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**VIGOUR CONTROL IN GRAPEVINES FOR WINE PRODUCTION:
THE EFFECTS OF ROOT RESTRICTION ON THE VEGETATIVE
GROWTH, FRUITFULNESS AND FRUIT MATURITY OF
Vitis vinifera cv. CABERNET SAUVIGNON**

**A thesis
submitted in partial fulfilment
of the requirements for the Degree of
Master of Applied Science**

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B.F.Kagi

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Abstract of a thesis submitted in partial fulfilment of the
requirement of the Degree of Master of Applied Science

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An hypothesis that root restriction bags affect the vegetative growth, fruitfulness and fruit maturity of minimally managed field grown grapevines (*Vitis vinifera* cv. Cabernet Sauvignon) was examined with data collected from 1991-1996 as part of an ongoing trial. Root restriction clearly reduced vegetative growth, however fruitfulness was less affected, resulting in improvements in crop load and the maturity of the grape berries. The proportionate bag volume effects on growth were less consistent.

Grapevine cuttings were planted at ground level in porous geotextile Duon[®] root control bags in the spring of 1989 in Canterbury, New Zealand. Treatments consisted of four bag volumes of 10, 25, 48 and 102 litres, 'bagged' and unrestricted 'control' vines. The grapevines were spaced at 2 metre between vines and trained to a single cordon. The vines were minimally managed with winter short spur pruning and irrigation was applied uniformly across all treatments. The experiment was divided into three sections to test two hypotheses. Firstly were the bagged vines different from the non bagged vines and secondly were the bag effects proportionate.

Root restriction treatments generally reduced all vegetative growth parameters including: pruning fresh weights; trunk cross sectional area; primary and lateral shoot number and length, node number (leaf number), internode length and leaf area per plant. Mean leaf size was smaller and despite the growth reductions the canopy density

was improved in the bagged vines, through less leaf shading. Root restriction affected fruitfulness to a lesser extent, leading to increased harvest efficiency indices; fruit weight per unit pruning weight, leaf area per unit pruning weight and the fruit weight produced per total shoot number. Moreover, root restriction treatments affected the main fruit maturity parameters used for wine production. At harvest root restriction treatments increased the juice total soluble solids concentrations and decreased the titratable acidity concentration leading to an increased total soluble solids to titratable acidity ratio. In the final year these differences occurred from 7 weeks prior to harvest. Root restriction treatments also decreased juice potassium ion concentration. Potassium ion concentration was correlated with pH, and pH was generally lower in the bagged vines. Berry colour development at veraison was also earlier in the root restriction treatments.

The hypothesis that bag volumes are proportionate to changes in vegetative growth, fruitfulness and fruit maturity is not clear. There was some evidence to suggest relationships between these parameters may exist, however, R^2 values were low. Clearly the smallest bag volumes had disproportionate growth suggesting root escapes and, or, changed root to shoot relationships which would confound results. Root escapes were confirmed by preliminary root excavation.

KEYWORDS: Vigour control; grapevine; root restriction; root escapes; minimal management; fruitfulness; fruit maturity; crop load; harvest index; reproductive growth; vegetative growth.

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Certificate

I hereby certify that the experimental work contained in this thesis was planned, executed and described by the candidate, under the direct supervision of Prof. R.N.Rowe and Dr. M.C.T. Trought. Data presented within this thesis prior to 1994 was collected by Mr. G. Wells.

A handwritten signature in cursive script, appearing to read 'G. Wells', is written over a horizontal dashed line.

(Supervisor)

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Chapter 1

INTRODUCTION

1.1 General introduction

The relationship between vegetative and reproductive growth is an important relationship in plant based agriculture (Wright, 1989). This is primarily due to the functional relationship of production of photosynthesis in source areas, such as the leaves, and carbohydrate partitioning to competing sinks, such as fruit growth (Wardlaw, 1990). The appropriate balance of vegetative to reproductive growth is a high priority area in horticulture, as cropping efficiency gains are expected by reductions in the amount of vegetative growth required for reproductive growth (Elfving, 1988).

The grapevine (of genus *Vitis*) is a genetically vigorous perennial climbing vine (Mullins *et al.*, 1992). In the wild forest canopy the strong growth habit of the grapevine is likely to be a strategy for survival and would most likely be a competitive advantage. However, grapevines are primarily cultivated for fruit production and means of reducing or better utilising the vines vegetative growth potential are required. Recently, excessive vegetative growth in grapevines has been attributed to technological and cultural improvements in soil preparation, irrigation, soil fertility, weed, pest and disease management (Smart *et al.*, 1990; Smart and Robinson, 1991). Moreover, the vegetative growth of grapevines is largely indeterminate during the growing season (Mullins *et al.*, 1992) and without remedial vigour control, such as trimming, is usually excessive to that required for the fruit growth.

Excessive vegetative growth has direct and indirect effects on the reproductive growth of the vine (Smart and Robinson, 1991). Direct effects include increased partitioning of carbohydrate to vegetative growth in favour of reproductive growth. An example of an indirect effect of excessive vegetative growth is within row and between row shading, leading to a less efficient canopy microclimate. Shading is generally understood to have detrimental effects on many physiological processes dependent on light and temperature, including efficiency of photosynthesis and other processes determining

fruitfulness. The combination of detrimental effects of shading on fruitfulness can lead to an unbalanced grapevine or a 'vegetative growth cycle' where vegetative growth dominates reproductive growth (Smart and Robinson, 1991). Shading also has negative implications for grape composition and the resultant wine quality (Smart *et al.*, 1985 & Morrison, 1988; Iland, 1989).

Recently work has been carried out on vigour control methods in viticulture to utilise excessive vegetative growth. This work has been largely remedial involving corrective techniques such as retraining, retrellising and altering plant rooting environments by reducing plant populations, through vine or even removal of entire vine rows (Smart and Robinson, 1991). However, difficulties remain in assessing the vigour potential of a soil, determining appropriate plant spacings and maintaining long term vine vigour control.

Growth control in many other species has focused largely on genetic or cultural techniques directed at the aerial part of the plant, such as pruning, training and the use of plant growth regulators (Elfving, 1988). Plant breeding and other genetic vigour control of grapevines, except rootstock use, has not found favour for grape wine production, as grapevines for wine production are usually vegetatively propagated to maintain desirable traditional cultivar or clonal characteristics (Mullins *et al.*, 1992). Thus vigour control is a high priority area of research in viticulture.

The role of the roots for growth control, through the functional relationship of the root and shoot has been an area of increasing research. Techniques that utilise the root to shoot relationship include rootstocks, root pruning and root restriction. Root restriction has resulted in reduced growth of various plant species including; peach seedlings (Richards and Rowe, 1977a), cucumber (Chung, 1983), tomato (Al-Sahaf, 1984; Hameed, 1988), grapevines in glasshouse trials (Ussahatanonta, 1992; Henry, 1993) and field grown apple trees (White, 1995). Importantly that research generally indicated that if fruit was present a higher crop load was evident in root restricted plants. Information on how root restriction affects growth and fruit composition of field grown species is currently limited. Moreover, root restriction as a technique of vigour control and effects on the vegetative and reproductive growth and fruit maturity of field grown grapevines is unknown.

1.2 Nature and scope of the investigation

The experimental chapters 4,5 and 6 show the results of testing the unifying hypotheses that root restriction by porous geotextile bags affects the long term vegetative growth, and subsequently the fruitfulness and fruit maturity, of minimally managed field grown grapevines. Vegetative growth parameters contrasted were; pruning weight, trunk cross sectional area (TCSA), primary and lateral node (or leaf number), internode length, leaf size, total leaf area per plant and canopy density. Fruitfulness parameters contrasted were; bunch number per vine, fruit fresh weight per vine, average bunch weight, average berry weight, berry number per bunch and mean stalk fresh weight and the harvest indices; fruit fresh weight per pruning fresh weight, leaf area per fresh fruit weight, fruit fresh weight per total and primary shoot number. Fruit maturity compositional parameters contrasted were: total soluble solids (TSS), titratable acidity (TA), the ratio TA: TSS, hydrogen ion concentration (pH), malic acid concentration (Ma), potassium ion concentration (K^+), the Ma.: K^+ ratio, glucose concentration (Gl), fructose concentration (Fr), the Gl: Fr ratio and colour development at version.

Chapter 2

REVIEW OF THE LITERATURE

2.1 Introduction

The grapevine, of the genus *Vitis*, is a vigorous tree climbing plant or 'Liana' of deciduous forests, however, the botanic family *Vitacea* are primarily of intertropical distribution (Mullins *et al.*, 1992). Subsequently, important biological characteristics of grapevines include; vigorous growth, floriferousness and stress tolerance (Mullins *et al.*, 1992). Morphologically grapevines are characterised by leaves opposite pressure sensitive (thigmotropic) tendrils for tree climbing, and in the wild grapevines are vigorous climbers, climbing up to 30 metres high into the forest canopy (Smart and Robinson, 1991; Mullins *et al.*, 1992). In contrast, under cultivated conditions grapevines are usually pruned and trimmed to retain a thin rectangular canopy between half a metre and three metres high. Canopies are preferentially managed to allow maximum exposure of fruit and leaves to light, to minimise shading, and to maximise fruitfulness and grape berry composition. However, cultivation often requires costly trellising and training to control the strong seasonal vegetative growth.

The first section of this review will consider the general growth characteristics of the grapevine and grape berry maturity concepts. The next section briefly reviews vigour control and growth control methods utilised in viticulture. The larger part of the review considers the technique of root restriction, the effects of root restriction on vegetativeness, fruitfulness, fruit composition and maturity in a range of plant species. In conclusion, proposed mechanisms of growth reduction due to root restriction are discussed.

2.2 Grapevine growth

2.2.1 Shoot growth

Shoot formation in grapevines for the summer begins with development of the auxiliary buds, in the axils of leaves, in the preceding spring. These buds generally remain

dormant through the growing season and subsequent winter, until the following spring when temperatures increase, buds burst and shoot growth begins (Coombe, 1988).

Shoot growth occurs as a consequence of continuous production of new leaf primordia and internodes by the apical meristem and the elongation of the internode and expansion of leaves (Mullins *et al.*, 1992). The growth derived from the axillary bud is close to exponential in the early part of the growing season. However, close to flowering, vegetative growth slows and the growth curve of the shoot becomes sigmoidal. Increases in shoot fresh weight accumulation follow a slight double sigmoidal curve and dry weight increase in the shoot is linear until fruit set. At fruit set the fruit begins to dominate photosynthate partitioning, although leaf and fruit weight continues to increase (Coombe, 1988). No 'terminal buds' form in grapevines as grape shoots are indeterminate and only terminate shoot growth with shoot tip abscission (Mullins *et al.*, 1992). Lignification of the shoot periderm starts at the shoot base at about the same time as the fruit pass through veraison (Mullins *et al.*, 1992; Coombe, 1988).

Lateral shoots from the auxiliary buds may develop late in the spring and continue growing after primary shoot growth has slowed. However, the increased leaf area and leaf layer number may result in within row shading of leaves and fruit. Generally, shading causes reductions in fruitfulness and grape berry composition (Smart *et al.*, 1985 a & b, Smart, 1983; Smart, 1987; Smart *et al.*, 1990, Morrison and Noble, 1990), although it has also been suggested that young lateral leaves may provide a more efficient source of photosynthates than older basal leaves (Koblet, 1975).

2.2.2 Root growth

New root growth in grapevines appears to occur in two main periods. The first is after budburst in spring reaching a maximum at flower set, with a second smaller flush of growth occurring after fruit harvest (Freeman and Smart, 1976; Freeman, 1983; Coombe, 1988; Mullins *et al.*, 1992). Root growth in grapevines, differs from most other species with root growth not occurring with or before bud burst (Richards, 1983; Coombe, 1988). Most of the growth of new roots appears to occur only when there is excess of photosynthates available (Mullins *et al.*, 1992). However, root dry weight

(Mullins *et al.*, 1992) and fresh weight (Coombe, 1988) increase throughout the entire growth period of the vine, suggesting the roots continue to be a carbohydrate sink.

The anatomy, morphology, development, distribution and soil factors affecting growth of grape roots are extensively reviewed by Richards (1983). In particular relevance to root restriction, new root growth occurs by extension and branching. Extension roots thicken, whilst lateral roots elongate and branch to form higher order lateral roots. The root branching and extension increases the ability of the grapevine to exploit water and nutrients (Richards, 1983). In spring there are very few white young unsuberised roots, most of the roots being old, woody and brown. Suberisation of the root hypodermis appears to be a strategy for survival in water stress and other unfavourable conditions (Mullins *et al.*, 1992). The absorption of water and nutrients was considered to be exclusive to the unsuberised roots, however, this theory is questionable as studies in other species have shown although uptake of nutrients vary depending on the degree of root suberisation, the uptake of water for both root types is similar (Richards, 1983; Freeman, 1983). The importance of distinct periods of new root growth on water and mineral nutrient uptake in the vine is largely unknown (Mullins *et al.*, 1992).

2.2.3 Fruit growth

Current season fruit development begins with inflorescence primordia initiation. This process starts at the basal bud at about anthesis, and progresses to subsequent buds along the shoot from that time on through the preceding spring (Mullins *et al.*, 1992). Initiation of next years inflorescences, and flowering and fruit setting of the current seasons crop occurs concurrently with the main periods of shoot and root growth, suggesting possible competition between the competing carbohydrate sinks. Flowering culminates the process of the development of the inflorescence (Coombe, 1988), which began about twelve months earlier.

Berry setting starts the main fruit growth period. Fruit growth occurs in two distinct phases, with fresh and dry weight development following a double sigmoid curve (Winkler, *et al.*, 1974). The first phase takes the berries to a hard green stage. The second phase, starting at veraison, takes the berries to final maturity. During berry

maturation, the shoots lignify, axillary buds go into dormancy, basal leaves begin to abscise, trunk growth occurs and new roots form (Coombe, 1988).

2.3 Fruit maturation

A shift in the partitioning of photosynthates occurs at veraison when the developing berries take over from the shoot tips as the dominant carbohydrate sink (Mullins *et al.*, 1992). The final stages of fruit ripening involves many physiological and biochemical changes in the grape berries. Grape maturation is a complex process and involves many independent biochemical changes, thus perfect synchronisation between maturity parameters does not occur, although some general relationships are evident. Independent parameters vary depending on factors such as canopy microclimate, crop load, and seasonal climatic variations (Zoecklein *et al.*, 1989). Important parameters from the perspective of grape ripening for wine production include accumulation of carbohydrates, decreases in organic acids, potassium migration into the berry, increases in pH and development of colour pigments from veraison.

2.3.1 Carbohydrates

Glucose and fructose are the main carbohydrates in grapes at maturity. They both contribute approximately 10g each per 100g grape of juice and during maturity are in similar proportions, however, during late stages of ripening the ratio of glucose to fructose usually decreases (Winkler *et al.*, 1974; Kliewer, 1967; Morrison, 1988; Zoecklein *et al.*, 1989; Ough, 1992). Temperature may affect this ratio, for example the ratio decreases in warmer seasons and increases in colder periods. Total carbohydrate may be estimated as total soluble solids (TSS) per 100g of juice (°brix) (Kliewer, 1967).

2.3.2 Organic acids

Organic acids in grape juice are the largest group of compounds after carbohydrates (Winkler *et al.*, 1974). In cool climates malic and tartaric acid are the most important acids quantitatively, with smaller amount of citric acid and trace amounts of other acids (Winkler *et al.*, 1974). In cooler climates the amount of malic acid may exceed the

tartaric acid component at ripeness (Ough, 1992). The reduction of malic acid is related to the respiration rate of the berry and is partly a function of temperature (Jackson and Lombard, 1993). Four different mechanisms contributing to the decrease of malic and tartaric acid concentration are; dilution by increase in berry volume, activation of acid breakdown, inhibition of synthesis and transformation from acid to sugars (Mullins *et al.*, 1992). The primary test used for quantifying acid in wine and juice is titratable acidity (TA). TA is a measure of hydrogen ions titrated with a base to a standard pH endpoint. TA is expressed as equivalent grams of tartaric acid per litre. One measure of grape maturity is the ratio of TSS to TA (Cooke and Berg, 1983).

2.3.3 Hydrogen ion concentration

The hydrogen ion concentration (pH) has been proposed as an influential parameter of grape juice for winemaking, the many implications pH has on juice quality and winemaking are reviewed in Zoecklein *et al.* (1989). During ripening there is a gradual rise in pH. This occurs as a result of increase in acid salts, mainly potassium, and to a lesser extent sodium, entering the cell in direct exchange for protons from the free acid (Boulton 1980a; Iland, 1987).

2.3.4 Potassium

Potassium is a mobile nutrient within the grapevine. Factors affecting potassium uptake include; soil exchange capacity type, root size, meristematic root tissue, cultivar, adenosine triphosphatase (ATPase) activity, rootstock, vine vigour, leaf shading, crop level, climatic variation (Zoecklein *et al.*, 1989) and vine water status (Trought, 1997; pers.comm.). After berry growth commences the fruit is the major sink for potassium, which is mostly taken up by the roots, but can also be remobilised from the roots, leaves and main axis of the shoots (Mullins *et al.*, 1992). In shaded canopies only the exterior leaves contribute significantly to photosynthesis (Smart, 1974) (It has been suggested that potassium may be substituted for sugar in translocation, when shade depresses photosynthesis and ATPase is channelled toward activation of enzymes for potassium exchange and with increased vine growth enzyme activity is more rapid and this may increase potassium uptake (Zoecklein *et al.*, 1989). The malate to potassium ion (K^+) ratio has been suggested as a maturity indicator (Heatherbell, 1983).

2.3.5 Colour development at veraison

Immature grape berries contain chlorophyll at high concentration. Total phenols concentration is low in the flesh, but high in the skins (Coombe and Iland, 1987). However at veraison anthocyanin synthesis occurs rapidly in coloured cultivars and net berry phenols increase (Mullins *et al.*, 1992). The anthocyanins are mainly responsible for the colour and are derived from the parent compounds known as anthocyanidins primarily through the attachment of sugar residues (Zoecklein *et al.*, 1989). Factors which can affect the level of phenols in the skin include irradiance, crop load, pH of the juice, berry size and berry maturity (Coombe and Iland, 1987) and sugar accumulation (Pirie and Mullins, 1976; Pirie and Mullins, 1977).

2.4 Vigour control

One of the most outstanding advances in plant based agriculture has been the increase in the portion of the harvestable part of the plant. In an extensive review of carbohydrate partitioning in crops (Daie, 1985), it was concluded that future yield advances would possibly occur through improvements in harvest indices and not through genetic improvements in photosynthesis. In agreement other reviewers of carbohydrate partitioning (Ho *et al.*, 1989; Wardlaw, 1990) have acknowledged scope for improvement in the efficiency of photosynthesis, but suggested further efficiency improvements are obtainable through increased harvest indices.

The initial objective of fruit crops is the establishment of a vegetative framework to maximise the interception of light, subsequently the objective is to reduce vegetative growth and maximise fruit growth (Wright, 1989; Martin, 1989). In order to increase productivity research has been directed at vigour control techniques (Elfving, 1988).

The grapevine has evolved in a "natural habitat" where vigour is possibly a competitive advantage, however problems have arisen in viticulture as a consequence of cultivation of the grapevine. Recently, particularly in newer grape growing regions of the world, technological advances in soil preparation, irrigation and nutrition as well as weed, pest and disease management have led to increased vigour problems (Smart *et al.*, 1990).

Vigour has been defined by Winkler *et al.*, (1974) as “the quality or condition that is expressed in rapid growth of the parts of the vine....essentially....the rate of growth”. Vegetative vigour may be referred to as the rate of shoot, internode or leaf growth during a time period, for example shoot growth per season. Vigour control involves strategies that are used to obtain the maximum fruit weight per leaf area, without incurring deleterious effects on fruit composition.

Vigour is often discussed concurrently with the implication of excess growth leading to an increased canopy density and subsequently shading. Canopy shading may be a consequence of an increased growth rate, which often leads to increased shading through excessive shoot length, inter-row shading, increased leaf size and lateral shoot number, resulting in an increased leaf layer number. In an open canopy, that is with a low leaf layer number, increased light and temperature can result in beneficial effects on fruitfulness and fruit composition (Smart and Robinson, 1991). Excessive vegetative growth has direct and indirect effects on reproductive growth of plants and fruit composition. Direct effects are increased carbohydrate partitioning to reproductive growth during inflorescence initiation, fruit set and fruit maturation (Coombe, 1988; Martin, 1989). Indirect effects are the effects of excessive growth on within or between canopy shading. Shading and the effects of decreased light and temperature on grape development have been reviewed by numerous authors (Morrison, 1988; Iland, 1989; Smart and Robinson, 1991; Jackson and Lombard, 1993; Zoecklein *et al.*, 1994). Shading has been shown to generally decrease total soluble solids, anthocyanin concentrations (in red varieties) and increase titratable acidity, malic acid concentration, pH, potassium, and arginine. Shading may also have important effects on reducing potential fruitfulness, such as inflorescence initiation, fruit set, and fruit maturation (Martin, 1989; Coombe, 1988).

2.4.1 Vigour control methods utilised in viticulture

Recently formalised canopy management has become a popular technique in newer wine producing areas to manage grapevine vigour (Smart 1983; Smart, 1987; Smart, 1988; Smart *et al.*, 1990, Smart and Robinson, 1991). Canopy management is based on research to better utilise the growth potential of a site by pruning the grapevine according to the growth made in the previous season. Subsequently, shoots are trained

to a suitable trellis to allow a better balance of fruit to shoot growth and to minimise the shading of leaves and fruit. Canopy management usually involves the remedial techniques of canopy trimming (Kliewer and Bledsoe, 1987; Koblet, 1987), which involves removing the primary and lateral shoot tips as competing carbohydrate sinks and decreases within and inter-row shading.

The control of vigour through water stress applied to the root system may involve the techniques of intercrop management, regulated deficit irrigation and partial root zone drying. Intercrop management (Lombard *et al.*, 1988; Naylor *et al.*, 1994) involves planting species such as grasses or legumes to regulate the availability of water and or nutrients for grapevine root uptake and subsequently decreasing shoot growth. Regulated deficit irrigation (Bravdo and Hepner, 1987; Williams and Matthews, 1990; Goodwin and Macrae, 1990) and partial root zone drying (Dry *et al.*, 1995) have been used to reduce vegetative growth by applying water stress to the whole or parts of the root system at periods of strong vegetative growth. In comparison root restriction limits the root growth to a limited volume. The limited soil media and presumably more limited root system resulting from root restriction would most likely be more susceptible to water stress. Thus, a practical implication of root restriction would be root restricted plants would probably be easier to water stress and subsequently control growth.

The use of chemicals in the form of plant growth regulators (Coombe, 1967; Weaver, 1975; Shulman *et al.*, 1980; Ussahatanonta, 1992) such as ethephon (ethylene) and paclobutrazol have resulted in reduced vegetative growth. However the general acceptance of the use of plant growth regulators in horticulture is questionable due to societal concerns on increasing chemical inputs in horticulture (Rowe, 1996; pers. comm.).

Other vigour control techniques which more actively involve the manipulation of the root and subsequently the root to shoot ratio of the grapevines include rootstocks, root pruning and physical root restriction. Rootstocks have been used to manipulate vine vigour (Pouget, 1987; Pool *et al.*, 1992), although the specificity of the scion growth response to rootstocks on different sites has meant their use for vigour control in new regions, and improved vigour control in older regions, is currently under utilised. Root

pruning reduces grapevine shoot growth (Buttrose and Mullins, 1968) and is a growth control technique that also utilises a functional root to shoot relationship. Root pruning can be carried out by inexpensive tractor mounted root pruners (Ferree *et al.*, 1992), but it is currently not universally utilised in viticulture. The remainder of this review will consider root restriction as a technique of vigour control.

2.5 Root restriction

Root restriction is not a new technique, with the practice of growing trees in pots being evident in many ancient cultures from at least 1400 BC (Rakow, 1987). Root restriction in this review refers to techniques that have utilised root restriction by;

1. Complete physical root containment in aerated nutrient solution (Cooper, 1972).
2. High density orchards with physically reduced root systems (Salomon, 1978).
3. Localised irrigation and water deficit, field experimentation utilising frequent fertigation applied to a limited soil volume (Bravdo *et al.*, 1992).
4. Partial root containment in porous fabric lined trenches (Williamson *et al.*, 1992).
5. Root restriction by planting in porous membrane bags (Myers, 1992).

For the purpose of this review techniques that have been reported as being due to 'root restriction' are treated similarly, where differences in results occur the techniques used may be further discussed.

Root restriction has been shown to have several practical benefits as a vigour control technique including; increasing the productivity and earliness of fruit, increasing the efficiency of irrigation and fertigation, growth control through deficit irrigation, reducing herbicide use in the tree rooting weed-free zone, better control of nematodes and soil borne diseases, and a more efficient selection of rooting media (Carmi and Shalhevet, 1983; Bravdo *et al.*, 1992; Mandre *et al.*, 1995; Vizzotto *et al.*, 1997).

2.5.1 Root: shoot ratio

Restricting the root to a small soil volume is a preventative vigour control strategy based on the functional relationship of the root and shoot system. The roots of plants are responsible for the uptake of nutrients and water and the shoot system is responsible for the supply of carbohydrates for further growth (Davidson, 1969; Atkinson, 1980). A

functional equilibrium based on these functions has been shown to exist between the root and shoot systems of plants grown under varying external conditions (Thornley, 1972; Hunt, 1975; Hunt *et al.*, 1975; Richards, 1981). The equilibrium based on dry weights has been altered due to stresses, for example research with root restriction has shown that under conditions of stress the ratio changed to partition assimilates in favour of the organ under stress (Chung, 1983; Henry, 1993).

The root to shoot relationship in perennial fruit trees and vines is not well documented. Research with fruit trees (Atkinson, 1980) and grapevines (Mullins *et al.*, 1992, Winkler *et al.*, 1974) has shown a wide range of root to shoot ratios. Differences possibly were derived from changes in the annual increase in dry mass of the permanent structure, cropping levels, soil type, tree age, rootstock, herbicide management, soil temperature, nutrient and water stresses (Mullins *et al.*, 1992; Atkinson, 1980).

2.5.2 Effects of root restriction on root: shoot ratios

Root to shoot ratios have been shown to vary widely in response to root restriction treatments. Root to shoot ratios have decreased in grapevine cuttings (Henry, 1993), tomato plants (Al-Sahaf, 1984; Hameed, 1988; Peterson *et al.* 1991a) and alder seedlings (Tschaplinski and Blake, 1985). In contrast, root to shoot ratios were shown to increase in grapevine cuttings (Henry, 1993), cucumber (Chung, 1983), tomato (Ruff *et al.*, 1987), barley (Huang *et al.*, 1996) and marigold seedlings (Latimer, 1991). In comparison, root to shoot ratios were not affected in wax-apple (Hsu *et al.*, 1996), cucumber (Robbins and Pharr, 1988), bell pepper (Ne Smith *et al.*, 1992) and little or no differences were found in spreading euonymus (Dubik *et al.*, 1989). These varying responses suggest that root restriction can alter the carbohydrate allocation to the root or shoot of the plant, possibly due to different stresses imposed by root restriction treatments, probably due to the changed morphology resultant from the changed root system.

2.5.3 Effects of root restriction on vegetative growth

Generally vegetative growth parameters have been reduced due to root restriction treatments in a range of plants. Canopy size was reduced in sweet cherry trees (Dolph

and Proebstring, 1989), peach trees (Williamson and Coston, 1990; Myers, 1992), apple trees (Dolph and Proebstring, 1989; White, 1995) and citrus (Bravdo *et al.*, 1992). In contrast to findings in other plants no differences were found in the height, and width of young oak trees in short term micro-irrigation and root restriction experiments (Gilman *et al.*, 1994). Why oak was not affected is unclear, however, the relatively slow growth rate of oak trees possibly requires longer term experiments to determine if vegetative growth would follow the general trends to growth reduction shown in other plant species.

Stem diameter and stem length have been consistently shown to be reduced by root restriction treatments. Stem diameter was reduced in peach trees (Williamson and Coston, 1990), apple and sweet cherry trees (Dolph and Proebstring, 1989) and tomato plants (Hameed, 1988). Stem length was reduced in cotton (Carmi and Shalhevet, 1983), soybean (Krizek *et al.*, 1985) and tomato (Hameed, 1988). However, the effects of root restriction on stem dry weight findings are less clear. For example, stem dry weights have been increased (Al-Sahaf, 1984; Hameed, 1988) or decreased (Ruff *et al.*, 1987) in tomato. In contrast, no differences were evident in peach seedlings (Richards and Rowe, 1977a) or bell peppers (Ne Smith *et al.*, 1992). The differences in tomato were possibly due to the effects of the presence of reproductive growth on carbon partitioning, i.e. when fruit was not present there was increased partitioning to the stem (Al-Sahaf, 1984).

Other shoot growth parameters have been consistently reduced by root restriction treatments. Shoot number has been shown to be reduced by root restriction of peach seedlings (Richards and Rowe, 1977a) and bud growth inhibition was reported in alder seedlings (Tschaplinski and Blake, 1985). Reduced lateral shoot number was reported in peach (Williamson *et al.*, 1990), tomato (Peterson *et al.*, 1991a), cucumber (Robins and Pharr, 1988) and spreading euonymus (Dubik *et al.*, 1989).

Primary and lateral shoot length and weight are consistently reduced by root restriction. Primary shoot length was reduced by root restriction in glasshouse grown grapevines (Komatsu and Nakagawa, 1989; Henry, 1993), kiwifruit vines (Tonutti and Giulivo, 1990), peach trees (Williamson *et al.*, 1990; Williamson and Coston, 1990), cotton (Carmi, 1986; Ben-Porath and Baker, 1990), alder (Tschaplinski and Blake, 1985) and

marigold seedlings (Latimer, 1991). Lateral shoot length was reduced in peach trees (Williamson *et al.*, 1992), peach seedlings (Richards and Rowe, 1977a), tomato (Al-Sahaf, 1984) and spreading euonymus (Dubik *et al.*, 1989). Primary shoot weight was reduced due to root restriction in grapevine cuttings (Henry, 1993), peach seedlings (Costa *et al.*, 1992), cotton (Carmi and Shalhevet, 1983), cucumber (Robbins and Pharr, 1988) and marigold seedlings (Latimer, 1991). The primary shoots received increased dry matter partitioning at the expense of lateral shoots in spreading euonymus (Dubik *et al.*, 1989).

Leaf or node number, internode length and average leaf area and leaf area per plant have been shown to be generally reduced, although the density, dry weight of leaves relative to the leaf area has increased in response to root restriction treatments. Node number was reduced in grapevines (Ussahatanonta, 1992; Henry 1993) and tomato (Ruff *et al.*, 1987). Internode length was reduced in grapevines (Ussahatanonta, 1992; Henry 1993), beans (Carmi and Heuer, 1981), cotton (Ben-Porath and Baker, 1990) and peach trees (Williamson and Coston, 1990). Leaf number was reduced in peach seedlings (Richards and Rowe, 1977a; Costa *et al.*, 1992), tomato (Hameed, 1988) and spreading euonymus (Dubik *et al.*, 1989). Leaf area was reduced in grapevine cuttings (Henry, 1993), peach seedlings (Richards and Rowe, 1977a), peach trees (Costa *et al.*, 1992; Rieger and Marra, 1994), sweet cherry, apple trees (Dolph and Proebstring, 1989) and in a wide range of other plants grown as annuals (Carmi and Heuer, 1981; Mutsaers, 1983; Tschapinski and Blake, 1985; Ruff *et al.*, 1987; Peterson *et al.*, 1991a; Latimer, 1991; Dubik *et al.*, 1989). Total and average leaf surface area was decreased in tomato (Al-Sahaf, 1984). A decrease in leaf expansion rate due to root restriction treatments was also reported in cucumber (Robbins and Pharr, 1988) and tomato (Peterson *et al.*, 1991a). Leaf density was increased in root restricted, tomato plants (Al-Sahaf, 1984; Hameed, 1988) and spreading euonymus (Dubik *et al.*, 1989).

2.5.4 Effects of root restriction on root growth

Root number and length generally decrease, although fine lateral rooting has been shown to increase in response to root restriction treatments. Root number reductions were reported in grapevine cuttings (Henry, 1993), peach trees (Williamson *et al.*, 1992) and tomato (Hameed, 1988). Root length was shown to be decreased in grapevine

rootlings (Henry, 1993), peach seedlings (Richards and Rowe, 1977a) and tomato (Ruff *et al.*, 1987; Hameed, 1988). However, lateral rooting increased in grapevine rootlings (Henry, 1993), peach seedlings (Richards and Rowe, 1977a), tomato plants (Al-Sahaf, 1984; Ruff *et al.*, 1987; Hameed, 1988; Peterson *et al.*, 1991a) and cotton plants (Ben-Porath and Baker, 1990). Other measures of lateral rooting, such as the ratio of root number to root length were increased in cucumber plants in response to root restriction (Chung, 1983), and the proportion of fine roots has been shown to increase in field grown peach trees (Ran *et al.*, 1992), cotton (Carmi and Shalhevet, 1983) and young oak trees (Gilman *et al.*, 1994). The increased lateral rooting possibly would have implications for increased root potential for water and nutrient uptake.

Root dry and fresh weight have been shown to generally decrease in response to root restriction. Root dry weight decreases were reported in kiwifruit vines (Tonutti and Giulivo, 1990), peach seedlings (Costa *et al.*, 1992) and in a range of plants grown as annuals (Al-Sahaf, 1984; Krizek *et al.*, 1985; Carmi and Shalhevet, 1983; Ruff *et al.*, 1987; Robbins and Pharr, 1988; Latimer, 1991). Root fresh weight decreases were also reported in kiwifruit vines (Tonutti and Giulivo, 1990).

2.5.5 Effects of root restriction on reproductive growth

Flowering has been shown to be either earlier or was not influenced by root restriction treatments. Effects on flower number from root restriction treatments are variable, as flower number has been increased, decreased or not affected. However, when expressed as flower number density (% per fruiting limb), an increased relative flower proportion is apparent. Earlier flowering was recorded in bell peppers (Ne Smith *et al.*, 1992) and cotton (Carmi, 1986; Ben-Porath and Baker, 1990). Flower initiation was hastened in starfruit (Mohd and Khuzaimah, 1996). In contrast flowering initiation was not affected in cotton (Carmi, 1986) and flowering duration was not affected in summer squash (Ne Smith, 1993a; Ne Smith, 1993b). Flower number per node was increased in peach trees (Williamson *et al.*, 1992), flowering was more 'profuse' in citrus trees (Salomon, 1978), flower cluster number was higher in apple trees (Myers, 1992). However, flower number per plant were not affected in tomato (Peterson *et al.*, 1991a), or cotton, except in smallest root treatment where the flower number was reduced (Carmi and Shalhevet, 1983). Blossom number per tree was reduced by root restriction of apples (Atkinson *et*

al., 1997), although in comparison when expressed as blossom number per tree size, increases were evident. Floral bud density, buds per meter shoot length, was also generally increased in sweet cherry trees (Webster *et al.*, 1997).

Fruit set and ovule development has been recorded as being earlier and increased or not affected due to root restriction treatments. Fruit set was increased in glasshouse grown grapevines (Komatsu and Nakagawa, 1989), apple trees (Myers, 1992) and in sweet cherries (Webster *et al.*, 1997). Fruit set was earlier in bell peppers (Ne Smith *et al.*, 1992) and cotton (Carmi, 1986; Ben-Porath and Baker, 1990), but not affected in summer squash (Ne Smith, 1993b). Ovule development and pollen tube penetration was promoted in glasshouse grown grapevines (Okamoto and Imai, 1989), and the number of seeded berries to total berry number was increased (Okamoto and Imai, 1989; Komatsu and Nakagawa, 1989).

Fruit number has most often not been affected or was reduced by root restriction treatments, although, when expressed relative to the root size, fruit size and fruit number increases have been reported. Total berry number per vine was not affected in glasshouse grown grapevines (Ussahatanonta, 1992), fruit number was also not affected in peach trees (Williamson and Coston, 1990; Myers, 1992). Boll number in cotton, however, was reduced in response to root restriction (Carmi and Shalhevet, 1983; Carmi, 1986), although when expressed as per m² few differences were evident. Apple number expressed as a ratio of root number (Bravdo *et al.*, 1992) or apple number per limb (Myers, 1992) were increased in response to root restriction.

Fruit size (volume, weight or diameter) effects in response to root restriction have been varied. Thus, any consistent results of root restriction are not clear. Possibly this is due to crop load or yield effects in response to root restriction. In glasshouse grown grapevines there was a trend to higher mean berry weights with root restriction (Ussahatanonta, 1992). No root restriction effects were evident on mean peach size (Myers, 1992), or fruit dry weight (Mandre *et al.*, 1995), although in other work with peach trees (Williamson and Coston, 1990), and sweet cherry trees (Webster *et al.*, 1997), small reductions in mean fresh size were reported. Fruit size reductions have also been reported in apple trees (Atkinson *et al.*, 1997; Bravdo *et al.*, 1992), and peach trees

(Vizzotto *et al.*, 1997). Crop load was identified as causing size differences in a long term field trial with root restricted 'Fuji' apple trees (White, 1995).

Yield per tree findings in response to root restriction have been variable, often with conflicting results. However, a general conclusion is that crop load has been increased by root restriction experiments in a range of plants. Yield per tree and the amount of marketable fruit was increased in sweet cherry (Webster *et al.*, 1997). Yield per tree was reported as being similar in peach trees (Williamson and Coston, 1990) and citrus (Salomon, 1978). Similarly, long term research with peaches in polypropylene porous nets showed no effect on yield, however, with pot plant root restricted plants yields were decreased (Vizzotto *et al.*, 1997). Yield per plant or tree decreases in response to root restriction have also been reported in apple (White, 1995), cotton (Carmi and Shalhevet, 1983), bellpepper (Ne Smith *et al.*, 1992) and tomato (Bar-Tal and Pressman, 1996). Crop load and fresh fruit weight per total plant fresh weight were increased in glasshouse grown grapevines (Ussahatanonta, 1992) and tomato plants (Klapwijk and Wubben, 1975). The amount of seed or fruit dry weight to whole plant dry weight was increased in peach trees (Vizzotto *et al.*, 1997; Mandre *et al.*, 1995), tomato (Al Sahaf, 1984), bellpepper (Ne Smith *et al.*, 1992) and cotton (Carmi and Shalhevet, 1983; Carmi, 1986; Ben-Porath and Baker, 1990). Crop load expressed as fruit fresh weight per trunk cross sectional area (TCSA) was increased in peach (Williamson and Coston, 1990) and apples (Bravdo *et al.*, 1992; White, 1995). Fruit fresh weight per total plant dry weight of pot root restricted trees was increased in the most severely pot root restricted peach trees in the second year of growth (Ran *et al.*, 1992). However, by the third year no clear differences were evident. Possibly this was due to the larger potted vine roots being increasingly restricted by the third year, and subsequently differences becoming less evident.

2.5.6 Effects of root restriction on fruit maturity and composition

There is a clear lack of research as to the effect of root restriction on fruit maturity and composition. Fruit maturity was advanced in terms of colour development in greenhouse grown grapevines (Ussahatanonta, 1992) and advanced based on an average harvest date in field grown apple trees and red colour in apples (Myers, 1992; White,

1995). In comparison a more green colour of peaches was suggested as being an indication root restriction delayed maturity by a few days in peach trees, although the red colour of the peaches was similar in restricted and control trees (Mandre *et al.*, 1995).

Total soluble solids (TSS) concentration has been increased by root restriction in glasshouse grown grapevines (Ussahatanonta, 1992), in field grown apple trees (Bar-Yosef *et al.*, 1988) and tomatoes (Manishi *et al.*, 1996). In contrast, two different types of root restriction had different effects on TSS concentration in peaches (Vizzotto *et al.*, 1997). The TSS concentration was decreased by pot root restriction of peaches, however, in net root restricted plants the concentration was slightly increased in comparison to control. Why the effect occurred is unclear but the soluble solids were correlated with specific leaf area (SLA), ie. leaf area per gram of fruit. The correlation may suggest the higher SLA in net restricted plants led to increased TSS in the fruit.

Mineral concentration in fruit has been shown to be not affected or increased due to root restriction. K^+ , Mg^+ and Ca^{2+} concentrations were not affected in tomato fruit (Al-Sahaf, 1984), in contrast Ca^{2+} concentrations were increased in apples (White, 1995). The differences in results has been suggested (White, 1995) as being due to the different type of root restriction; in the former case the tomato roots were confined to a non-porous container with limited opportunity for new root growth, where as in the latter case the new apple tree root growth occurred around the periphery of porous root restriction bags. Because Ca^{2+} is a non-mobile soil nutrient the new root growth was suggested as leading to higher fruit calcium concentrations (White, 1995).

2.6 Proposed mechanisms of plant growth reduction from root restriction

2.6.1 Water stress

Water stress has often been suggested as a mechanism behind growth reductions due to root restriction. The loss of water from leaves by transpiration is the driving force for the uptake of water in the roots, the decrease in leaf water potential establishing a gradient in water potential between the leaf and the soil (Mullins *et al.*, 1992). Water flux through the root vascular tissue is determined by the type of roots, unsubsided

roots taking up the greater amount of water per unit surface area. However, the usefulness of leaf water potential as an indicator of plant growth has recently been questioned and the use of physiological responses such as stomatal conductance have been suggested (Ussahatanonta, 1992). However, in practice stomatal conductance has rarely been used to indicate water stress and resultant growth reductions in root restriction research, although decreased leaf water potential has generally been used to suggest plant water stress.

Leaf water potential has been shown to be generally decreased in numerous root restriction experiments, for example in starfruit (Mohd and Khuzaimah, 1996), alder seedlings (Tschaplinski and Blake, 1985), tomato plants (Hameed, 1988; Hameed *et al.*, 1987) pine seedlings (Will and Teskey, 1997), peach trees (Proebstring *et al.*, 1989), and apple trees (Atkinson *et al.*, 1997). Furthermore, water stress was implicated in causing root restriction growth reductions in tomatoes (Manishi *et al.*, 1996) and was not excluded as a contributing factor to growth reductions in salvia (Van Iersel, 1997). Water uptake was proportional to the root weight per plant (Ran *et al.*, 1992) and limited root growth in smaller containers had the effect of not being able to supply the potential water demands of tomato (Choi *et al.*, 1997).

In contrast, water potential has been shown to be only slightly decreased or similar in cotton (Carmi and Shalhevet, 1983; Krizek *et al.*, 1985) when comparing soil moisture stress (SMS) and root restriction treatments, leading researchers to believe the main mechanism behind root restriction effects on growth reductions was not water stress. Stomatal conductance was also reported as similar in control versus root restricted cotton (Krizek *et al.*, 1985), in comparison to lower values in soil moisture stress treatments. Why these different results were evident in cotton but not other crops is unclear. However, possibly a similar leaf water potential and stomatal conductance under restricted root growth conditions indicate cotton plants exhibit a greater drought tolerance than other species used in root restriction research.

2.6.2 Nutritional effects

Nutrition does not appear to be the main cause of root restriction growth reduction effects. There is some conflict in the literature. Some results have suggested that

nutrition was not responsible for growth reductions due to root restriction. However, a changed root morphology resultant from root restriction most likely has implications for nutrient uptake and subsequently effects plant growth.

There have been many examples where nutrition does not appear to have been the cause of plant growth reduction due to root restriction. For example nitrate uptake was proportionally higher in root restriction treatments but plant top dry weight was proportionally lower (Richards and Rowe, 1977a). Increased nutrient concentration did not result in increased leaf growth in root restricted bean plants (Carmi and Heuer, 1981). Varying concentrations of nitrogen did not effect root: shoot ratios in root restriction treatments of bell pepper (Ne Smith *et al.*, 1992). Nitrogen concentration in plant organs was not affected by root restriction treatments in tomato plants, leading the researchers to conclude that reduction in dry matter production in root restriction treatments were not caused by nitrogen deficiency (Bar Tal *et al.*, 1995).

In contrast, nutrition has been suggested in some trials as being responsible for reduced growth in root restricted plants. A larger average flux of nitrate uptake has been reported in root restricted plants (Ran *et al.*, 1992). This was believed to occur as the smaller root restriction treatments had a larger proportion of <1 mm diameter roots. However, the nitrate concentration in tree xylem fluid were sub optimal, leading to reduced net photosynthesis and growth rates. Why the larger average flux rate of nitrate from the smaller roots was associated with lower nitrate concentrations in the root restricted tree xylem fluid was not clear, but may explain the cause of reduced growth. Low nitrogen and total ionic solution in hydroponically root restricted cucumber was suggested as enhancing root length at the expense of leaf area growth (Chung, 1983). In other research nutrient deficiency was not excluded as a contributing factor but could not be isolated as the main reason for growth differences in root restricted salvia (Van Iersel, 1997).

Reduced mineral uptake in response to root restriction treatments has often been reported by various researchers. For example root restriction was suggested to result in increased requirement for minerals and eventually a shortage due in the dynamic balance between plant uptake and growth (Mutsaers, 1983). Potassium concentration and the $K^+ : Ca^{2+}$ ratio was decreased in tomato plant organs due to root restriction (Bar

Tal *et al.*, 1995; Bar Tal and Pressman, 1996) and Calcium (${}_{45}\text{Ca}^{2+}$) movement to new leaves and apices was strongly suppressed by root restriction treatment in tomato plants (Choi *et al.*, 1997). Total mineral (K^+ , Ca^{2+} , Mg^+) amounts taken up were less, though not deficient in root restricted tomato plants (Al-Sahaf, 1984). Although, when expressed as mineral uptake per unit root length or root number the root restricted plants had an increased ability to absorb the minerals.

2.6.3 Plant growth regulators

Cytokinin produced in root tips has been suggested as stimulating shoot growth, with auxin produced in young shoot apices stimulating root growth (Richards, 1986).

Cytokinin is believed to be a precursor to auxin production therefore, cytokinin has been postulated as the controlling mechanism of root and shoot growth relationships. In support of this general contention root tip number has been demonstrated to be positively correlated with leaf number and application of cytokinin to leaves partially overcame growth reductions due to root restriction (Richards and Rowe, 1977 a & b; Richards, 1986).

Cytokinin and gibberellin produced in the root apices have been widely implicated in plant growth reduction in previous research and further implicated in growth reduction in root restricted field grown apple and citrus trees (Bravdo *et al.*, 1992). Cytokinin and gibberellin applied exogenously, relieved root restriction growth retardation effects in beans (Carmi and Heuer, 1981). Changes in cytokinin and gibberellin levels were thought to control reduced growth through reduction in the absorption of nutrients in cotton (Carmi and Shalhevet, 1983), and growth substances, most likely cytokinin and gibberellin, were believed to cause growth reductions in tomato (Ruff *et al.*, 1987). Translocation of cytokinin and gibberellins and other plant growth regulators from the roots, was suggested as causing growth reductions from reduced shoot branching in root restricted spreading euonymus (Dubik *et al.*, 1989; Dubik *et al.*, 1990).

Ethylene production was increased in physically impeded tomato root systems at the time when adventitious rooting was initiated in response to root restriction (Peterson *et al.*, 1991 a & b). These researchers concluded that further research was necessary to determine the role of ethylene in control of leaf size and elongation.

Abscisic acid (ABA) concentrations up to seven fold higher in the xylem sap was suggested as a chemical signal from the plant that mechanical stress of root zone drying may be responsible for growth reductions in root restricted sunflower plants (Ternes *et al.*, 1994). ABA has been implicated in extreme cases of root restriction and growth reduction (Rowe, 1993), although the influence of ABA accumulation in root restricted plant leaves is still unknown (Carmi, 1995). ABA produced in the roots in response to soil drying was proposed to reduce stomatal conductance, with cytokinin and nutrition also involved (Davies and Zhang, 1991). Plant growth regulators have been generally implicated in shoot growth reductions due to root restriction in marigold seedlings (Latimer, 1991), and growth differences that could not be explained by water or nutrient deficiencies in root restricted field grown peach trees (Williamson *et al.*, 1992).

2.6.4 Other physiological and physical factors influencing growth

Monitoring the effects of root restriction on plant physiological responses has shown that photosynthetic, assimilation and transpiration rates are generally decreased due to root restriction, although when expressed per unit leaf area or per unit fruit weight, efficiency has been improved. Reduced photosynthetic rates have been reported due to root restriction in tomato (Hameed, 1988), cucumber (Robbins and Pharr, 1988), pine seedlings (Will and Teskey, 1997) and starfruit (Mohd and Khuzaimah, 1996). Whole plant and leaf photosynthetic rates during fruit expansion were recorded as being positively correlated with container volume (Ne Smith *et al.*, 1992). In fruiting bell peppers (Ne Smith *et al.*, 1992) and non fruiting alder seedlings (Tschaplinski and Blake, 1985) chlorophyll levels were decreased, leading to early senescence. In contrast, chlorophyll was increased in root restricted tomato leaves (Al-Sahaf, 1984), suggesting possible increased photosynthesis in response to proportionally more fruit in root restricted plants.

Reduced net CO₂ assimilation rate in root restricted salvia (Van Iersel, 1997) and mango (Schaffer *et al.*, 1997) has led to reduced plant growth, although the latter research indicated the more severely root restricted plants were more efficient at assimilating CO₂. Transpiration rate was also reduced in root restricted tomato plants (Hameed, 1988; Bar Tal *et al.*, 1995).

Under some root restriction regimes anaerobic conditions can result due to reduced area for air exchange, physical space limitations (Robbins and Pharr, 1988; Peterson *et al.*, 1991a) and water logging (Peterson *et al.*, 1991a). As a response, tomato plants increased lateral rooting to improve oxygen uptake (Peterson *et al.*, 1991a). Higher temperatures in root restriction treatments further reduced root growth (Dubik *et al.*, 1992), although growth responses to temperature are likely to be plant species dependent. Container geometry, including growing media type and nutrient and water exchange capacity have been suggested as being important to match with a particular plant species' growth habit (Carmi and Shalhevet, 1983; Tilt *et al.*, 1987; Dubik *et al.*, 1992; Henry, 1993; Edwards, 1997).

2.7 Conclusions

The grapevine is an inherently a vigorous perennial plant. A study of the phenology of the grapevine shows that root, shoot and reproductive growth occur concurrently, suggesting possible competition between the competing sinks for carbohydrate allocation. The composition of the fruit of the grapevine at harvest has important implications for winemaking. Generally, during fruit maturation colour develops, carbohydrates increase, organic acids decrease and potassium ion concentration increases. The vigour of the grapevine and shading, which is often a consequence of excess vigour, have important implications for grapevine fruitfulness, fruit composition and maturity. Subsequently, the cultivation of the grapevine has required special considerations on how best to manage vigorous, indeterminate, shoot growth.

Various strategies are involved in plant growth regulation. Root restriction is a preventative and efficient low management strategy that has been shown to generally reduce the vegetative growth of many plant species. Moreover when reproductive growth was present, root restriction has often resulted in increased crop loads, indicating partitioning of carbohydrate to reproductive growth is increased relative to root and shoot growth. Scant research has however been carried out on the effects of root restriction on fruit composition, however fruit maturity is generally advanced. The changed root morphology in response to physical root restriction most likely has

implications for water and nutrient uptake, and plant growth regulator formation. The mechanism by which root restriction induces reduced vegetative growth has often been suggested as being water stress as indicated by leaf water potential. However, there are poor correlations between leaf water potential and reductions in shoot growth and some suggest the use of stomatal conductance may be superior. The involvement of plant growth regulators in controlling water and nutrient usage and uptake is implied, but the role of ethylene in root branching and ABA in stomatal closure requires further investigation. Reductions in physiological processes such as photosynthesis, CO₂ assimilation and transpiration suggest that the effects of root restriction on carbohydrate partitioning are primarily due to efficiency improvements per unit source area.

Chapter 3

MATERIALS AND METHODS

3.1 Site

The grapevines used in this experiment are planted on a stony silt loam over sand, described as 'Templeton-Eyre Paparoa'. The location is Lincoln University Horticultural Research vineyard on the Canterbury plains of New Zealand (43 degrees, 39 minutes south; 11 metres above sea level). The climate is temperate with average daily minimum and maximum temperatures of 6.2 and 16.7 degrees Celsius, respectively, the average rainfall is 666 millimetres with approximately 62 percent falling in September to April (Nagle *et al.*, 1992).

3.2 Experimental design and planting procedure

The grapevines of *Vitis vinifera* cv., Cabernet Sauvignon were planted as rootlings in the spring of 1989. The vines were either planted conventionally as 'unrestricted' controls, i.e. unlimited soil volume; or 'bagged', that is planted in the ground within porous fabric bags of four volumes: 10, 25, 48 and 102 litres, as the experimental treatments. The site soil was removed when establishing the bags in the ground, but replaced and used as the growing media within the bags.

The experiment design consisted of randomised complete blocks, with each block containing 5 vines (Figure 3.1). The vines were spaced at 2 metres (m) between vines within the row, and 2.8 m between other rows in the vineyard.

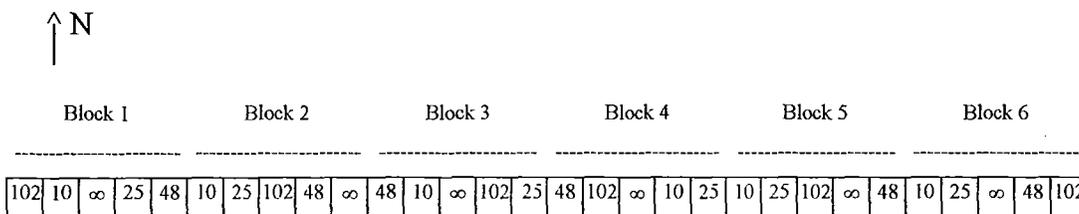


Figure 3.1 Randomised complete block design layout, and bagged volumes (litres) or unlimited volumes (∞).

3.3 Root control bags

The Root Control™ bags (Root Control Incorporated, Okalahoma City, USA) are constructed of 5.3 ounce UV stabilised Duon® (Phillips Fibers Corporation), a porous synthetic fabric, allowing movement of nutrients and moisture between the inside of the bag and the surrounding environment. The fabric bags are cylindrical, with one end sealed with clear plastic to form the bottom of the bag. Bag volumes were the following dimensions: diameter in millimetre (mm) x height in mm; 15 litre (250mm x 275mm), 34 litre (350mm x 325mm), 65 litre (450mm x 375mm), and the 139 litre was (600mm x 450mm). However, as bags were planted 50 mm above the ground the soil volumes available to the plants were estimated to be 10, 25 ,48 102 litres, respectively. Plate 3.1 illustrates the relative bag dimensions.



Plate 3.1 Root control bags of volumes 10, 25, 48, and 102 litres.

3.4 Training and minimal management

The vines were trained along the fruiting wire to obtain a 2 metre cordon in the first two seasons of growth. The trellis was a vertical trellis with the vines trained to a spur pruned, single one armed cordon. Shoot growth was trained to a vertical shoot alignment. The fruiting wire was approximately 80 centimetres (cm) above the ground, and three sets of foliage wires were used to support shoot growth (plates 3.2 and 3.3). The entire canopy were netted from veraison to deter fruit losses from birds. No bunch thinning was carried out in any year. Lateral shoots were not removed and summer pruning was not carried out in any growing seasons, although in 1994 shoots were accidentally trimmed at approximately 200 cm above the ground. Irrigation was applied by dripper under normal field conditions with all vines receiving the same amount of application. The inter-row area was maintained free of weeds using pre-emergent (Simazine[®]) and post emergent (Roundup[®]) herbicides.



Plate 3.2 A non restricted vine illustrating the training wires and shoot growth at the end of the sixth growing season (1995).

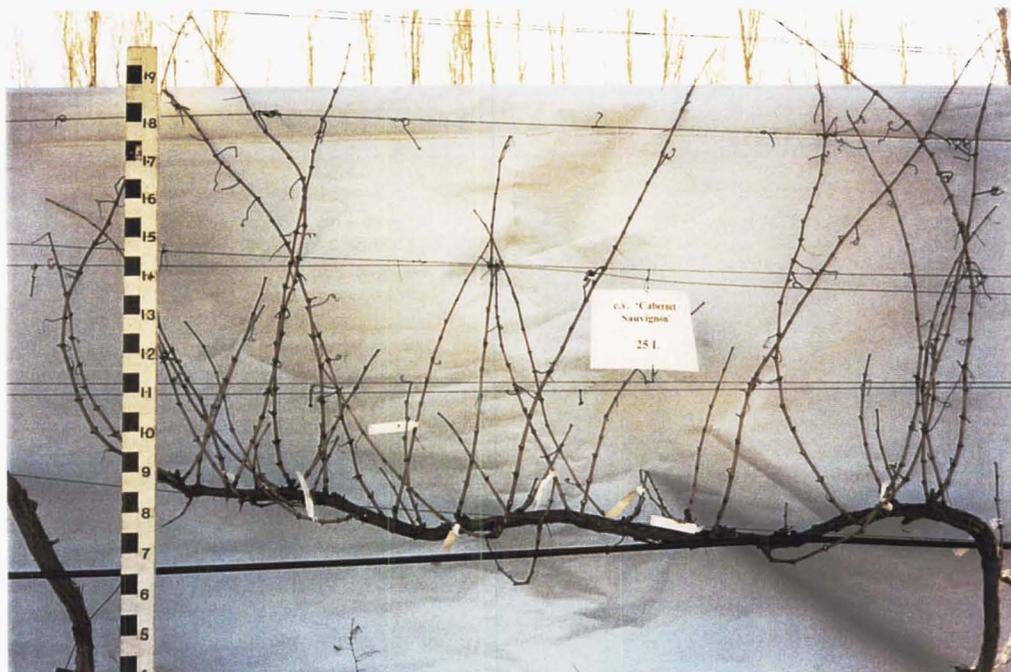


Plate 3.3 A 25 litre bagged vine illustrating the training wires and shoot growth at the end of the sixth growing season (1995).

3.5 Statistical analysis

Statistical analysis of the experiment was carried out on untransformed data. The analysis was designed to test two hypothesis; firstly to test if differences existed between the bagged versus the non restricted vines, and secondly, to test if there was a proportionate bag effect within the bagged vines, for example a linear relationship between different bag volumes and a growth parameter. Statistical analysis was performed by analysis of variance, apportioning the sum of squares into the following single degree of freedom and orthogonal contrasts using regression. An orthogonal contrast was used to compare non restricted versus bagged, and within the bagged regression effects were examined by: linear within bagged, quadratic within bagged and cubic within bagged. The means of the bagged treatments were obtained by use of a general linear model. All statistical tests were applied to all data, however, only contrasts where at least one significant result was obtained were included in tables. Correlations and correlation coefficients were obtained by regression (Microsoft Excel version 5, statistical 'add ons'). Specific experimental procedures are detailed in each experimental chapter.

Chapter 4

THE EFFECTS OF ROOT RESTRICTION ON VEGETATIVE GROWTH

4.1 Introduction

Grapevines are climbing plants or 'Lianas' with a strong vegetative growth cycle (Mullins *et al.*, 1992). Although shoot growth slows in mid-summer, grapevines do not develop terminal buds as shoot growth is largely indeterminate (Coombe, 1988). Vegetative growth can be quantified by measuring pruning weights, and 'shoot vigour' can be examined by the number of primary and lateral shoots, node number, internode length, and leaf size at the end of the growing season (Smart and Robinson, 1991). Excessive vegetative growth can result in a dense, shaded vine canopy with undesirable consequences for inflorescence initiation, fruit set, fruit ripening, and the occurrence of pests and diseases (Coombe, 1988). A high shoot density has a greater requirement for shoot thinning to reduce the grapevine canopy density and the within row shading. Extensive shoot growth requires trimming to avoid between row shading. However, these remedial practices are expensive, thus alternative strategies for preventative vigour control are desirable. Previous research with root restriction in a range of plant species (Chung, 1983; Al Sahaf, 1984; Hameed, 1988; White, 1995), including grapevines in artificial environments (Ussahatanonta, 1992; Henry, 1993), indicated strong reductions in vegetative growth.

The objective of this research was to test the hypothesis that root restriction bags reduce the long term vegetative growth of perennial field grown grapevines. This was tested by looking at the effects of root restriction on: pruning fresh weights, trunk cross sectional area (TCSA), primary and lateral shoot number; node (or leaf) number, and internode length, average leaf size, total leaf area per plant and canopy density.

4.2 Experimental procedure

4.2.1 Pruning procedure

Pruning was carried out to obtain approximately 30 nodes per vine. Short one or two count node spurs were used. Only approximate the same node number could be obtained for each vine as this was governed by the availability of healthy and well spaced spurs to evenly fill the canopy. No shoot thinning was carried out.

4.2.2 Measurement of shoot parameters

At pruning shoots for each vine were numbered and collected, and subsequently a pruning fresh weight was obtained. Shoots were measured to determine length and number of primary and lateral shoot nodes. Average internode length was derived by dividing total primary and lateral shoot length, by respective node numbers.

4.2.3 Measurement of trunk cross sectional area

At the end of each growing season each vine's trunk cross sectional area was measured. The vine was marked 30 cm up from the base of the vine. North-south and east-west trunk diameters were measured using vernier callipers, and averaged to obtain the diameter. Trunk area cross sectional area was calculated using the equation for deriving the area of a circle, $\pi (\text{diameter} / 2)^2$.

4.2.4 Measurement of leaf area

In 1995 leaf average area per vine was determined by taking a random sample of approximately 10 percent of the leaves per vine, in the previous year. The leaves were collected and measured using a lamp leaf area meter (Li Cor, Model 3100, Area Meter), to determine average leaf area per vine. Subsequently, total leaf area per vine was derived by multiplying leaf average area by leaf (node) number per vine.

4.2.5 Canopy density

In 1995 canopy density was derived using the ratio of, **leaf area per vine: canopy surface area** (m^2 / m^2) as detailed in Smart and Robinson (1991).

Where;

Canopy surface area (m^2) = [average shoot length (x m) x between vine spacing (2m) x 2 (two sides of the canopy)] + [canopy top width (0.3m) x between vine spacing (2m)].

4.3 Results

When compared to the non restricted control vines, vines grown in bags generally had significantly lower pruning weights, thinner trunk cross sectional areas, reduced primary and lateral shoot number, as well as node, or leaf number, and internode lengths, and leaf area per vine. This resulted in fewer shorter shoots with a reduced leaf area per vine (Table 4.1 to 4.6). Average leaf area and canopy density were also decreased in the bagged vines, although not significantly at ($P < 0.05$) (Table 4.6).

The influence of different bag size on vegetative growth was less consistent (Tables 4.1 to 4.6). Linear and positive correlations ($P < 0.05$) between bag volume and pruning weights were present in 1991, 1994 and 1995, and other parameters such as primary shoot node, or leaf, number in 1993 and 1995, internode lengths in 1994, and leaf area per vine in 1995. Vegetative growth of the 10 litre bagged vine was always disproportionate to the others and subsequently, R^2 of the within bag regression effects were always low, however, quadratic correlations ($P < 0.05$) between bag volume and pruning weights in 1995, and vegetative parameters such as primary shoot node, or leaf number in 1995, internode length in 1995 and leaf area per vine in 1995 had slightly increased R^2 values. In comparison, the 25, 48 and 102 litre bagged vines were positively and proportionally correlated with pruning weights, primary and lateral shoot number, primary shoot node, or leaf number, from 1992 to 1995 and with trunk cross sectional area, lateral shoot node or leaf number, and primary and lateral shoot internode length in 1994 and 1995 (statistical analysis not shown).

Figure 4.1 shows bag and block effects on vines from 1991 to 1995. The bagged vines generally had reduced growth up until 1995, although some bagged replicates grew disproportionately. Figure 4.2 shows that from 1992 the 10 litre vines pruning weights were between the 48 and 102 litre bags, but all other bagged vines had average pruning weights proportionate to bag size from 1991 to 1995.

4.4 Discussion

The trial investigated the response of grapevines to root restriction caused by Duon[®] bags, a porous synthetic fabric. The bags were expected to reduce root growth by two physical means, firstly, allowing some fine root penetration through the bag but reducing further growth by girdling any root thickening, and secondly, by limiting the physical volume of the soil exploited by the vines roots.

The reduction in vegetative growth of the vines, indicated by the lighter pruning weights, suggests that the bags were limiting root development in the restricted versus non restricted vines in the early stage of the experiment. These results are similar to those reported where lighter shoot weights resulted from root restriction for glasshouse grown grapevines (Ussahatanonta, 1992; Henry, 1993) and other plant species (Robbins and Pharr, 1988; Latimer, 1991), including peach trees (Costa *et al.*, 1992). The reduced shoot number found in this experiment is in agreement with previous root restriction research which has reported reduced shoot number in peach seedlings (Richards and Rowe, 1977a) and a reduced lateral shoot number found in a range of other species (Peterson *et al.*, 1991a; Robbins and Pharr, 1988; Williamson *et al.*, 1992). (The increased primary shoot number in the larger bagged and the non restricted vines suggests insufficient buds were left at pruning to meet the growth potential of the vine and the increased lateral shoot number is a reflection of the auxiliary buds that have grown due to their increased growth potential) (Winkler *et al.*, 1974; Mullins *et al.*, 1992). The smaller TCSA resulting from root restriction in my experiment is similar to results reported for field grown peach trees (Williamson and Coston, 1990; Myers, 1992) and apple and sweet cherry trees (Dolph and Proebstring, 1989).

The shorter shoot length (derived) evident in my research was due to a reduced node number and reduced internode length. Similar results have been reported in other root restriction research with glasshouse grown grapevines (Komatsu and Nakagawa, 1989; Ussahatanonta, 1992; Henry, 1993), kiwifruit vines (Tonutti and Giulivo, 1990) and findings in a range of other plant species (Chung, 1983; Tschaplinski and Blake, 1985; Latimer, 1991; Carmi and Shalhevet, 1983; Ben-Porath and Baker, 1990). For grapevines the lower node number represents a lower leaf number which is similar to

previous general findings in other species in response to root restriction (Richards and Rowe, 1977a; Costa *et al.*, 1992; Hameed, 1988). Moreover, my research suggested the main effect of root restriction was a decreased node number, for example, comparing the bagged vines as % of the non restricted vines (Table 4.4). In contrast, previous root restriction research with grapevines (Ussahatanaonta, 1992; Henry, 1993) led Henry (1993) to conclude that the main effect of root restriction was reduced internode length, and the research of Ussahatanaonta (1992) showed only very small differences in the effect of root restriction on node number and internode length, although there was also a trend to a greater effect on internode length. Why this different effect occurred is unclear but possibly reflects the higher degree of root restriction in the earlier research, in comparison, in my research preliminary investigation revealed new root growth occurred around the periphery of the bags. A reduced node number is in agreement with previous root restriction research with grapevines (Henry, 1993; Ussahatanaonta, 1992) and tomatoes (Ruff *et al.*, 1987). Up to the first 12 nodes in a shoot are proposed to be 'fixed' (Mullins *et al.*, 1992), that is present in the bud at shoot emergence in spring. In 1995, shoots on the bagged vines had an average of approximately 16 nodes (derived data), while non restricted vines had an average of 23. The shorter internodes as a result of root restriction in my work are also in agreement with the previously discussed research with glasshouse grown grapevines (Ussahatanaonta, 1992; Henry, 1993), field grown peach trees (Williamson and Coston, 1990) and other species (Carmi and Heuer, 1981; Ben-Porath and Baker, 1990). Investigation of factors determining node number and internode length should reveal more understanding about the mechanism of root restriction in reducing grapevine growth.

The smaller average leaf area and leaf area per vine in my research are similar to results of research using grapevine cuttings (Henry, 1993), sweet cherry and apple trees (Dolph and Proebstring, 1989) and also a range of other plant species (Richards and Rowe, 1977a; Costa *et al.*, 1992; Carmi and Heuer, 1981; Mutsaers, 1983; Tschaplinski and Blake, 1985; Al-Sahaf, 1984; Ruff *et al.*, 1987; Peterson *et al.*, 1991a; Latimer, 1991; Ne Smith *et al.*, 1992). The trend to a decreased canopy density in the bagged vines used in my results suggests less mutual leaf shading and the possibility of a reduced total photosynthetic potential. Likewise, the lower number of lateral shoots and subsequently fewer lateral leaves suggests reduced shading in the fruiting zone of the bagged vines. No other research that the author is aware of has looked at the effects of

root restriction on canopy density. The effects of an increased canopy density and subsequently increased shading on fruitfulness and fruit maturity will be considered in the following two experimental chapters.

Although root restriction resulted in decreased vegetative growth parameters, the replicate and proportionate bag effects of root restriction on the grapevines were less consistent. Figures 4.1 and 4.2 show that up until 1995, the vines generally continued to have proportionally heavier annual pruning weights in each successive years, suggesting that the bags were proportionally restricting root growth in the early stages of the experiment. In 1995, the increasing variation relative to the treatment size (correlation of variation) and the continued but unexplained disproportionate vegetative growth parameters of the 10 litre bagged vines, prompted investigation as to the source of variation. Preliminary root excavation revealed unintended root escapes were evident in all treatments.

The bags used in this experiment were expected to allow the growth of fine roots through to the periphery of the bag, but subsequently were expected to girdle these roots if they thickened. However, root excavation revealed that not all roots were girdled (see Agronomic Implications and Further Research Chapter 8). Thus, roots were not confined to the area of the bag, and differences in growth could diminish between the bagged vines and the non restricted vines with time. Further long term research work with root restriction using porous bags is clearly required to establish if growth control can be sustainable. The disproportionate vegetative growth of the 10 litre bag also poses a further question; is the growth due entirely to root escapes or also changes in the root to shoot ratios of the bagged vines?

In general there is a consistent relationship between the root and shoot weights in annual plants in a given environment (Richards, 1981; Chung, 1983), although the relationship between shoots and roots appears to be less consistent in fruiting perennials (Atkinson, 1980), in particular grapevines (Mullins *et al.*, 1992). Results presented on different root to shoot ratios in grapevines (Winkler *et al.*, 1974) confirm that it varies widely under field conditions. Destructive harvest should reveal if the bagged vines had different root to shoot ratios and will possibly assist in explaining the disproportionate vegetative growth of the 10 litre bagged vines in my research.

Table 4.1 The effect of bag volume on pruning fresh weights¹ per vine (kg) from 1991-1995.

	Volume (L)	Year					Average
		1991	1992	1993	1994	1995	
Bagged	10	0.09±0.03	0.81±0.11	1.38±0.13	2.27±0.19	2.42±0.37	1.40±0.16
	25	0.13±0.02	0.62±0.08	0.95±0.20	1.58±0.23	1.26±0.38	0.91±0.18
	48	0.12±0.02	0.75±0.10	1.13±0.27	2.00±0.24	1.82±0.35	1.16±0.20
	102	0.20±0.04	0.96±0.09	1.57±0.23	2.61±0.29	3.08±0.62	1.68±0.25
	Average	0.13±0.03	0.79±0.10	1.26±0.21	2.11±0.24	2.15±0.43	1.29±0.20
Unrestricted	∞	0.20±0.04	1.37±0.16	2.84±0.20	3.86±0.13	4.98±0.30	2.65±0.17
SED bagged VS unrestricted		0.04	0.17	0.23	0.19	0.39	
Orthogonal contrast ²							
bagged VS unrestricted		ns	0.000***	0.000***	0.000***	0.000***	
Regression ²							
linear within bagged		0.038*, 0.23 ³	ns	ns	0.032*, 0.13 ³	0.035*, 0.13 ³	
quadratic within bagged		ns	ns	ns	ns	0.039*, 0.25 ³	

¹ Mean of 6 replicates.

² Regression and contrast significance at $P < 0.05$ and $P < 0.001$ denoted by *, *** respectively, ns is not significant.

³ R² value.

±SEM.

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Table 4.2 The effect of bag volume on trunk cross sectional area¹ per vine (mm²) from 1991-1995.

	Volume (L)	<i>Year</i>					<i>Average</i>
		<i>1991</i>	<i>1992</i>	<i>1993</i>	<i>1994</i>	<i>1995</i>	
Bagged	10	134±13	343±21	590±21	834±30	1088±36	598±24
	25	150±15	344±29	568±44	772±61	962±55	560±41
	48	139±18	330±28	558±45	801±49	986±71	563±42
	102	161±17	368±20	595±31	803±60	1146±88	615±54
	Average	146±16	346±25	578±35	803±50	1045±63	584±40
Unrestricted	∞	162±11	392±18	659±23	959±38	1208±45	676±27
SED bagged VS unrestricted		13	22	29	45	56	
Orthogonal contrast ² bagged VS unrestricted		ns	ns	0.020*	0.006**	0.020*	

¹ Mean of 6 replicates.

² Regression and contrast significance at $P < 0.05$, $P < 0.01$, denoted by *, **, respectively, ns is not significant.
±SEM.

Table 4.3 The effect of bag volume on shoot number¹ per vine from 1992-1995.

	Volume (L)	Primary					Lateral				
							<i>Year</i>				
		1992	1993	1994	1995	Average	1992	1993	1994	1995	Average
Bagged	10	23±2	35±2	48±2	42±3	37±2	12±8	4±1	45±10	15±5	19±6
	25	19±1	28±1	44±2	41±2	33±2	8±5	4±1	24±7	5±2	10±5
	48	23±2	30±1	47±3	43±2	36±2	5±2	9±3	40±14	7±2	15±5
	102	25±3	32±3	47±5	48±3	38±4	13±7	7±3	46±11	16±7	21±7
	Average	23±2	31±2	47±3	44±3	36±3	13±7	7±3	46±11	16±7	16±6
Unrestricted	∞	24±2	36±2	54±2	52±2	42±2	18±7	35±8	80±7	42±4	44±7
SED bagged VS unrestricted		2	2	3	5		5	8	9	4	
Orthogonal contrast ² bagged VS unrestricted		ns	0.037*	0.044*	0.010*		0.000***	0.000***	0.002**	0.000***	

¹ Mean of 6 replicates.

² Contrast and regression significance at $P < 0.05$, $P < 0.01$, $P < 0.001$ denoted by *, **, *** respectively, ns is not significant. ±SEM.

Table 4.4 The effect of bag volume on shoot node¹, or leaf number, per vine from 1992-1995.

	Volume (L)	Primary					Lateral				
							<i>Year</i>				
		<i>1992</i>	<i>1993</i>	<i>1994</i>	<i>1995</i>	<i>Average</i>	<i>1992</i>	<i>1993</i>	<i>1994</i>	<i>1995</i>	<i>Average</i>
Bagged	10	333±25	588±34	639±20	727±84	572±41	28±14	17±6	114±30	37±19	49±17
	25	267±27	464±40	549±47	578±57	465±43	22±16	13±5	48±16	9±3	23±10
	48	321±47	473±70	625±62	640±72	515±63	13±6	33±10	117±52	11±5	44±18
	102	374±48	618±68	662±53	910±104	641±68	38±16	28±8	129±24	31±15	57±16
	Average	324±37	618±68	62±53	714±79	548±54	25±13	23±7	102±31	22±10	43±15
Unretracted	∞	453±43	829±36	775±45	1204±32	815±39	80±35	207±54	330±38	115±24	38±15
SED bagged VS unrestricted		47	47	51	56		36	54	42	24	
Orthogonal contrast ² bagged VS unrestricted		0.001**	0.000***	0.005**	0.000***		0.002**	0.000***	0.000***	0.000***	
Regression ² linear within bagged		ns	ns	ns	0.009**,0.18 ³		ns	ns	ns	ns	
quadratic within bagged		ns	0.015*,0.21 ³	ns	0.037*,0.30 ³		ns	ns	ns	ns	

¹ Mean of 6 replicates.

² Contrast and regression significance at $P < 0.01$, $P < 0.001$ denoted by **, ***, respectively, ns is not significant.

³ R² value.

±SEM

Table 4.5 The effect of bag volume on shoot internode length¹ (cm²) from 1992-1995.

	Volume (L)	Primary					Lateral				
							Year				
		1992	1993	1994	1995	Average	1992	1993	1994	1995	Average
Bagged	10	4.94±0.18	5.21±0.11	6.55±0.17	5.93±0.13	5.66±0.15	1.33±0.53	3.27±0.14	2.51±0.32	3.49±0.32	2.65±0.33
	25	4.97±0.17	5.04±0.12	6.11±0.22	5.22±0.27	5.34±0.20	5.68±2.59	3.57±0.12	2.11±0.23	2.33±0.48	3.42±0.86
	48	4.95±0.12	5.04±0.26	6.55±0.39	5.48±0.31	5.51±0.27	1.62±0.25	3.69±0.37	2.54±0.43	2.35±0.36	2.55±0.35
	102	5.14±0.30	5.29±0.15	6.96±0.23	6.15±0.21	5.89±0.22	3.53±0.85	3.42±0.39	2.89±0.11	2.63±0.35	3.12±0.43
	Average	5.00±0.19	5.15±0.16	6.54±0.25	5.70±0.23	5.60±0.21	3.04±1.06	3.49±0.26	2.51±0.27	2.70±0.38	2.94±0.49
Unrestricted	∞	5.60±0.20	5.86±0.10	7.51±0.11	6.87±0.12	6.46±0.13	2.49±0.22	4.37±0.23	3.96±0.06	3.49±0.35	3.58±0.22
SED Bagged VS unrestricted		0.22	0.13	0.18	0.18		0.76	0.27	0.16	0.40	
Orthogonal contrast ²											
bagged VS unrestricted		0.017*	0.000***	0.000***	0.000***		ns	0.016*	0.000***	ns	
Regression ²											
linear within bagged		ns	ns	0.041*,0.12 ³	ns		ns	ns	ns	ns	
quadratic within bagged		ns	ns	ns	0.020*,0.24 ³		ns	ns	ns	ns	

¹ Mean of 6 replicates.

² Contrast and regression significance at $P < 0.05$, $P < 0.001$ denoted by *, *** respectively, ns is not significant.

³ R² value.

±SEM

C6

4.6 The effect of bag volume on average leaf area⁶, total leaf area⁶ per vine and canopy density⁶ in 1995.

	Volume (L)	Average leaf area ¹ (cm ²) <i>leaf</i>	Leaf area per vine ⁴ (cm ²) <i>total</i>	Canopy density ⁵ (m ² /m ²) <i>= total leaf area / vine / canopy area / vine</i>
Bagged	10	95.2±5.7	74,524±12,831	1.55±0.17
	25	80.9±5.4	48,178±6,936	1.36±0.14
	48	91.4±4.9	59,842±7,866	1.52±0.06
	102	95.2±3.3	91,419±15,056	1.69±0.14
	Average	90.7±6.3	68,491±10,672	1.53±0.17
Unrestricted	∞	95.6±4.4	125,542±4,055	1.82±0.16
SED Bagged VS unrestricted		5.1	7,422	0.170
Orthogonal contrast ² bagged VS unrestricted		ns	0.000***	ns
Regression ² linear within bagged		ns	0.041*, 0.13 ³	ns
quadratic within bagged		ns	0.047*, 0.24 ³	ns

¹ Mean based on sample of 10% of 1994 total leaf number per vine.

² Contrast and regression significance at $P < 0.05$ denoted by *, ns is not significant.

³ R² value.

⁴ Total leaf area per vine = average leaf area (cm²) x total leaf number per vine.

⁵ Canopy density = leaf area per vine (m²) / canopy area per vine (m²).

⁶ Mean of 6 replicates.

±SEM.

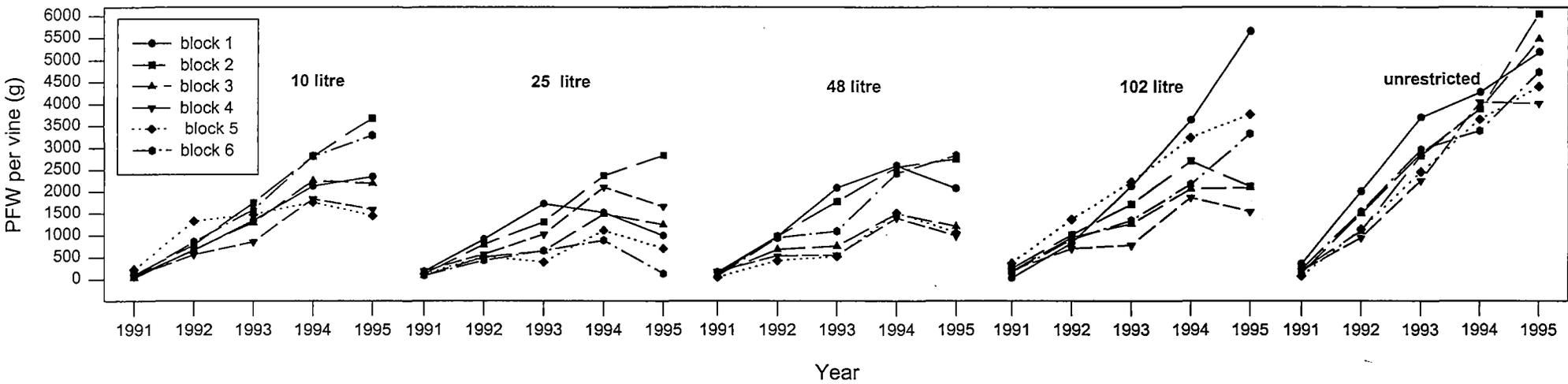


Figure 4.1 The effect of block and bag volume on pruning fresh weights (PFW) from 1991 to 1995.

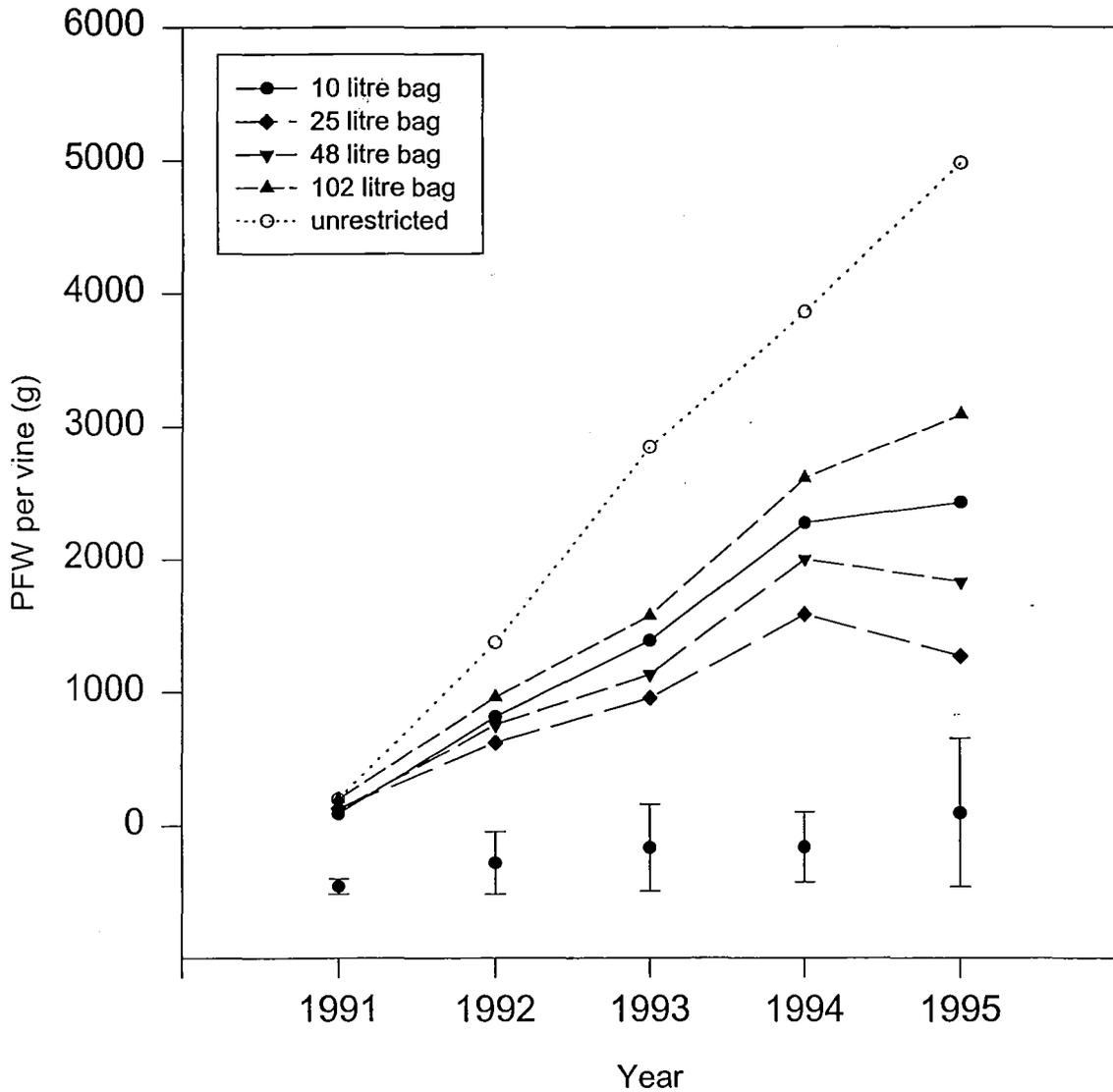


Figure 4.2 The effect of bag volume on the pruning fresh weights (PFW) per vine from 1991 to 1995. The error bars denote \pm SEM, and are applicable to bagged and unrestricted vines.

Chapter 5

THE EFFECTS OF ROOT RESTRICTION ON FRUITFULNESS

5.1 Introduction

Productivity in horticulture has been defined as partitioning a high proportion of assimilates to economically important organs (Daie, 1985). Reproductive growth is suggested to generally dominate vegetative growth (Wardlaw, 1990). However, sink strength depends on the developmental stage of the plant, for example, in flowering tomato plants the sink hierarchy changes from roots > young leaves > inflorescences, in fruiting plants the hierarchy is reversed to fruit > young leaves > flower > roots, the competition between rapidly growing fruit and young leaf growth, representing competition between storage and utilisation sinks (Ho *et al.*, 1989). Root restriction treatments of tomato resulted in improved development of inflorescence (Cooper, 1972) and was implicated in diverting assimilates from leaf to fruit growth (Al-Sahaf, 1984). Root restriction of grapevines in artificially controlled environments resulted in accelerated ovule development (Okamoto and Imai, 1989), promoted seeded berry set (Okamoto and Imai, 1989; Komatsu and Nakagawa, 1989), increased berry weight and berry number per vine and subsequently increased the crop load, fruit fresh weight per unit shoot weight (Ussahatanonta, 1992).

The objective of my research was to test the hypothesis that root restriction bags increase long term fruitfulness of perennial field grown grapevines. This was tested by investigating the effects of root restriction on annual reproductive growth and derived harvest efficiency indexes.

5.2 Experimental procedure

5.2.1 Annual reproductive growth

Fruit fresh weight per vine was determined at the end of each growing season by weighing all bunches in the main fruiting zone. The fruiting zone extended forty centimetres above the cordon. Bunch number was determined by counting berry clusters

8-7
45
Arabidopsis

within the main fruiting zone, only including lateral shoot clusters of a maturity appearance similar to primary shoot bunches, unripe (unmarketable) second set bunches were excluded from any analysis. Average bunch weight was determined by dividing the fruit fresh weight per vine by the bunch number per vine.

Average berry weight per vine was obtained in 1992 by dividing five randomly selected bunch weights by berry number, minus the stalk weights. In 1995 average berry weight was based on a sample of 100 randomly selected berries per vine. Stalk weights in 1992 were based upon a sample of 5 randomly selected bunch stalks. In 1995 stalk weights were derived by separating all berries from the stalks, obtaining a total stalk weight per vine and dividing by bunch number per vine. Average berry number per bunch in both years was derived by subtracting the average stalk weight per vine, from average bunch weight per vine and dividing by average berry weight.

5.2.2 Harvest efficiency indexes

Four measurement of harvest efficiency were contrasted;

1. Fruit fresh weight per vine / unit fresh pruning weight per vine, [FFW/PW] (g/g),
- ✓ 2. Leaf area per vine / unit fresh fruit weight per vine, [LA/FFW] (cm²/g)
3. Fruit fresh weight per vine / unit primary shoot number per vine [FFW/PSN] (g/shoot)*¹ ?
4. Fruit fresh weight per vine / unit total shoot number per vine [FFW/ TSN] (g/shoot)*¹.

conflict

* Inclusive of lateral shoots

5.3 Results

When compared to the unrestricted 'control' vines, vines grown in bags had generally, though usually not significantly ($P < 0.05$), reduced fruit fresh weights and bunch numbers (Tables 5.1 and 5.2). However, the influence of root restriction on the average bunch weight was less consistent, average bunch weight was reduced in bagged vines in 1992 and 1994, however in 1995 and subsequently, the average bunch weight was slightly increased in the bagged vines (Table 5.3). Within the bunch weight variables,

the bagged vines compared to the non bagged vines had: average stalk weights that were similar in 1992, although significantly ($P<0.039$) heavier in 1995 (Table 5.4); average berry number per bunch was generally lower in 1992, but similar in 1995 (Table 5.5); and average berry weight was higher in 1992, but lower in 1995 (Table 5.6). The harvest efficiency indices indicated that the bagged vines produced more fruit fresh weight (FFW) per unit of pruning weight in all years, though only significantly ($P<0.005$) in 1994 (Table 5.7). Similarly, leaf area per gram of fruit fresh weight was significantly ($P<0.036$) improved in the bagged vines (Table 5.8). FFW produced per total shoot number (inclusive of lateral fruit) was increased in the bagged vines, alternatively, if expressed as FFW per primary shoot number (but still inclusive of lateral fruit), was decreased (Table 5.9 and 5.10), although neither index were ever significantly ($P<0.05$) different in the bagged compared to the unrestricted vines.

The proportionate influence of bag size was inconsistent, the 25, 48 and 102 litre bags were positively and proportionally correlated with FFW, bunch number, bunch weight, stalk weight, average berry number per vine and average berry weight in 1992, FFW and bunch number in 1993 and 1994, FFW, bunch number, average berry weight and the harvest index leaf area present per gram of FFW in 1995 (Tables 5.1 to 5.6). There was a negative linear relationship between bag volume and FFW produced per unit of pruning weight in 1995 ($P<0.041$), although the R^2 value was low. The 25, 48 and 102 litre bags were negative and proportionally correlated with fruit fresh weight per unit pruning weight in 1994 and 1995 (Table 5.7). However, in contrast to the other smaller bag sizes, the 10 litre bagged vine had disproportionate fruitfulness measurements more like those for larger bagged vines. For example, the 10 litre vine had similar FFW to the 48 litre bag in 1992, but by 1996 had similar FFW to the 102 litre bagged and unrestricted vines (Table 5.1).

5.4 Discussion

The trial investigated the annual reproductive growth measurements and derived harvest efficiency of vines in response to root restriction imposed by planting vines in porous Duon[®] bags. Growing the grapevines in bags was expected to reduce the amount of root growth in proportion to the shoot growth. It was hypothesised that the reproductive growth of root restricted vines would benefit from the reduced root and shoot growth.

Reproductive growth was thought to benefit in two ways; firstly directly, by possibly receiving a greater portion of carbohydrate partitioning and secondly, indirectly, by allowing increased light into the vine canopy due to a lower leaf layer number, and subsequently a decreased canopy density. Thus introducing the possibility of promoting reproductive processes dependent on light and temperature. Difficulties in interpretation of the influence of bags on the reproductive growth and the inability to show strong consistent relationships between fruitfulness parameters and reduced rooting volume were probably due to root escapes from all bags (see Chapter 4). A further complication in the interpretation of the results were the wide variations of crop loading on the vines, due to the minimal management interference, i.e. winter pruning only.

The reduction in fresh fruit weight of bagged vines in my research is similar to the results reported in previous research, where fruit weight per plant decreases were shown in long term research with apple trees using the same root restriction bags (White, 1995), in root restriction of peach trees by fabric lined trenches (Williamson and Coston, 1990), with pot root restricted peach trees (Vizzotto *et al.*, 1997) and with other species grown as annuals (Carmi and Shalhevet, 1983; Ne Smith *et al.*, 1992; Bar Tal and Pressman, 1996). In comparison to these findings is the report that the yield of root restricted lemon trees was of a 'similar magnitude' (data not shown) to that of unrestricted trees (Salomon, 1978). In contrast to general research findings is research with sweet cherries root restricted by woven porous (50-60mm) membranes (Webster *et al.*, 1997). In that research both the number of marketable fruit and the fruit weight per tree were increased by root restriction treatments. Possibly, the 'larger pore sizes' allowed root growth outside the bags and this assisted in maintaining yield per plant. Longer-term results would reveal if this result could be sustained, or if the differences between the restricted and control plants would be diminished in time.

The clear trend to increased fruit weights and other fruitfulness measurements being positively correlated with the 25, 48 and 102 litre bag sizes was also reported for fruit weight per tree in the later two years of a trial with apple trees (White, 1995) using the same make and type of bags as used in my research. That research also showed the disproportionate effect of the 10-litre bag in the later part of the trial. Although the proportionate results of the larger bagged vines were not as consistent as found here.

Possibly this was due to biannual bearing that was clearly evident in the research with apples (White, 1995).

The reduction in yield in my results was most clearly reflected in the reduction in bunch number in the root-restricted vines. Similarly, in response to root restriction slight reductions in fruit number were reported in peach trees (Williamson and Coston, 1990) and in cotton plants, where the cotton boll number was reduced (Carmi and Shalhevet, 1983; Carmi, 1986). In contrast to these results, there was 'no effect' (no results shown) on root restricted peach number per tree (Myers, 1992) using the same make and type of bags as used in my research. However, those results were based on data collected for only two years.

The results presented in my research suggested that average bunch weight of bagged vines was reduced at three to four years after establishment of the trial, however, this trend was reversed in the later part of the trial, possibly due to root escapes and an increased rooting volume. Results presented elsewhere are in agreement with the earlier results obtained in my research. For example other research indicated a reduced average peach weight after two years (Williamson and Coston, 1990), a reduced mean cherry weight (Webster *et al.*, 1997) after three years, and a reduced fruit size (diameter and volume) after three years in apple trees (Atkinson *et al.*, 1997). In comparison to these results is the research where unmanaged (unpruned) root restricted and control apple trees went into biannual bearing, leading to a clear alternating pattern of increased followed by decreased fruit weights in both bagged and non bagged apple trees (White, 1995). Variations in crop load in my data was reduced in comparison to White's (1995) research probably due to minimal management (winter pruning only) used here, and the different species and cultivar predisposition to biennial bearing.

Bunch weight is dependent on three variables: stalk weight, berry number and berry weight. The two years of results presented in my research indicated no consistent differences were evident in factors determining bunch weight. Stalk weight was similar or increased in the average of the bagged vines and the root restricted vines, possibly due to a similar potential in the root restricted vines for bunch size, based on inflorescence size. No previous research has been published on the effects of root restriction on stalk weight. However, the effects on berry number and weight were

opposing and most likely counteractive.) For example in 1992 when berry weight tended to be higher in the root restricted vines berry number was reduced, in comparison, in 1995 when berry weight tended to be lower in the root restricted vines, berry number was increased. In contrast to my results is the research with root confined glasshouse grown grapevines (Ussahatanonta, 1992) which resulted in a trend to heavier average berry weights and greater berry number, leading to a higher total berry weight per plant in inverse proportion to the root restriction treatment size. The reason for the increased berry weight and number leading to a larger yield per plant in the glasshouse work (Ussahatanonta, 1992) but not in the field is not clear, but was possibly due to the higher degree of control over root confinement and environment at critical reproductive growth periods in the glasshouse work.

The increased harvest efficiency indices used in my research indicate that root restricted vines were more efficient in terms of fruit produced per unit leaf area or per unit pruning weight. The results obtained showed that the field trial grown vines had higher crop loads than previous research findings with glasshouse grown root restricted grapevines (Ussahatanonta, 1992). In that study fresh fruit weight per unit shoot weight in the average of the two smallest root restricted vines resulted in a FFW/ PFW of 1.07 (range 0.65-1.49), whereas the average of the bagged treatments was 1.56 (range 1.32-1.86). However, this balance of fruit fresh weight to unit pruning weights is well below 5-10:1 ratio (of trimmed shoots) that is commonly considered necessary for managed grapevine with 'balanced' fruit and vegetative growth (Smart and Robinson, 1991). The type of pruning used in my research possibly accounts for some differences between these studies. The short spur pruning I used left the basal nodes which are reported to produce small bunches in Cabernet Sauvignon (Winkler *et al.*, 1974). The small bunches would possibly have been a small carbohydrate sink. Further research utilising spur pruning could utilise cultivars such as Riesling or Pinot Noir, which have more fruitful basal nodes (Winkler *et al.*, 1974). Alternatively, long spur or cane pruning, utilising the more fruitful nodes, and shoot thinning may give a better indication of the fruit sink's ability to compete with root and shoot growth. The effect of trimming the shoots would also probably further improve the fruit: shoot ratio of the root-restricted vines.

Research with other crops has reported similar findings to the results presented here in terms of increased harvest efficiencies, for example fresh fruit weight per fresh plant weight was increased in pot root restricted tomato plants (Klapwijk and Wubben, 1975) and increased fresh fruit weight per trunk cross sectional area increases were reported in root restricted peach (Williamson and Coston, 1990) and apple trees (Bravdo *et al.*, 1992; White, 1995). In contrast to the general results is the research with 5-80 litre pot restricted peach trees (Ran *et al.*, 1992), where fruit weight per total plant dry weight was increased in the second year of growth but in the subsequent year was clearly reduced. Possibly, this was due to root restriction effects only becoming evident in the large pots, for example the 80 litre trees, in the third year of the trial.

The decreased leaf area per gram of fruit weight found in my work is in agreement with the previous work with root restricted glasshouse grown grapevines (Ussahatanonta, 1992), although the average of the bagged vines $34 \text{ cm}^2/\text{g}$ (range 27-42 cm^2/g) was clearly much more efficient than the average of $109 \text{ cm}^2/\text{g}$ for the smallest pots (range 92-125 cm^2/g) as reported in the work of Ussahatanonta (1992). These ratios of leaf area per gram of fruit are clearly much higher than the optimum of $12 \text{ cm}^2/\text{g}$ (trimmed vines) generally suggested by Smart (Smart and Robinson, 1991). The higher leaf area or ratio of leaf area: fruit weight in all vines is possibly due to the same reasons as discussed previously with regard to FFW per PFW.

The FFW when expressed per primary shoot suggests that root restricted vines were generally less fruitful, inclusive of lateral bunches, alternatively, when expressed per total shoot number, but still inclusive of lateral shoots the root restricted vines showed trends to being more fruitful. In comparison, apple number per limb (Myers, 1992) was increased due to root restriction using the same bags as used in my work. Differences between treatments in my research and possibly the earlier research (Myers, 1992) could have been better resolved by discriminating between primary and lateral shoot fruit that could be considered marketable yield. Future research, in line with more management practices imposed on the treatments, should look at the effect of the same shoot number on root restriction fruitfulness.

In conclusion, root restriction of the grapevines led to generally reduced fruitfulness in the bagged compared to the unrestricted vines, although differences between bagged

and the unrestricted vines appeared to be reducing with time, possibly due to root escapes. The most common measurement of grapevine crop loading the FFW per PFW was improved in bagged vines, or alternatively the bagged vines were more efficient in terms of having less leaf area per gram of FFW.

Table 5.1 The effect of bag volume on fruit fresh weight per vine (kg/vine) in 1992 and from 1994 to 1996.

	Volume (L)	<i>Year</i>				<i>Average</i>
		<i>1992</i>	<i>1994</i>	<i>1995</i>	<i>1996</i>	
Bagged	10	1.67±0.23	2.03±0.18	2.10±0.30	3.74±0.34	2.38±0.26
	25	1.16±0.12	1.65±0.18	2.05±0.54	3.45±0.50	2.08±0.33
	48	1.86±0.39	1.72±0.20	2.60±0.50	3.64±0.18	2.46±0.32
	102	2.15±0.59	1.93±0.27	2.78±0.67	3.78±0.40	2.66±0.48
	Average	1.71±0.33	1.83±0.21	2.38±0.50	3.65±0.35	2.39±0.35
Unrestricted	∞	1.91±0.28	2.33±0.29	2.83±0.56	3.72±0.49	2.70±0.33
SED bagged VS unrestricted		0.34	0.31	0.61	0.52	
Orthogonal contrast bagged VS unrestricted		ns	ns	ns	ns	

Mean of 6 replicates.

ns is not significant.

+/- SEM.

Table 5.2 The Effect of bag volume on bunch number per vine from 1992-1996.

	Volume (L)	Year					Average
		1992	1993	1994	1995	1996	
Bagged	10	50±4	58±6	94±5	73±8	60±5	67±6
	25	37±3	47±3	77±6	67±7	55±5	57±5
	48	51±4	48±6	84±6	77±6	65±3	65±5
	102	54±11	49±7	92±17	89±12	70±7	71±11
	Average	48±6	51±6	87±9	77±8	63±5	65±7
Unrestricted	∞	52±5	69±7	98±6	97±6	72±6	78±6
SED bagged VS unrestricted		6	7	8	8	7	
Orthogonal contrast bagged VS unrestricted ¹		ns	0.008**	ns	0.036*	ns	

Mean of 6 replicates.

Contrast significance at $P < 0.05$, $P < 0.01$ denoted by * and **, respectively.

ns is not significant.

+/- SEM.

Table 5.3 The effect of bag volume on average bunch weight (g) per vine in 1992, and 1994 to 1996.

	Volume (L)	<i>Year</i>				<i>Average</i>
		<i>1992</i>	<i>1994</i>	<i>1995</i>	<i>1996</i>	
Bagged	10	33.7±3.0	21.6±0.9	28.5±2.6	63.1±6.0	36.7±3.1
	25	32.0±2.1	21.5±2.0	28.6±4.4	62.5±5.6	36.2±3.5
	48	34.8±6.4	20.5±1.9	33.2±5.5	56.7±3.0	36.3±4.2
	102	36.7±6.0	21.8±1.5	29.2±3.9	54.4±4.2	35.5±3.9
	Average	34.3±4.4	21.4±1.6	29.9±4.1	59.2±4.7	36.17±3.7
Unrestricted	∞	37.1±4.1	23.1±1.6	28.0±3.9	50.6±3.7	34.7±3.3
SED bagged VS unrestricted		4.7	1.8	4.4	4.4	

Mean of 6 replicates.

Orthogonal contrasts bag VS unrestricted were not significant.

+/- SEM.

Table 5.4 The effect of bag volume on average stalk weight (g) in 1992 and 1995.

	Volume (L)	Year		Average
		1992	1995	
Bagged	10	3.3±0.2	2.8±0.1	3.1±0.2
	25	3.0±0.2	3.0±0.2	3.0±0.2
	48	3.2±0.3	2.9±0.2	3.1±0.3
	102	3.2±0.3	3.1±0.5	3.2±0.4
	Average	3.2±0.3	3.0±0.3	3.1±0.3
Unrestricted	∞	3.3±0.3	2.3±0.2	2.8±0.3
SED bagged VS unrestricted		0.3	0.2	
Orthogonal contrast bagged VS unrestricted		ns	0.039*	

Mean of 6 replicates.

Contrast significance at $P < 0.05$ and denoted by *.

ns is not significant.

+/- SEM.

Table 5.5 The effect of bag volume on average berry number per bunch in 1992 and 1995.

	Volume (L)	Year		Average
		1992	1995	
Bagged	10	36.4±3.2	23.9±3.0	30.2±3.1
	25	35.6±2.2	24.5±3.6	30.1±2.9
	48	37.1±6.4	26.3±4.1	31.7±5.3
	102	39.5±6.2	22.4±3.2	31.0±4.7
	Average	37.2±4.5	24.3±3.5	30.8±4.0
Unrestricted	∞	42.6±5.0	22.6±2.8	32.6±3.9
SED bagged VS no bag		5.5	3.3	

Mean of 6 replicates.

ns is not significant.

+/- SEM.

Table 5.6 The effect of bag volume on average berry weight (g) in 1992 and 1995.

		<i>Year</i>		
		<i>1992</i>	<i>1995</i>	<i>Average</i>
<i>Volume (L)</i>				
Bagged	10	0.83± 0.02	1.09±0.04	0.96±0.03
	25	0.81±0.04	1.03±0.04	0.92±0.04
	48	0.84±0.04	1.13±0.07	0.99±0.06
	102	0.84±0.04	1.14±0.05	0.99±0.05
	Average	0.83±0.04	1.10±0.05	0.97 ±0.05
Unrestricted	∞	0.79±0.03	1.13±0.04	0.96±0.04
SED bagged VS unrestricted		0.04	0.05	

Mean of 6 replicates.

Orthogonal contrasts bagged VS unrestricted were not significant.

+/- SEM.

Table 5.7 The effect of bag volume on the harvest index: fruit fresh weight / pruning fresh weight (g/g) in 1992, 1994 and 1995.

		<i>Year</i>			
	Volume (L)	1992	1994	1995	<i>Average</i>
Bagged	10	2.08±0.16	0.92±0.09	0.95±0.20	1.32±0.12
	25	1.95±0.20	1.10±0.11	2.52±0.85	1.86±0.30
	48	2.48±0.50	0.89±0.09	1.67±0.52	1.68±0.31
	102	2.47±0.70	0.75±0.08	0.95±0.21	1.38±0.31
	Average	2.24±0.39	0.92±0.09	1.53±0.45	1.56±0.31
Unrestricted	∞	1.54±0.32	0.61±0.07	0.58±0.14	0.91±0.16
SED bagged VS unrestricted		0.39	0.09	0.31	
Orthogonal contrast bagged VS unrestricted		ns	0.005**	ns	
Regression linear within bagged		ns	0.041*, 0.17 ¹	ns	

Mean of 6 replicates.

Contrast significance at $P < 0.05$ and $P < 0.01$ denoted by * and ** respectively.

¹ R² value.

ns is not significant.

+/- SEM.

**Table 5.8 The effect of bag volume on the crop load:
leaf area per gram of fruit fresh weight (cm²/g) in 1992.**

Volume (L)		Year
		1992
Bagged	10	37.88±5.76
	25	27.90±4.00
	48	26.98±4.63
	102	41.66±10.99
Average		33.61±6.35
Unrestricted	∞	54.32±11.39
SED bagged VS unrestricted		11.91
Orthogonal contrast bagged VS unrestricted		0.036*

Mean of 6 replicates.

Contrast significance at $P < 0.05$ denoted by *.

+/- SEM.

0.15
> 1200 g

Table 5.9 The effect of bag volume on the harvest index: fruit fresh weight /primary shoot number (g/shoot) in 1992, 1994 and 1995.

	Volume (L)	Year			Average
		1992	1994	1995	
Bagged	10	74.51±8.10	41.87±2.58	49.25±5.83	55.21±5.50
	25	59.68±4.61	37.08±3.45	48.34±11.87	48.37±6.64
	48	80.52±16.40	36.38±3.48	59.62±10.21	58.84±10.03
	102	79.25±17.42	40.58±3.01	56.08±10.66	58.64±10.36
	Average	73.49±11.63	38.98±3.13	53.32±9.64	55.26±8.13
Unrestricted	∞	79.84±11.45	42.69±4.14	54.74±9.91	59.09±8.5
SED bagged VS unrestricted		13.04	4.42	10.98	

Mean of 6 replicates.

Orthogonal contrasts bagged VS unrestricted were not significant.

+/- SEM.

Table 5.10 The effect of bag volume on the harvest index: fruit fresh weight /total shoot number (FFW/TSN) in 1992, 1994 and 1995.

	Volume (L)	Year			Average
		1992	1994	1995	
Bagged	10	55.19±10.17	22.71±2.29	38.66±6.71	38.85±6.39
	25	48.58±7.39	25.48±3.34	43.34±10.83	39.13±7.19
	48	69.00±14.64	20.96±2.17	51.81±8.84	47.26±8.55
	102	58.60±14.45	23.12±5.21	42.22±6.39	41.31±8.68
	Average	57.84±11.66	23.07±3.25	44.00±8.19	41.64±7.70
Unrestricted	∞	50.74±11.10	17.55±2.31	31.02±6.70	33.10±6.70
SED bagged VS unrestricted		12.53	2.87	7.82	

Mean of 6 replicates.

Orthogonal contrasts bagged VS unrestricted were not significant.

+/- SEM.

Chapter 6

THE EFFECTS OF ROOT RESTRICTION ON FRUIT MATURITY

6.1 Introduction

Juice soluble solids, acidity and pH are usually used to determine optimum maturity and harvest date of grapes grown for wine production. However, the complexity of determining the optimum harvest date was emphasised by Zoecklein *et al.*, (1989) who added that "Maturity is clearly a multidimensional phenomenon, and should be viewed on a relative rather than an absolute basis". The main carbohydrates in grape juice are the fermentable reducing sugars, glucose and fructose. During maturation the glucose to fructose ratio usually decreases (Kliewer, 1967; Zoecklein *et al.*, 1989). In cool climates malic acid is often the main organic acid at harvest, but concentrations decrease during late maturation (Kliewer, *et al.*, 1967; Ough, 1992). An important aspect of acidity in grape juice for wine production is the pH (hydrogen ion concentration) (Boulton, 1980 a & b; Zoecklein *et al.*, 1989). Hydrogen ion concentration has been correlated to the main inorganic cation found in grape juice, potassium (Boulton, 1980a). It has been suggested that potassium may be imported into cells in exchange for protons derived from organic acids such as malate (Zoecklein *et al.*, 1989). The malate, or malic acid, to potassium ion ratio has been suggested as an indicator of grape maturity (Heatherbell, 1983). Maturity differences may also be indicated by berry colour, in particular anthocyanin pigment development from veraison (Mullins *et al.*, 1992). Root restriction was found to advance maturity in terms of colour development and concentration of total soluble solids in glasshouse grown grapevines (Ussahatanonta, 1992). Fruit maturity, based on an average harvest date was advanced by root restriction in field grown peach trees (Myers, 1992) and increased total soluble solids were reported in field grown apple trees under root restriction conditions (Bar-Yosef *et al.*, 1988).

The objective of my research was to test the hypothesis that root restriction bags affect maturity of the fruit of field grown grapevines. This was tested by investigating the effects of root restriction on: total soluble solids (TSS), titratable acidity (TA), the ratio of TSS: TA, hydrogen ion concentration (pH), the malic acid (Ma) and potassium ion

(K⁺) concentrations, and the ratio of Ma: K⁺, the glucose (Gl) and fructose (Fr) concentrations, and the ratio Gl: Fr and the development of berry colour at veraison.

6.2 Experimental procedure

6.2.1 Maturity sampling in 1995

Development of total soluble solids, titratable acidity and pH was monitored by sampling berries from approximately 10% of bunches on each vine at similar intervals from veraison. Bunches were chosen from eight locations on either side of the vine and sampled alternately from the inside and outside of the vine canopy. Bunches were tagged so the same bunches could be monitored during maturity. Three berries from each bunch were picked, one each from the top middle and bottom of each bunch. The juice was extracted from the berries by hand pressing in a plastic bag.

6.2.2 Final harvest juice separation

All treatments were harvested on the same date. Juice was obtained by pressing all berries after the harvest. In 1994 two replicates were pooled from each treatment prior to pressing. In 1995 all replicates were pressed separately. Juice separation was carried out using 20 and 40 litre water membrane juice press (Pillan, Enotechnica). Berries were pressed for; 1 minutes at 1 bar, 2 minutes at 2 bar, and 3 minute at 3 bar. The juice was subsequently frozen. Samples were thawed over 24 hours and warmed to approximately 40⁰C and then cooled to room temperature prior to chemical analysis.

6.2.3 TSS, TA and pH measurement

Total soluble solids was determined by a degrees brix glass hydrometer in 1994, and a degrees brix electronic digital refractometer (Atago) in 1995. Hydrogen ion concentration was determined by a pH meter (Metrohm, 600 series). Titratable acidity expressed as equivalents of tartaric acid, was determined by the titratable acidity method (Zoecklein *et al.*, 1989), using a 'Dosimat' titrator (Metrohm 665 series), linked to a titroprocessor (Metrohm 670) and the pH meter.

6.2.4 Glucose, fructose and malic acid

Glucose, fructose and malic acid were determined by HPLC analysis. The technique used was based upon the method of direct analysis of major organic components in grape must (Frayne, 1986). Differences were the guard cartridge was a mini column (HPX-87H Bio-rad Laboratories). The guard column was maintained at 27 degrees Celsius by a column heater (Spectra physics SP8792). The mobile phase was degassed and filtered 0.002 *Normal* H₂SO₄ (Aristar grade). Dilution was made with nano-pure H₂O. The delivery system controller (Waters Associates model 600MS) operated at 0.4 millilitres/ minute.

The standards concentrations were 10.0, 5.0, 3.0 grams / litre (g/L) for glucose and fructose; and 0.4, 0.2, and 0.1 g/L for malic acid determination. The concentration range of standards was determined to cover the expected range concentration of samples to be analysed. The juice samples were prepared in a similar range by a 1:10 dilution with nano-pure H₂O. Prior to analysis the samples and standards were filtered through a 0.45 micron (sterile) 4 mm membrane syringe filter into 3 millilitre 'Wisp' vials.

The injection volumes were 5 microlitres for standards and juice samples, using a 48 'Wisp' sampler for an autosampler (Waters 717). The eluting compound was monitored by a ultraviolet (uv) detector (Waters 490E programmable) set at 210 nanometres for L-malic determination, and connected in series to an array refractive index (RI) detector, used for glucose and fructose determination.

Quantification was carried out by computer integrator software (Millenium Chromatography Manager version 2.1.), which provided graphical output of peak heights and peak volumes. Peak height was used to quantify the samples as regression analysis showed peak height had a higher R² values with the standards than peak area. Linear regression (Microsoft Excel version 5) was used to determine the equation of the line for quantification of sample concentrations.

6.2.5 Potassium analysis

Potassium concentration was determined by atomic absorption spectrometer (Shimadzu, model AA670) (Zoecklein *et al.*, 1989). Standards were made to cover the range of 1-10 mg/L. Juice samples were obtained in a similar range by a 1:200 dilution with de-ionised distilled water. To calibrate the atomic absorption spectrometer the standards were run through in order of the lowest to highest concentration. During the sampling procedure the atomic absorption spectrometer calibration was checked by running the standard closest in value to the samples every 15 samples. Sample concentrations were determined from a standard curve of concentration versus absorbance.

6.2.6 Colour development during veraison

Colour development during veraison in 1995 was monitored weekly by sampling approximately 10 percent of berry bunches from each vine. Bunches were chosen from eight similar locations on either side of the vines. Bunches were tagged so the same bunches could be monitored during veraison. Berry colour was judged by vision and scored on a scale of 1 to 10, based on the percent of the total berries through veraison. Subsequently, a mean percentage of berries through veraison was determined for each vine.

6.3 Results

When compared to the unrestricted 'control' vines, vines grown in bags generally, though not always significantly, had more mature berries based on composition, with higher, TSS, TSS to TA ratio, and lower, TA, Gl to Fr ratio, and also a lower K^+ concentration and pH (Tables 6.1 to 6.4, 6.6, 6.10). Ma and the ratio of Ma to K^+ was decreased in 1994, suggesting increased maturity, however in 1995, an unexplained higher Ma, despite a lower TA, in the bagged vines resulted in an increased Ma to K^+ ratio (Tables 6.5 and 6.7).

Maturity monitoring in 1995, based on colour development at veraison, from March 7 to March 28, indicated that grapes on the bagged vines had earlier colour development, although at the end of this period colour was not different in bagged compared to unrestricted vines (Figure 6.1). Maturity sampling in 1995, based on berry composition, from March 16 until the final harvest date of May 1, indicated that the average of

bagged vines compared to non bagged vines had lower TA, generally higher TSS (and subsequently a higher TSS: TA ratio) and also a higher pH until April 10, but a lower pH at harvest (Figures 6.2 to 6.4).

The influence of bag size on maturity was inconsistent. In 1994, TSS and Ma were linearly and positively related to bag volume ($P < 0.05$) despite disproportionate bag treatment responses, however, the R^2 values were low (Tables 6.1 and 6.5). In 1994 the 25, 48 and 102 litre bags were positively and proportionally correlated with TA and pH and negatively correlated with TSS and TSS: TA ratio. In comparison, in 1995 only pH and Gl (Tables 6.4 and 6.8) showed this trend. By contrast, the response of the vines in the 10 litre bag treatment was disproportionate, and generally more that of larger bag sizes. Furthermore, by removing the bag effect as the main variable, that is correlating crop load against composition, crop load (FFW/ PFW) was positively correlated with TSS and TSS: TA ratio, but negatively correlated with TA, pH, and Ma in 1994 and K^+ concentration in 1994 and 1995 (Figures 6.6 to 6.10). Potassium was positively correlated with pH in 1994 and 1995 (Figure 6.13). In comparison, in 1995 significant correlations could only be shown when crop load was conversely expressed as leaf area per fresh fruit weight (LA/ FFW), i.e. LA per FFW was positively correlated with TA and negatively correlated with TSS: TA (Figures 6.11 and 6.12). However, R^2 values were low.

6.4 Discussion

The previous results presented in this thesis showed that root restriction clearly reduced the vegetative growth, and to a lesser extent, the reproductive growth leading to an increase in the relative crop load. The final part of my research looked at maturity indices of the fruit from root restricted grapevines. It was hypothesised that root restriction would lead to advanced maturity in the grape berries, despite the reduced leaf area and or higher crop load. This was proposed to occur directly by increased partitioning of carbohydrate to reproductive growth at the expense of root and shoot growth. Indirectly it was thought an improved canopy microclimate would result from a reduced lateral shoot number in the root-restricted vines, and subsequently a lower leaf layer number allowing more light and higher temperatures in the fruiting zone.

A possible criticism that could be directed at my research was a failure not to discriminate the lateral shoot bunches or of a similar maturity within the main fruiting zone. However, while this influenced the composition to an unquantified degree, independent monitoring of the main maturity parameters of the primary shoot bunches in 1995, revealed that the primary shoot bunch composition at maturity, was indicative of the final average composition of the harvested fruit per vine. Moreover this predicament is not unlike a commercial situation where both hand and mechanically harvested fruit often include a proportion of marketable lateral shoot fruit of a similar maturity appearance to primary shoot bunches.

The higher total soluble solids and decreased titratable acidity, and subsequent higher ratio of TSS: TA, clearly suggest that root restricted vines had more mature fruit based on the concentrations of the main maturity compositional constituents at harvest. This, importantly, occurred with lower concentration of K^+ and pH. Scant research has been carried out on the effects of root restriction on fruit maturity. However, in agreement with my results is research with root confined glasshouse grown grapevines (Ussahatanonta, 1992). That research also showed increased TSS, TSS: TA ratio (derived data) and generally decreased TA and pH in more severely root confined vines. Also in general agreement with my results, root restriction of apples in containers of 10, 50 and 200 litres (Bar-Yosef *et al.*, 1988), resulted in TSS being increased with the smallest root restriction treatments, though not in the 50 litre container. My work similarly showed the 48 litre bag had lower TSS than the 10 litre bag in 1995, in contrast in the earlier year when it was not different, although the significance of this is not clear. The earlier colour development of berries in bagged grapevine during veraison is supported by my data. Similar research with apples (White, 1995) using the same make and size of root restriction bags showed increased red colour development in fruit on root restricted versus unrestricted 'control' trees.

The results of maturity based on the ratios of Ma : K^+ and Gl : Fr concentrations were less clear. Trends to decreased Fr to Gl ratios in the bagged vines were indicative of earlier maturity, but not of a convincing magnitude. However, the general decreases were in agreement with other research that has shown this ratio reduces during maturation (Kliewer, 1967). The decreased Ma: K^+ ratio in 1994 suggests that this ratio could be useful in judging the maturity of the different bagged versus unrestricted grape

berries. These results were in agreement with a decreased Ma: to K^+ ratio in data presented for vigorous vines (Smart *et al.*, 1985b) and shaded canopies (Smart *et al.*, 1985b; Morrison and Noble, 1990; Zoecklein *et al.*, 1989), all using derived data. However, using this ratio to interpret the effects of vigour or shading, could be confusing. For example, generally K^+ concentration increases and Ma decreases during maturation. In contrast, in 1994 the vigorous bagged vines' fruit, tended to have higher K^+ and Ma, than the unrestricted vines' fruit, which had lower K^+ and Ma, although in 1994 the results showed the expected lower Ma : K^+ ratio. This could result in similar ratios between treatments, even though clearly earlier maturity is evident in the less vigorous vines. This scenario highlights shortcomings of using a single ratio in time to compare differences between treatments. Further maturity research should monitor the ratios of Ma: K^+ and Gl: Fr during maturation.

The higher Ma result in the second year was clearly reflected in and dominated the Ma: K^+ ratio, despite the highly significant decreased K^+ in the root restricted vines in that year. Similarly, other research (Morrison and Noble, 1990) has shown the greatest accumulation of Ma in berries in more open canopies versus shading treatments, although generally results (Smart *et al.*, 1985b; Morrison and Noble, 1990) indicate that Ma is reduced in open versus shaded or vigorous canopies at 'final maturity'. Possibly my unusual higher Ma result in the bagged vines in the later year could be explained by an initially higher accumulation of Ma in the bagged vines, but subsequently a delayed respiration of Ma in the bagged vines at harvest.

The proportionate relationship between the 25, 48 and 102 litre bag volumes and composition parameters suggest that relationships between root volume and these parameters were evident in 1994. In 1995 the beneficial proportionate maturity trends within the bagged treatments were limited, however, crop load was positively correlated with TA, malic acid and pH, and conversely, pruning weights (not shown) were positively correlated with TA, K^+ concentration and pH, but negatively correlated with TSS: TA and TSS in 1994, but the correlations were less evident in 1995. The earlier and later result to a lesser extent indicate that the increased crop load resulting from root restriction generally promoted TSS: TA, TSS concentration and decreased TA, Ma and pH. Why these relationships were much better in the earlier year but less valid in

the later year was not clear. However, possibly this was due to root escapes and subsequently a wider range of crop loads in the bagged vines in 1995.

The results of my research also presented a question; were the composition effects due to decreased vine vigour or differences in canopy shading? In comparison, the research of Smart (1985 a & b), concluded that the effects of canopy shading on fruit composition were similar to the effects of an increased vine vigour, through the interaction of shading within a block of vines of varying vigour. My results are in agreement with this earlier conclusion. However, the effects of shading were not elucidated in my research. Also, Smart *et al.* (1985b) in research investigating shade and vigour effects on Shiraz grape berry composition, concluded "It is not reasonable to argue that increased yield causes any quality decline noted." In comparison, my results suggested that yield increases *per se*, within the space confines of unmanaged vertical shoot positioned canopies can be detrimental to quality, as demonstrated with the unrestricted 'control' vines. Moreover, my results suggest that it is more useful to talk in terms of a crop load (i.e. a sink to source ratio), than yield *per se*, and the contention presented here is that the higher crop load imposed by root restricted minimally managed vines, was generally not detrimental to fruit maturation.

In conclusion the results presented in this work suggest that grapevine vigour reductions imposed by minimal management, root restriction and short spur pruning, advanced grape berry maturation. The contribution of vigour versus canopy density (shading) effect was not elucidated. However, my results showed that an increased crop load was generally not detrimental to fruit composition, although in the final year of results where crop loads tended to be higher than earlier years results were not as definitive, possibly due to root escapes and subsequently larger variations in crop load. Moreover, my results suggest root restriction could be a useful tool in reduced input vineyard management and promotion of fruit maturity.

Table 6.1 The effect of bag volume on total soluble solids concentration ($^{\circ}$ brix) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	20.1±0.2	20.1±0.1	20.1±0.2
	25	20.2±0.1	20.1±0.2	20.2±0.2
	48	20.1±0.1	19.9±0.2	20.0±0.2
	102	19.8±0.2	20.2±0.7	20.0±0.5
	Average	20.1±0.2	20.1±0.3	20.1±0.3
Unrestricted	∞	19.6±0.2	19.6±0.2	19.6±0.2
SED bagged VS unrestricted		0.2	0.3	
Orthogonal contrast ⁴ bagged VS unrestricted		0.004**	ns	
Regression ⁴ linear within bag		0.031*,0.24 ³	ns	

¹Mean of 3 replicates.

²Mean of 6 replicates.

³R² value.

⁴Contrast and regression significance at $P < 0.05$, $P < 0.01$ denoted by *, ** respectively, ns is not significant.

+/- SEM.

Table 6.2 The effect of bag volume on titratable acidity concentration (g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	7.45±1.05	5.15±0.10	6.30±0.58
	25	6.24±0.21	5.21±0.26	5.73±0.24
	48	6.59±0.36	5.18±0.16	5.89±0.44
	102	6.94±0.66	5.27±0.44	6.12±0.55
	Average	6.81±0.57	5.20±0.24	6.01±0.41
Unrestricted	∞	9.36±0.14	6.02±0.31	7.69±0.45
SED bagged VS unrestricted		0.34	0.33	
Orthogonal contrast ³ bagged VS unrestricted		0.007**	0.012*	

¹Mean of 3 replicates.

²Mean of 6 replicates.

³Contrast and significance at $P < 0.05$, $P < 0.01$ denoted by *, ** respectively.

+/- SEM.

Table 6.3 The effect of bag volume on total soluble solids concentration: titratable acidity concentration (°brix: g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	2.81±0.40	3.91±0.08	3.36±0.24
	25	3.24±0.12	3.90±0.17	3.57±0.15
	48	3.07±0.15	3.86±0.14	3.47±0.15
	102	2.91±0.28	3.92±0.21	3.42±0.25
	Average	3.01±0.24	3.90±0.15	3.46±0.20
Unrestricted	∞	2.09±0.05	3.31±0.20	2.70±0.13
SED bagged VS unrestricted		0.13	0.22	
Orthogonal contrast bagged VS unrestricted		0.012*	0.004*	

¹Mean of 3 replicates.

²Mean of 6 replicates.

Contrast and significance at $P < 0.05$, denoted by *.

+/- SEM.

Table 6.4 The effect of bag volume on pH (hydrogen ion concentration) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	3.67±0.05	3.74±0.08	3.71±0.07
	25	3.59±0.03	3.67±0.05	3.63±0.04
	48	3.65±0.01	3.74±0.03	3.70±0.02
	102	3.68±0.03	3.77±0.06	3.73±0.05
	Average	3.65±0.03	3.73±0.06	3.69±0.05
Unrestricted	∞	3.70±0.03	3.76±0.03	3.73±0.03
SED bagged VS unrestricted		0.04	0.04	

¹Mean of 3 replicates.

²Mean of 6 replicates.

+/- SEM.

Table 6.5 The effect of bag volume on malic acid concentration (g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	3.54±0.13	3.92±0.37	3.73±0.25
	25	3.76±0.23	3.80±0.34	3.78±0.29
	48	3.52±0.25	3.71±0.21	3.62±0.23
	102	4.21±0.11	3.73±0.30	3.97±0.21
	Average	3.78±0.18	3.79±0.31	3.79±0.25
Unrestricted	∞	4.81±0.17	3.52±0.22	4.17±0.20
SED bagged VS unrestricted		0.20	0.26	
Orthogonal contrast ⁴ bagged VS unrestricted		0.000***	ns	
Regression ⁴ linear within bag		0.043*, 0.24 ³	ns	

¹Mean of 3 replicates.²Mean of 6 replicates.³R² value.⁴Contrast and regression significance at $P < 0.05$, $P < 0.001$ denoted by *, *** respectively, ns is not significant.

+/- SEM.

Table 6.6 The effect of bag volume on potassium ion concentration (g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	0.80±0.09	1.65±0.15	1.23±0.12
	25	0.80±0.04	1.49±0.09	1.15±0.07
	48	0.75±0.04	1.61±0.05	1.18±0.05
	102	0.88±0.01	1.54±0.08	1.21±0.05
	Average	0.81±0.05	1.57±0.09	1.19±0.07
Unrestricted	∞	1.00±0.03	1.83±0.06	1.42±0.5
SED bagged VS unrestricted		0.03	0.08	
Orthogonal contrast bagged VS unrestricted		0.009**	0.006**	

¹Mean of 3 replicates.²Mean of 6 replicates.Contrast significance at $P < 0.01$ denoted by **.

+/- SEM.

Table 6.7 The effect of bag volume on malic acid: potassium ion concentration (g/L: g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	4.48±0.33	2.43±0.27	3.46±0.30
	25	4.76±0.41	2.59±0.28	3.68±0.35
	48	4.72±0.15	2.30±0.10	3.51±0.13
	102	4.79±0.09	2.44±0.22	3.62±0.16
	Average	4.69±0.25	2.44±0.22	3.57±0.24
Unrestricted	∞	4.80±0.14	1.95±0.18	3.38±0.16
SED bagged VS unrestricted		0.19	0.21	

¹Mean of 3 replicates.

²Mean of 6 replicates.

Contrast bagged VS unrestricted not significant.

+/- SEM.

Table 6.8 The effect of bag volume on glucose concentration (g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	57.28±0.91	92.19±1.56	74.74±1.24
	25	69.86±8.90	94.83±2.39	82.35±5.65
	48	56.31±0.14	94.31±3.34	75.31±1.74
	102	65.07±5.60	87.74±3.49	76.41±4.55
	Average	62.13±3.89	92.27±2.70	77.20±3.30
Unrestricted	∞	58.32±1.96	96.59±4.56	77.46±3.26
SED bagged VS unrestricted		3.54	4.78	

¹Mean of 3 replicates.

²Mean of 6 replicates.

Contrast bagged VS unrestricted not significant.

+/- SEM.

Table 6.9 The effect of bag volume on fructose concentration (g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	68.22±1.06	96.96±1.31	82.59±1.19
	25	80.37±8.28	100.53±1.77	90.45±5.03
	48	66.72±3.82	101.36±4.71	84.04±4.27
	102	74.90±5.50	92.40±3.22	83.65±4.36
	average	72.55±4.67	97.81±2.75	85.18±3.71
Unrestricted	∞	68.06±1.80	99.83±4.35	83.95±3.08
SED bagged VS unrestricted		3.34	4.63	

¹Mean of 3 replicates.

²Mean of 6 replicates.

Contrast bagged VS unrestricted not significant.

+/- SEM.

Table 6.10 The effect of bag volume on glucose concentration: fructose concentration (g/L: g/L) in 1994 and 1995.

	Volume (L)	Year		Average
		1994 ¹	1995 ²	
Bagged	10	0.84±0.00	0.95±0.00	0.90±0.00
	25	0.86±0.02	0.94±0.01	0.90±0.02
	48	0.84±0.02	0.93±0.02	0.89±0.02
	102	0.87±0.01	0.95±0.01	0.91±0.01
	average	0.85±0.01	0.94±0.01	0.90±0.01
Unrestricted	∞	0.86±0.01	0.97±0.01	0.92±0.01
SED bagged VS unrestricted		0.01	0.01	
Orthogonal contrast ³ bagged VS unrestricted		ns	0.032*	

¹Mean of 3 replicates.

²Mean of 6 replicates.

³Contrast significance at $P < 0.05$ denoted by *.

+/- SEM.

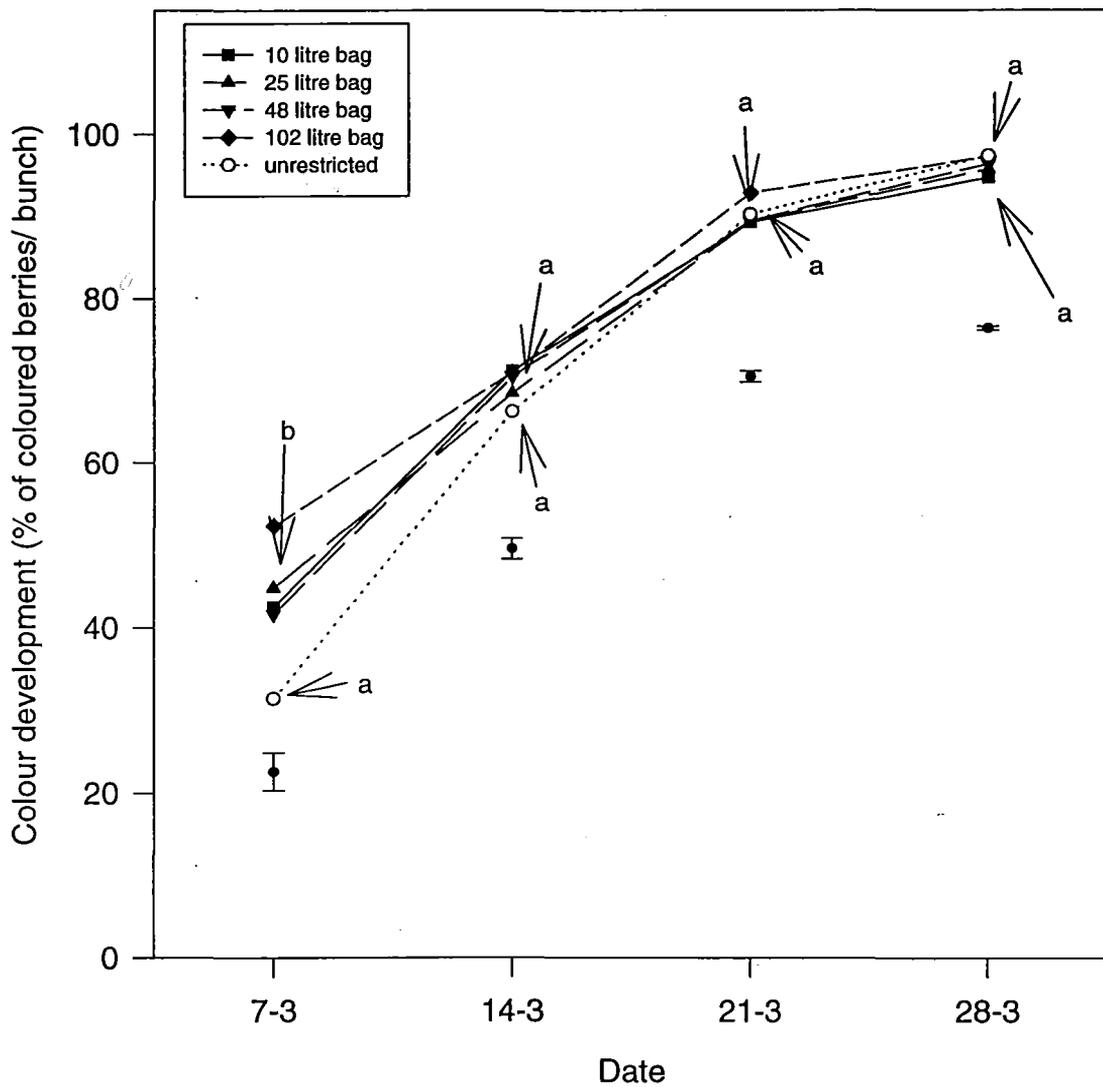


Figure 6.1 The effect of bag volume on colour development during veraison in 1995. The contrast unrestricted versus mean of bagged treatments use the same letter at $P < 0.05$. Error bars denote \pm SEM, applicable to all vines.

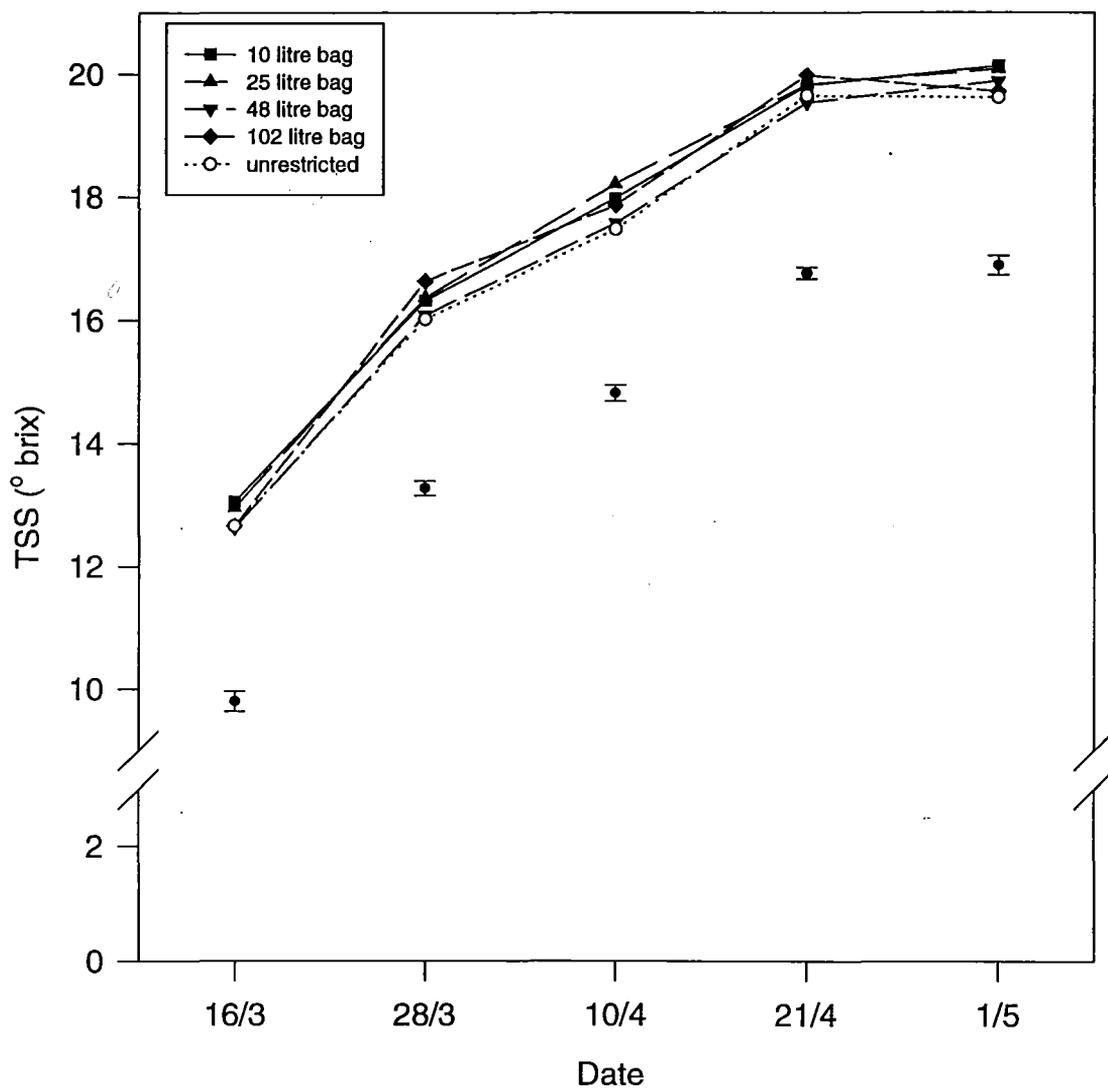


Figure 6.2 The effect of bag volume on maturity development of total soluble solids (TSS) in 1995. No significant difference between mean of bagged and unrestricted vines at $P < 0.05$. Error bars denote \pm SEM, applicable to all vines.

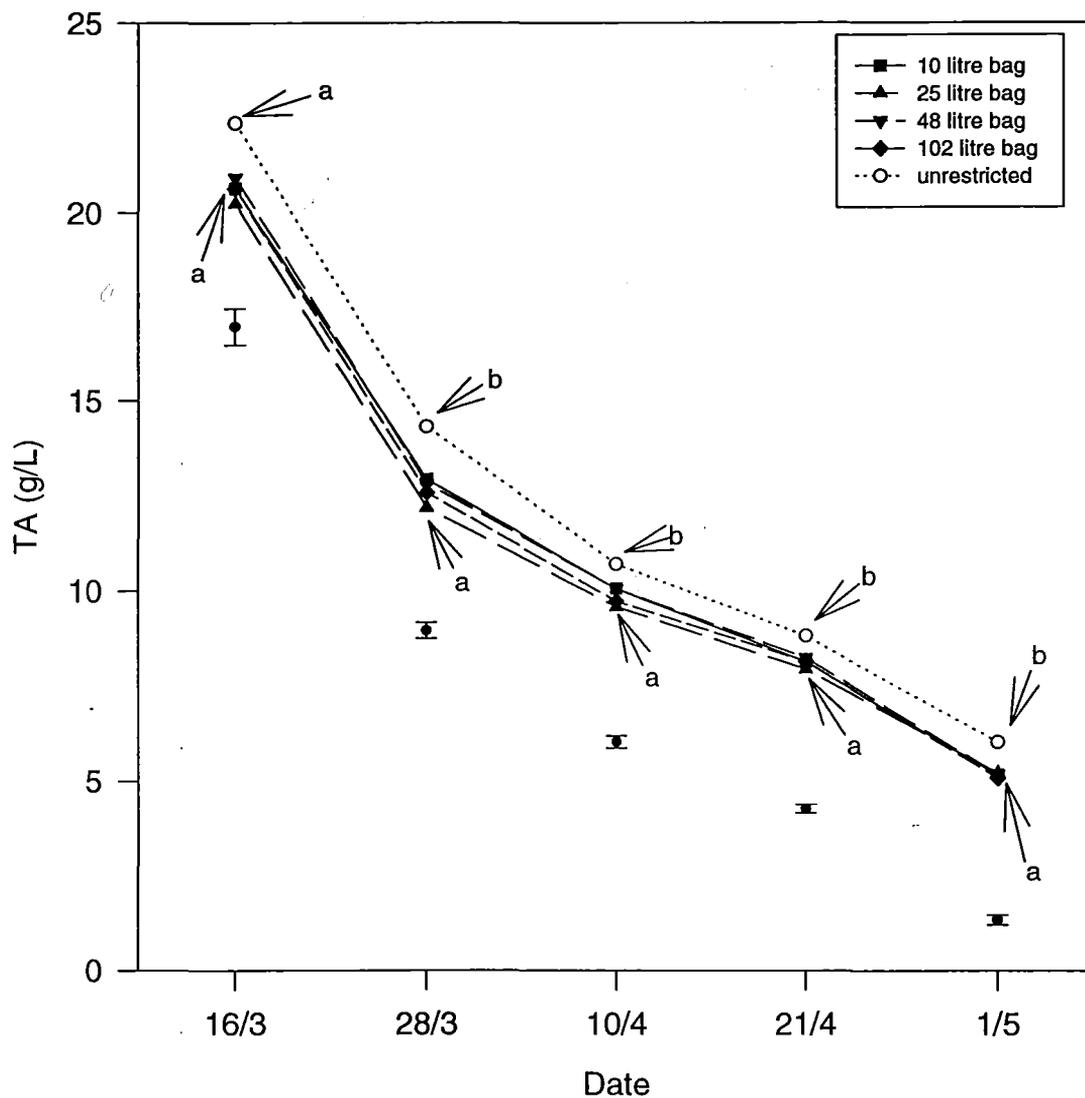


Figure 6.3 The effect of bag volume on titratable acid during 1995. The contrast unrestricted versus mean of bagged treatment use same letter at $P < 0.05$. Error bars denote \pm SEM, applicable to all vines.

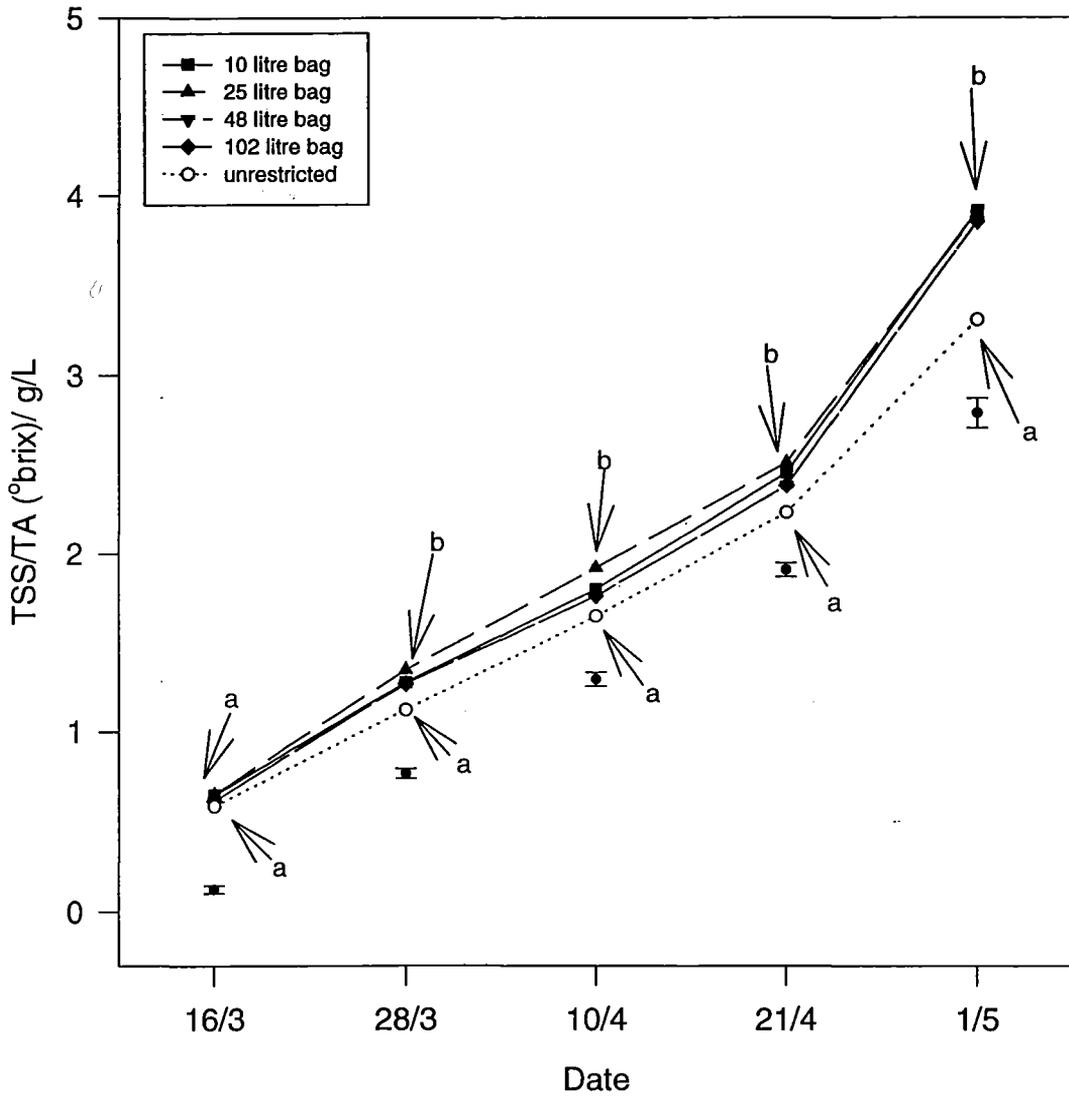


Figure 6.4 The effect of bag volume on total soluble solids: titratable acid ratio (TSS: TA) during 1995. The contrast unrestricted versus mean of bagged treatments use same letter at $P < 0.05$. Error bars denote \pm SEM, applicable to all vines.

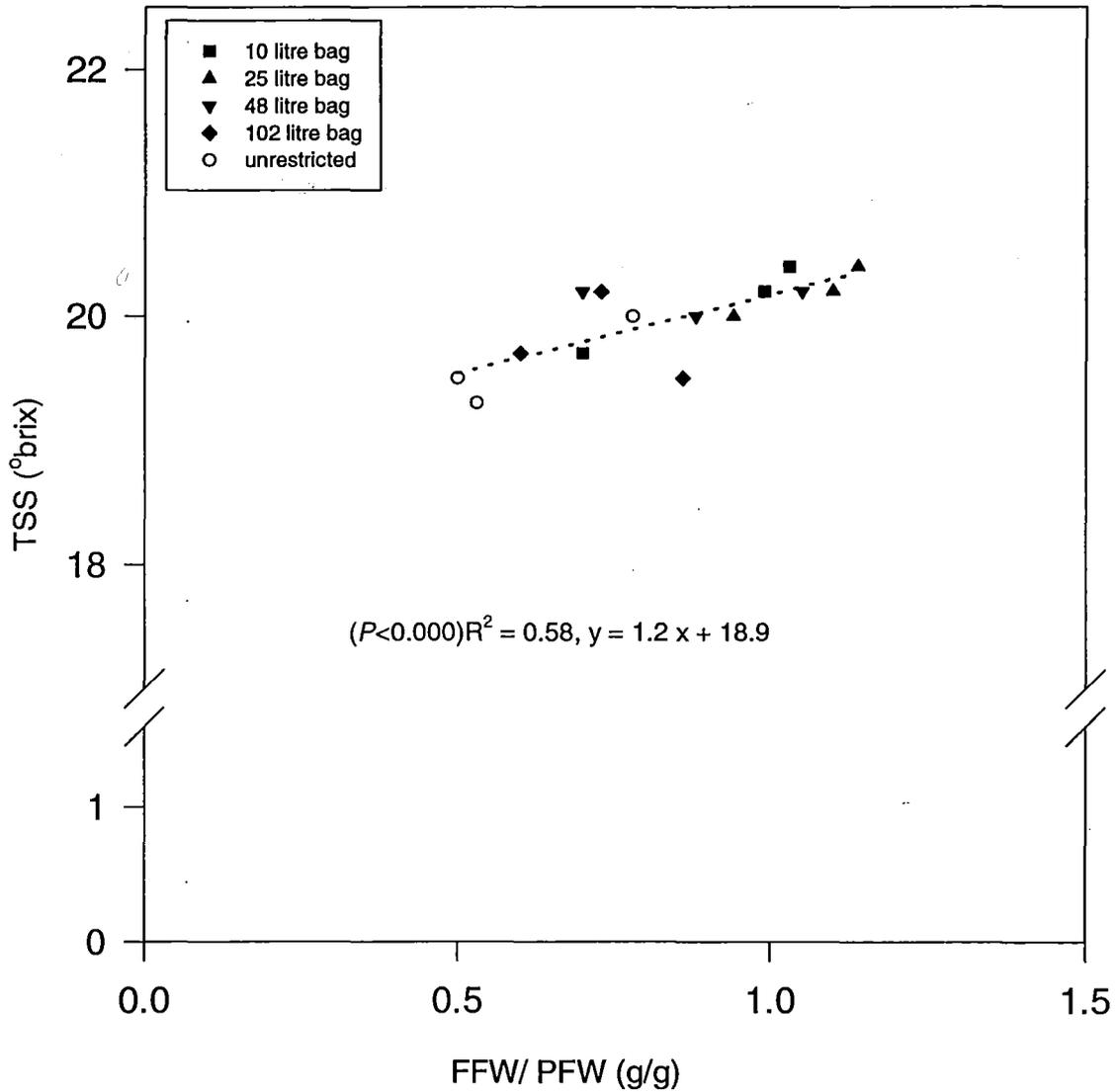


Figure 6.5 The effect of crop load, fruit fresh weight per unit pruning fresh weight (FFW/PFW), on total soluble solids (TSS) at harvest in 1994.

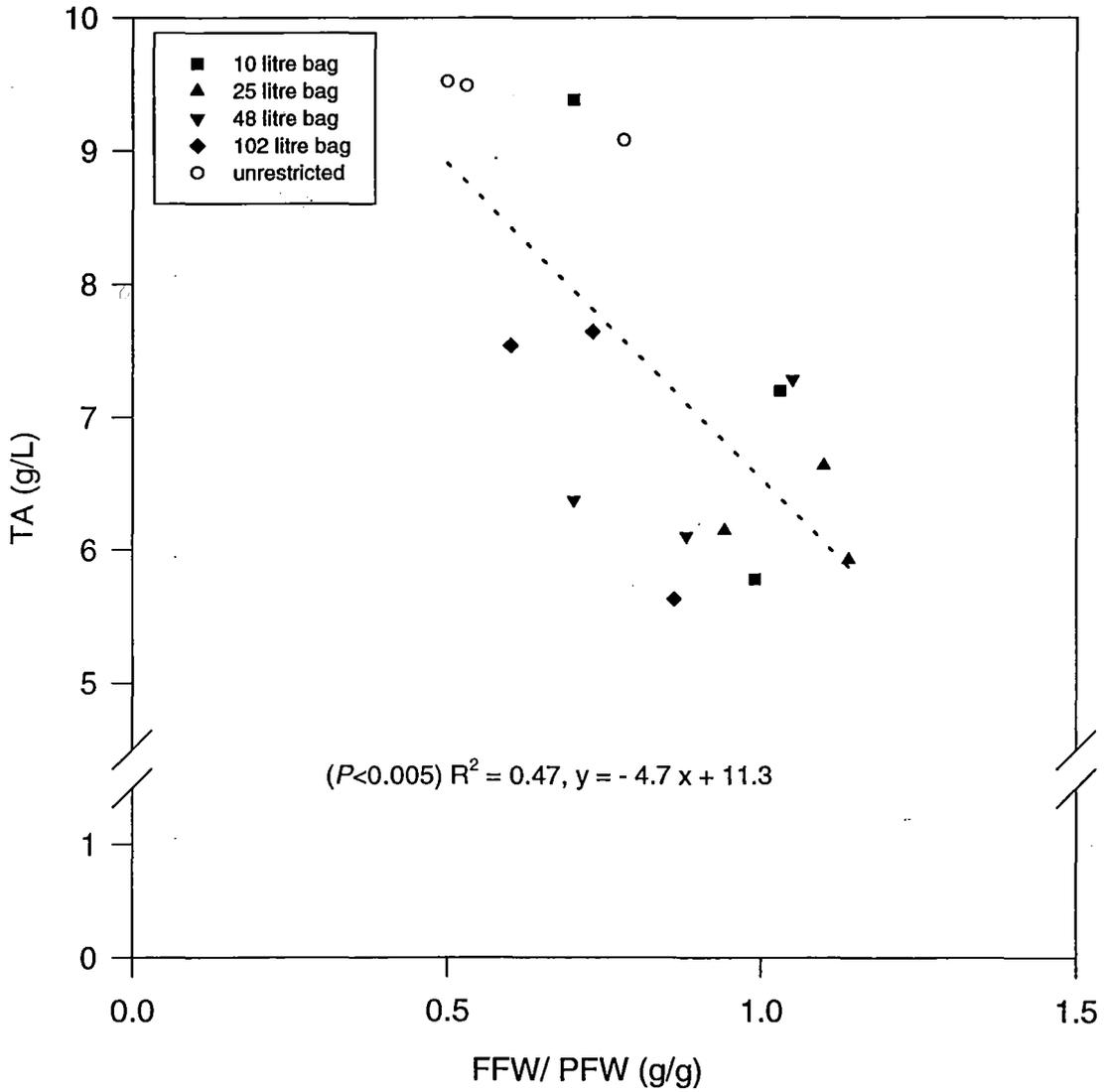


Figure 6.6 The effect of crop load, fruit fresh weight per unit pruning fresh weight (FFW/ PFW), on titratable acidity (TA) at harvest in 1994.

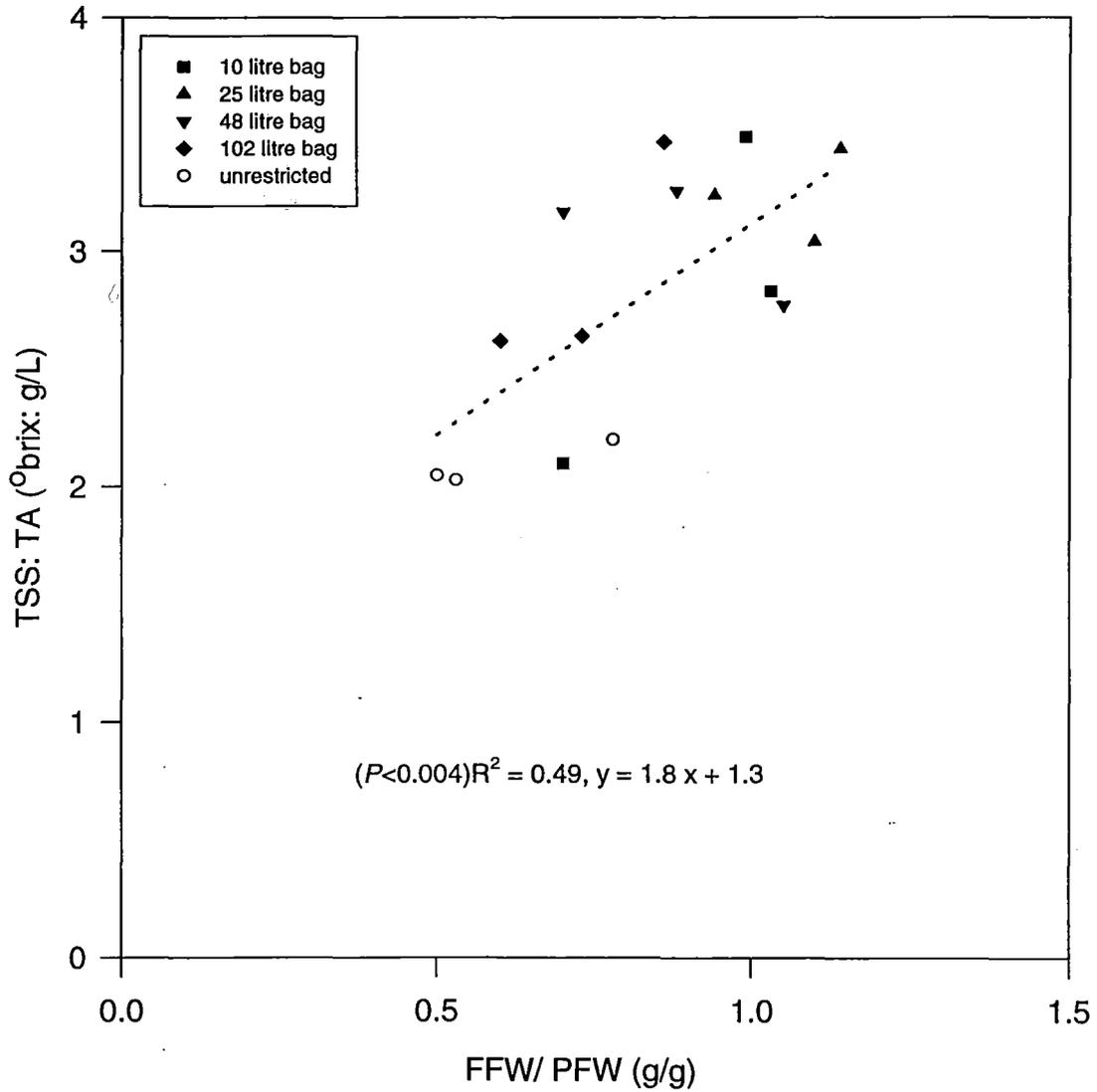


Figure 6.7 Effect of crop load fruit fresh weight per unit pruning fresh weight (FFW/PFW), on total soluble solids: titratable acidity ratio (TSS:TA) at harvest in 1994.

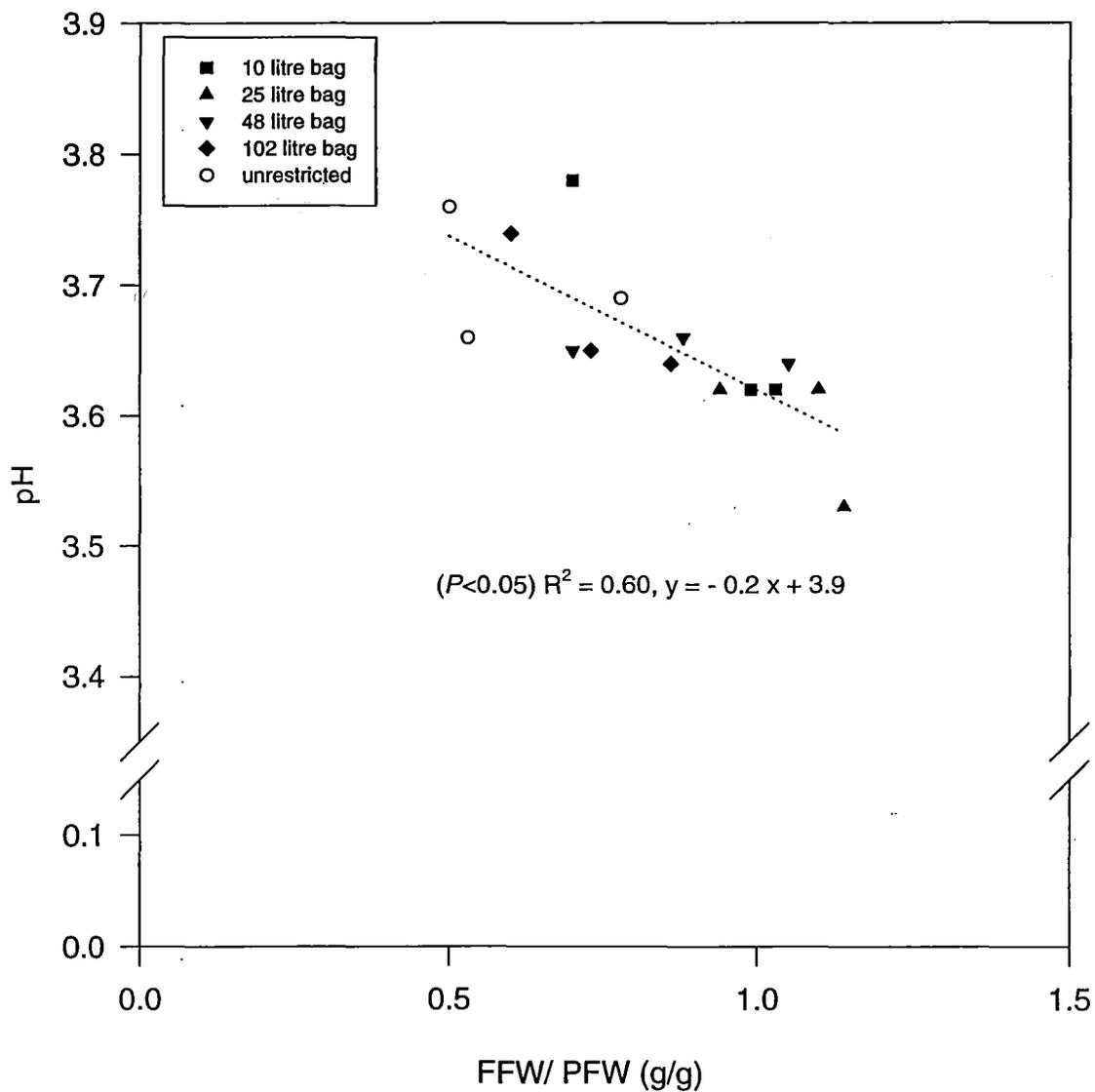


Figure 6.8 The effect of crop load, fruit fresh weight per unit pruning fresh weight (FFW/FPW), on pH (hydrogen ion concentration) at harvest in 1994.

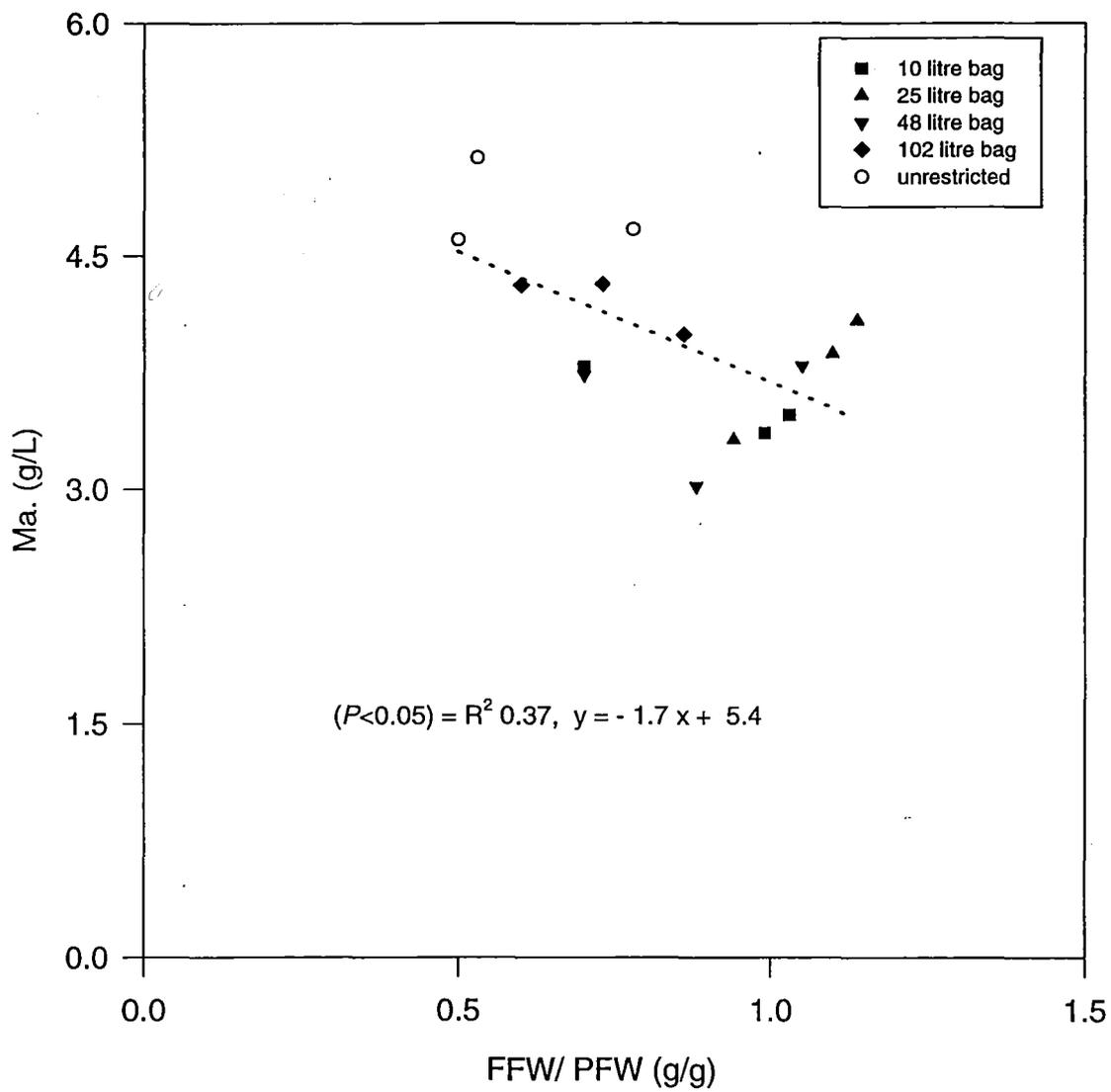


Figure 6.9 The effect of crop load, fruit fresh weight per unit pruning fresh weight (FFW/ PFW), on malic acid concentration (Ma.) at harvest in 1994.

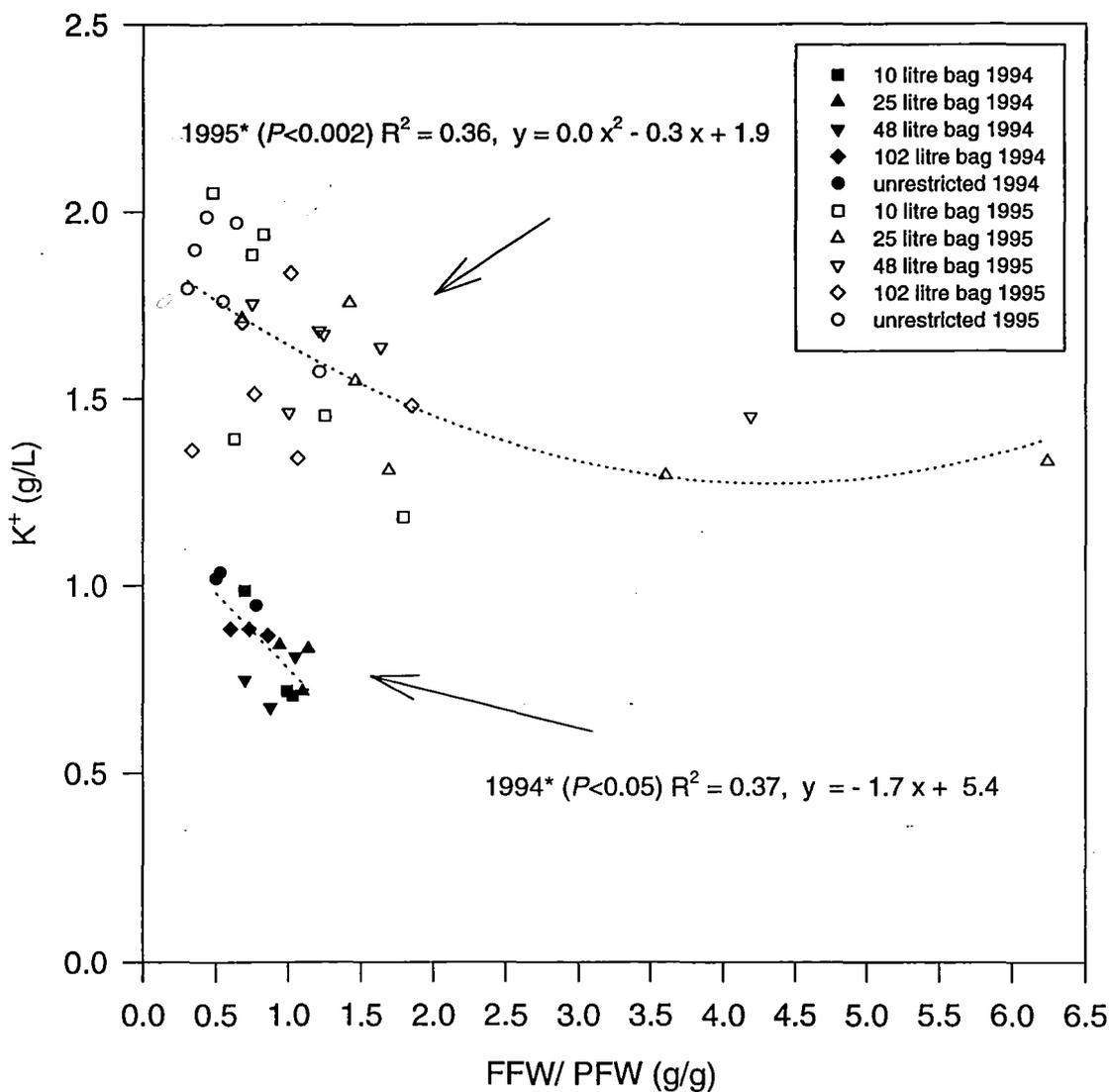


Figure 6.10 The effect of crop load, fruit fresh weight per unit pruning fresh weight (FFW/PFW), on potassium ion concentration (K^+) at harvest in 1994 and 1995.

* 3 replicates in 1994 and 6 replicates in 1995 (see experimental procedure).

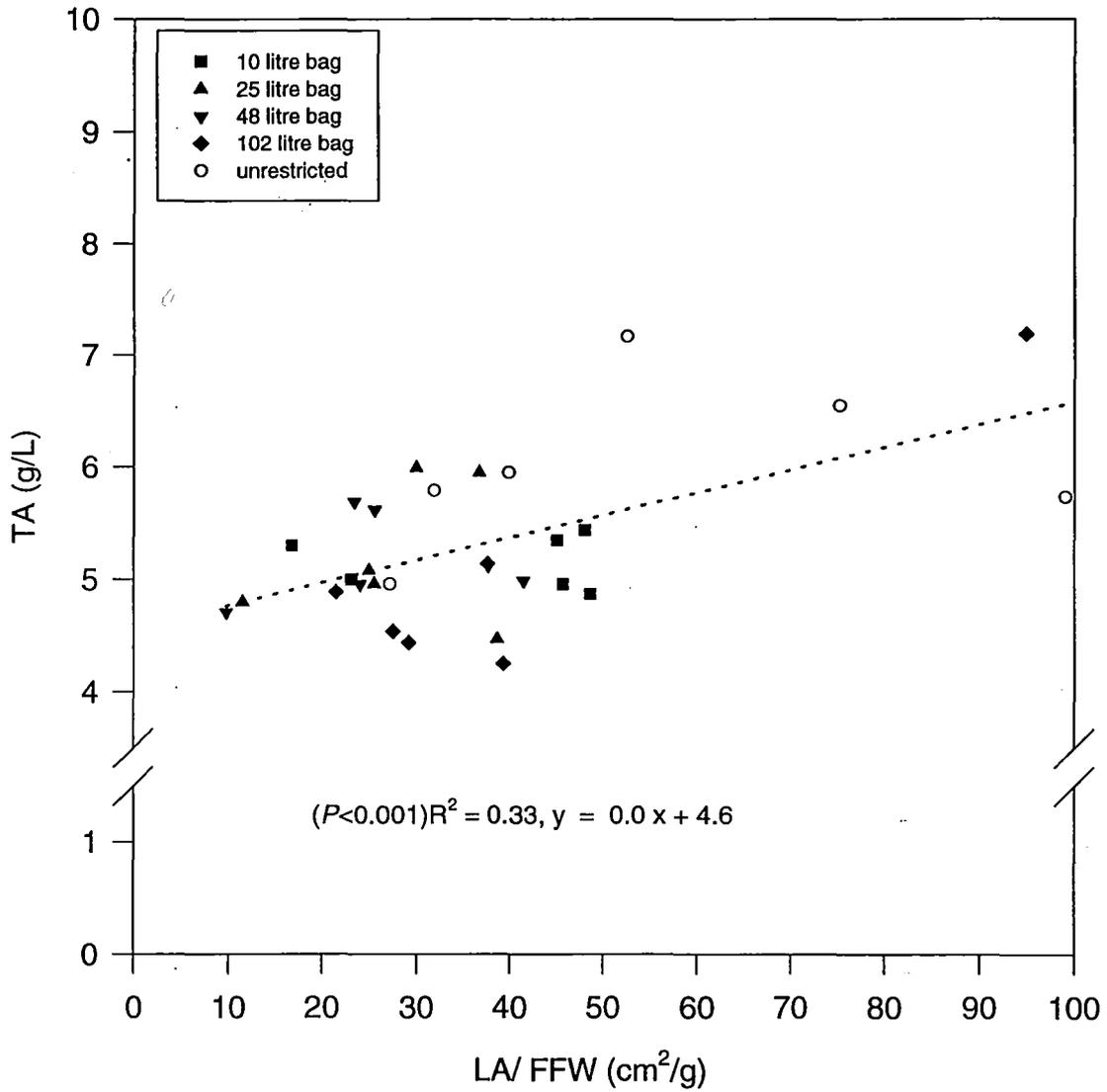


Figure 6.11 The effect of crop load, leaf area per unit fruit fresh weight (LA/ FFW) on titratable acidity (TA) at harvest in 1995.

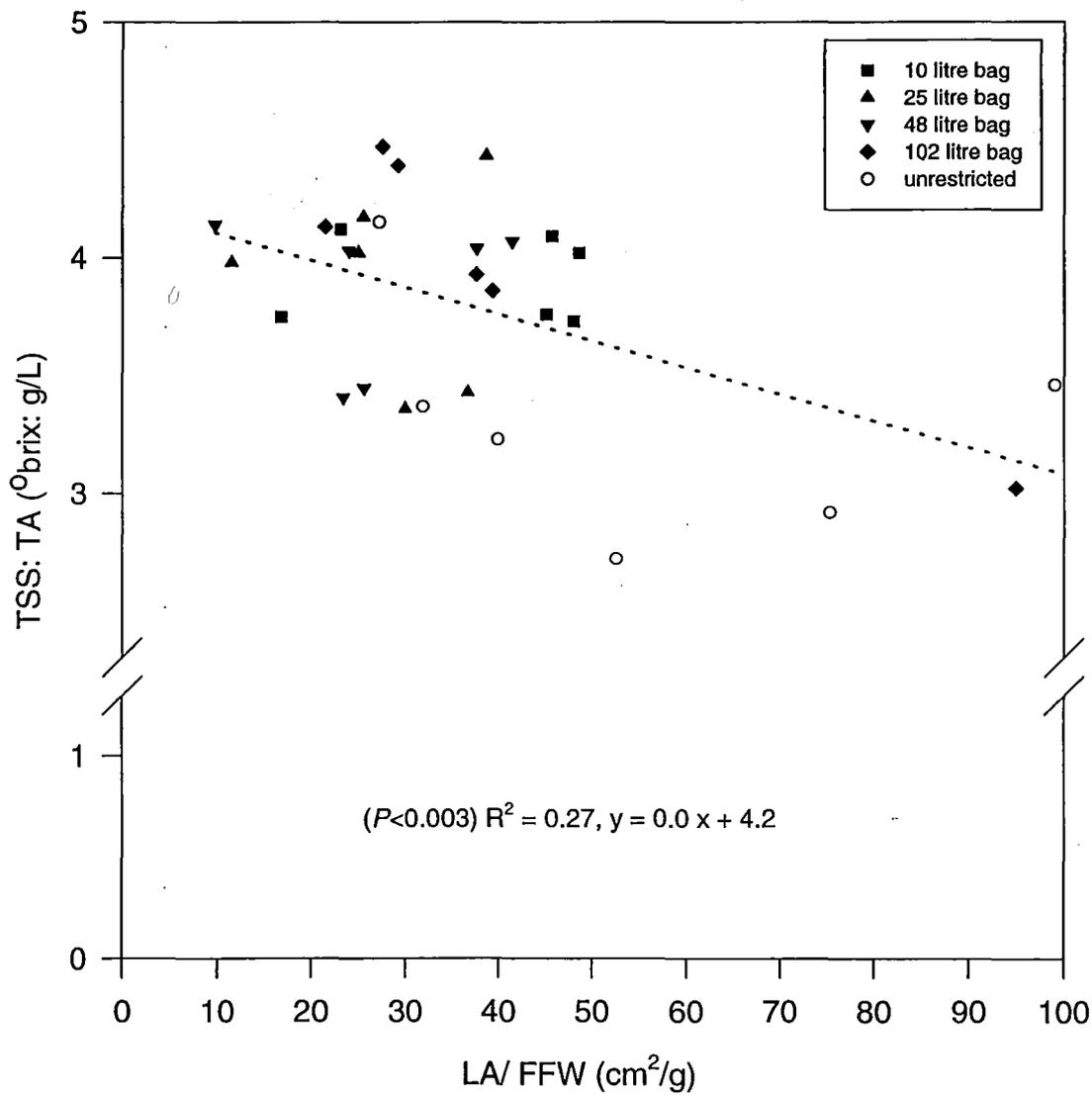


Figure 6.12 The effect of crop load, leaf area perunit fruit fresh weight (LA/ FFW), on total soluble solids: titratable acidity ratio (TSS: TA) at harvest in 1994.

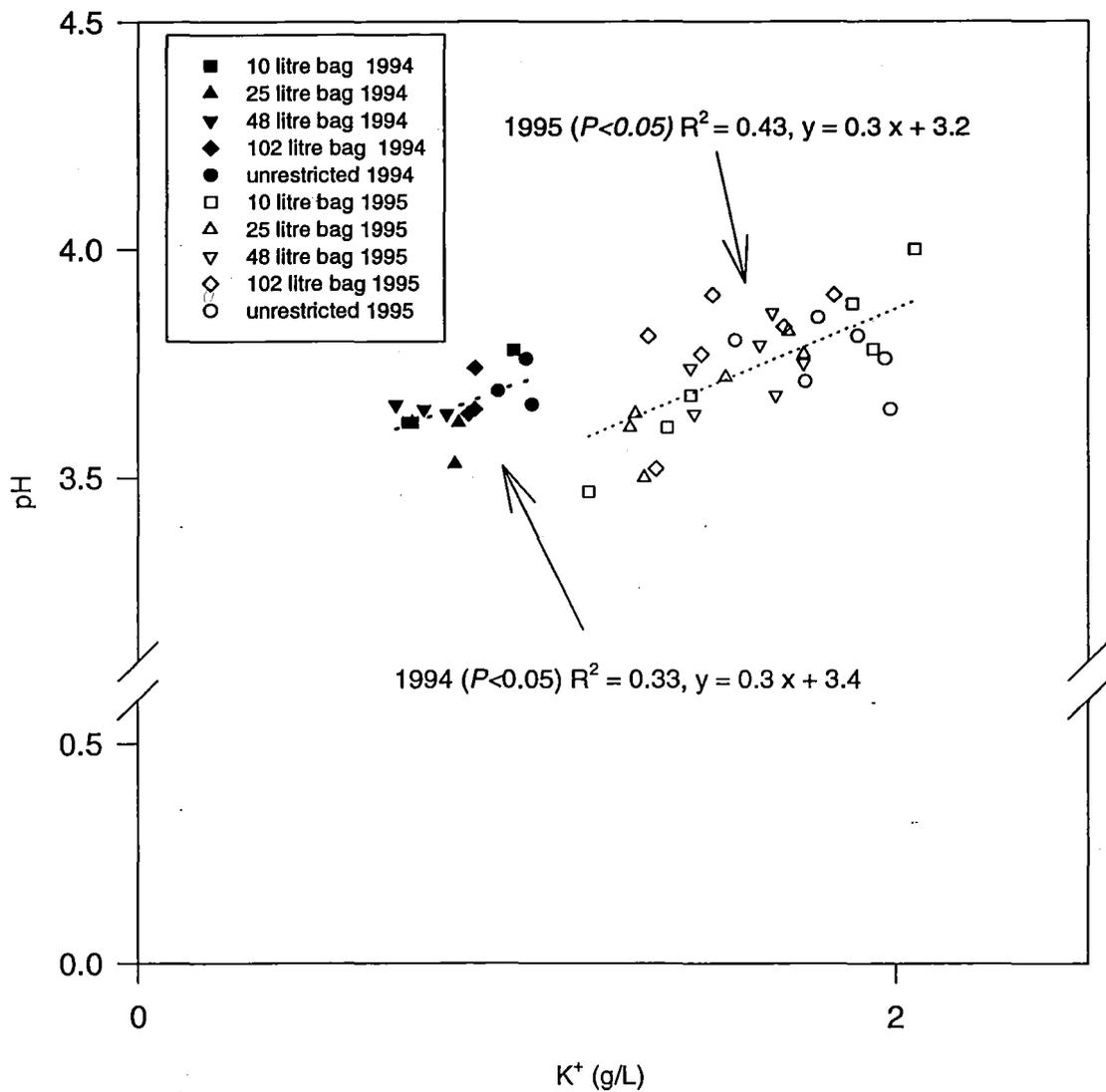


Figure 6.13 The effect of potassium ion concentration (K^+) on hydrogen ion concentration (pH) at harvest in 1994 and 1995.

* 3 replicates in 1994 and 6 replicates in 1995 (see experimental procedure).

Chapter 7

CONCLUSIONS

The unifying hypothesis proposed at the outset of this work was does root restriction by porous Duon[®] bags affect the long term vegetative growth, and subsequently the fruitfulness and fruit maturity of field grown grapevines?

The first experimental chapter tested the hypothesis that root restriction reduces the vegetative growth of grapevines. The results indicated root restriction generally reduced all vegetative growth parameters measured including; pruning fresh weights, trunk cross sectional areas, primary and lateral shoot; number, leaf number, internode number, length, average leaf size and leaf area per vine. In contrast, the average canopy density was improved due to less leaf shading.

The second experimental chapter tested the hypothesis that root restriction affects grapevine fruitfulness. Root restriction tended to decrease the fruit fresh weight and bunch number. However, the effects on average bunch weight and the variables determining bunch weight were less consistent, but indications suggest differences between the bagged and unrestricted vines decreased with time. Berry number probably influenced berry size. Root restriction also clearly had a lesser effect on fruitfulness compared to vegetative growth, leading to improvements in the harvest indices: fruit fresh weight per unit pruning weight, leaf area per gram of fruit fresh weight, fruit fresh weight produced per total shoot number. In contrast, if fruit fresh weight was expressed per primary shoot number, but still inclusive of lateral shoots, bagged vines were similar to or less efficient than unrestricted vines.

The final experimental chapter tested the hypothesis that root restriction affects the main maturity parameters. The results showed that root restriction decreased the titratable acidity and increased the total soluble solids and total soluble solids to titratable acidity ratio at final harvest. These differences were shown to occur from at least 7 weeks prior to harvest in 1995. Furthermore, potassium concentration was lower and colour development during veraison was earlier in root restriction treatments. There was also evidence to show root restriction decreased the glucose: fructose ratio in both

years, and the malic acid concentration, potassium ion concentration and the malic acid to potassium ion ratio in one year.

The hypothesis that long term vegetative growth, fruitfulness and fruit maturity of root restricted vines is proportionate to the porous Duon[®] bag volumes used in my experiment was not clear and requires further research. Early trends suggested that some growth and maturity parameters were linearly correlated to rooting volume, although the R^2 values were very low. Moreover the 25, 48 and 102 litre bags were often proportionate to parameters of vegetative growth, fruitfulness and fruit maturity, suggesting such relationships could exist. However, the vines in 10 litre bags were disproportionate. Preliminary root excavation to identify the source of variation revealed that the bags failed to confine the roots in the manner expected, as unintended root escapes were evident in all bagged treatments. Thus, root escapes and possibly crop loading due to the constraints of the pruning used could explain why the earliest linear relationships were short term and may suggest differences between treatments will decrease with time.

In conclusion, the results of my work indicate that the main effect of root restriction was to decrease vegetative growth and to a lesser extent the reproductive growth which led to an increase in the harvestable part of the crop. This occurred with trends to earlier maturity in root restricted vines. However, the bag volume effects were not proportionate over the range of bag volumes used and indications are that the effects of the treatments will possibly be decreased with time. Thus, alternative strategies of sustainable root restriction are required and should be contrasted with bagging as a minimal management technique. Moreover, my results suggest root restriction could be a useful tool in reduced input vineyard management, as a preventative strategy of vigour control, and if sustainable root restriction is obtained, this should result in agronomic benefits.

Chapter 8

AGRONOMIC IMPLICATIONS AND FURTHER RESEARCH

8.1 Agronomic implications

The control of excessive vegetative growth is an important consideration for maximising the fruitfulness and improving the grape composition of a vineyard. Excessive vegetative growth has direct and indirect implications on fruitfulness and grape composition. The direct effect is the partitioning of carbohydrate to vegetative growth at the expense of reproductive growth. This may result in greater internode growth, larger average leaf areas and higher primary and lateral shoot numbers. Indirect effects include the consequences of within and between row shading resulting from the increased vegetative growth. Shading has been shown to be generally detrimental to physiological processes in the plant: processes that are dependent on light and temperature, which influence fruitfulness and fruit composition. Currently the use of size reducing rootstocks and the acceptance of plant breeding contributions to vigour control of grapevines for wine production is limited. Thus vigour control in grapevines for wine production has been primarily at the level of husbandry. Recently much effort has been devoted to remedial canopy management techniques to reduce or better utilise the vegetative growth potential of grapevines.

The results obtained in my thesis indicate that root restriction by bags as a preventative vigour control technique and minimal management by winter pruning reduced the vegetative growth of grapevines, resulting in higher crop loads and earlier maturity in comparison to unrestricted control vines. However, before extrapolating on agronomic implications of my research, attention should be drawn to the technique of root restriction used. Preliminary excavation revealed that unexpected root escapes had occurred in all treatment replicates. The root escape situation possibly exacerbated some differences between treatments, such as crop loading variations and arguably could reduce differences between the restricted vines and non restricted vines in time, such as was evident in some of the smallest bagged vines. However, the results obtained in my work also showed root restriction generally reduced the long term vegetative growth of vines grown in the intermediate bag volumes. Clearly, longer term research

would be required to determine if root restriction would arrest the growth of the largest bag treatments and if after growth was arrested whether the preliminary indications of increased crop loads and earlier maturation are sustainable and commercially viable.

The main effects of root restriction were to primarily reduce the internode number and length. Table 8.1 has extrapolated from these effects of root restriction to predict the agronomic implications of effects on plant spacings and yield. The data presented uses the 1995 data and predicts the yield based on;

1. The current minimally regulated crop loading scenario as presented in this thesis.
2. A potential crop loading scenario based on recommended crop loading references of a leaf area per unit fresh fruit weight of $12 \text{ cm}^2/\text{g}$ (Smart and Robinson, 1991).

The preliminary assumptions are the canopy is a divided vertical shoot positioned canopy, with both tiers 0.6m in height, ie. total canopy height of 1.2 m, the row width is 1.2 m. Clear limitations of the exercise include;

1. Using the 10, 102 and control treatments that have not reached a balance in their growth.
2. The first scenario is inclusive of root restriction effects on carbohydrate partitioning, specifically the crop loading effects in 1995. Based on no trimming, minimal management and the 2m x 2m canopy space limitation of the current experiment. In comparison the second scenario uses a well established crop loading reference (Smart and Robinson, 1991) for all treatments and control.

Moreover, while both scenarios have clear limitations, the results show the effects of different internode length and number on the potential yield and also more appropriate plant spacing based on the data collected in 1995. The derived data also includes general crop load data that should improve on some of the limitations of experimental techniques used in my research.

8.2 Further research

The mechanisms by which root restriction exerts its effects were not investigated in this experiment. However, the effects of root restriction reported in this experiment are generally similar to those effects that may result from water, nutrient and hormone regulated stresses as reviewed in Chapter 2. The research presented in this thesis showed root restriction resulted in beneficial attributes for improved grapevine crop loading capacity and maturity composition improvements in comparison to non restricted vines. Thus, resources should be directed to a study of the physiological processes and consequences that result from long term field root restriction.

The root restriction bags were proposed to work physically on the premise of allowing limited root growth to penetrate the Duon[®] porous fabric in the form of a fine periphery of roots around the bags, but as the roots reached a diameter of the size of the pore the roots were girdled and subsequent growth was slowed. The work of Edwards (1997) suggested that the root restriction by bags used for *Populus* and *Dodonea* did not allow the turnover (decay and renewal) of roots within the bags, which supposedly, along with the peripheral roots outside the bag, could maintain shoot growth. Edwards (1997) research was based on the initial premise of root restriction acting in a similar manner to Bonsai. However, Bonsai, in contrast to root restriction, is clearly a technique that is dependent on active physical root pruning. Root pruning in contrast to root restriction as a method of vigour control in fruit trees was differentiated previously in a review by Ferree *et al.*, (1992), and subsequently by White (1995).

In my research, preliminary investigation carried out around the bags revealed that girdling did occur and limited root growth outside that bag. However, unexpected root escapes (i.e. continued girth expansion of girdled roots) were also evident in all of the treatment replicates. In comparison, research carried out with *Populus* and *Dodonea* (Edwards, 1997) using similar porous bags for control of plant growth showed clear root escapes in *Populus* a species with a vigorous root systems, although in contrast no major root escapes were evident in *Dodonea*. Long term work with root restricted apples (White, 1995) showed suckers shoots outside of root restriction bags, suggesting root escapes. Edwards (1997) concluded that the means of root escapes was that the roots travelled within the bag fabric obliquely to the outer thinner part of the bag with

least resistance where they broke through the bag. Subsequent secondary thickening of the roots dependent on the plant vigour, exerted lateral pressure on the bag allowing increasing rooting volume outside the bag. While root escapes in my research were not evident in the preliminary investigation to the extent of those shown in the destructively harvested *Populus* (Edwards, 1997) the unintended root escapes possibly explain some of the unusual results obtained, most clearly evident in the smallest bags of my work.. Also, the congestion from root restriction by bags poses the question, are the fine peripheral roots adequate to supply water and nutrition to the plant if the bag material is completely impenetrable to larger roots? In the current trial the vines appear healthy nine years after planting, and the author is not aware of any other reported research with root restriction over such an extended period. If root escapes had not occurred in all treatments, the question arises, “would the vines have been detrimentally affected?”

A comparison of impenetrable potted root restriction versus porous bags and root restriction by constant or limited irrigation may reveal the more sustainable technique suitable for long term root restriction. Alternative methods of root restriction such as fabric lined trenches, competitive companion planting and constant or restricted irrigation combined with high density planting should be contrasted with root bags. Improving the current bag design with increased resistance to stretching and thus eventual breakage of the bag material, would allow further conclusions to be gathered from bagging as a form of root restriction.

Rootstocks may be a means of obtaining more natural root restriction effects whilst maintaining the favourable characteristics of the scion variety. Some preliminary evidence however has indicated root restricted apple trees were manipulated more strongly by root restriction than rootstock (White, 1995), but, this has not been confirmed over a wide variety of rootstocks. Dwarfing rootstocks are not yet widely used for grapevines. However, this is probably an area of plant breeding progress in vigour control for grapevines and allowing the favourable composition characteristics of the scion, for wine production.

A further step in research would be to impose more management practices on to the root restricted plants. Minimal management and subsequent minimal interference was the main priority of this experiment. Subsequently, short spur pruning utilising the basal

nodes was used. However small and fewer bunches most likely resulted from the pruning which utilised the less fruitful basal buds in the cultivar Cabernet Sauvignon (Winkler *et al.*, 1974). Thus the crop load was clearly lower than that suggested as being appropriate for a well balanced vine.

Increased crop loading would be expected to result in increased competition with the root and shoot growth as has been suggested by work with root restricted apples (White, 1995) and fruit bearing grapevines grown in pots (Petrie, 1997). Future research should consider cane pruning in the cool climate to infer a higher potential fruitfulness by; utilising the nodes further along a spur/ short cane, or alternatively by utilising different cultivars such as Riesling or Pinot Noir with more fruitful basal nodes (Winkler *et al.*, 1974). Other management practices such as shoot thinning and crop regulation should be incorporated into future trials so vigour and shading effects can be more accurately determined. Crop regulation should assist in determining bag treatment effects versus crop load and bienniality effects that have been imposed by root restriction treatments with root restricted Fuji apple trees (White, 1995).

In conclusion, due to the preliminary investigation showing unintended root escape, and crop load limitations determined by the current cordon and short spur pruning system used for minimal management interference. Destructive harvest of the trial seems an inevitable action. Destructive harvest would allow further study of morphological characteristics resultant from long term root restriction, and should reveal more details about root morphology in response to root restriction and root escapes. A carbon balance should also be carried out on the grapevines. This information would improve the knowledge of the functional root to shoot ratios in bagged compared to unrestricted grapevines.

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Table 8.1 Effects of root restriction on predicted node number per shoot, shoot number per vine, within row spacing, vine number per hectare and yield per hectare scenarios. Predicted from 1995 total shoot internode length and total node number per vine.

Bag volume (L)	<i>1995 total shoot internode length</i>	<i>Predicted node number per shoot *¹</i>	<i>1995 total node number per vine</i>	<i>Predicted shoot number per vine *²</i>	<i>Predicted within row spacing (m) *³</i>	<i>Predicted vine number per hectare *⁴</i>	<i>Scenario 1. predicted tonnes per hectare *⁵</i>	<i>Scenario 2. predicted tonnes per hectare *⁶</i>
10	5.84	10.27	764	74.39	2.17	3840	7.6	23.9
25	5.18	11.58	588	50.78	1.32	6313	10.9	25.3
48	5.43	11.05	652	59.00	1.60	5208	11.6	26.0
102	6.05	9.92	942	94.96	2.87	2904	6.4	22.1
∞	6.59	9.10	1319	144.95	4.78	1743	4.0	18.2

*¹ Assumption, 0.6 meter height of each tier (Smart and Robinson, 1991).

*² Total node number per vine / node number per shoot.

*³ Shoot number per vine x total shoot internode length, and based on 1.2 meter total height of double tier (0.6 meter height of each tier).

*⁴ Within row spacing x 1.2 m spacing between rows.

*⁵ Based on 1995 treatment, leaf area per vine / per unit fruit fresh weight per vine (LA/ FFW), averages.

*⁶ Based on potential, LA/ FFW, 12 cm²/ g (Smart and Robinson, 1991).

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