, as higher EC levels are associated with higher levels of free electrolytes. This indicates that boron may have protected the membranes of the treated fruit. However, as the values for control and treated fruit after storage are similar, the lower EC after shelf life is probably due to binding of the electrolytes to the cell walls along with water, resulting in GB and IB.

The higher level of gel breakdown found in the control was contrary to what we expected. The only explanation is that the damage caused to the cuticle of the treated fruit had an effect on internal breakdown. In a study done on cucumbers, chilling injury symptoms developing during storage at 15°C were significantly correlated with weight loss (i.e. moisture loss) in the preceding 5 days of storage at 5°C (Purvis, 1995). Therefore, water loss in the plums (indicated by severe shrivel) could have had a similar effect. The higher level of OR found in the control fruit could be due to a few factors. Firstly, IB and GB could have masked the OR in the treated fruit. The reduction in levels of OR in treated fruit could also be due to the binding of cell fluids to form rigid gel complexes (Taylor *et al.* 1993a; 1993b).

While these results are preliminary and therefore inconclusive, indications are that the correct use of boron, possibly applied pre- and postharvest, may affect fruit quality and reduce the incidence of internal breakdown in plums. Flesh firmness, TSS and EC values indicate that there may have been positive effects of the boron on the cell walls, membranes and other cell constituents but that these effects were overridden by the cuticular damage from the dip.

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Table 1.

Firmness (F), electrical conductivity (EC In and EC Out), total soluble solids (TSS), titratable acidity (TA), gel breakdown (GB), internal browning (IB), overripeness (OR) and shrivel (S) (at harvest, after cold storage and after shelf life) of 'Songold' plums treated with a 1.06% postharvest boron solution.

		Firm. (kg)	EC In (mS/cm)	EC Out (mS/cm)	TSS (%)	TA (%)	Disorders GB%	IB%	OR%	Shrivel%
Initial	**- control**	6.8	2.9	2.1	15.5	1.69	0	0	0	0
	- boron	6.7	3.1	2.4	15.2	1.66	0	0	0	0
P > F		NS	NS	NS	NS	NS	NS	NS	NS	NS
Storage	**- control**	5.8	3.1	2.1	14.4	1.55	20	0	0	0
	- boron	6.3	3.1	2.4	15.0	1.48	20	0	0	0
P > F		0.0042	NS	NS	0.0016	NS	NS	NS	NS	NS
Shelf	**- control**	3.1	3.6	3.0	13.4	1.25	10	0	12	0
	- boron	3.2	3.2	2.2	15.2	1.29	16	6	2	70
P > F		NS	NS	0.0181	0.0001	NS	NS	NS	NS	0.0001