CSIRO PLANT INDUSTRY

AGRICULTURE VICTORIA

Grape and Wine Research and Development Corporation

Optimisation of quality wine grape production through modelling vine phenology, canopy architecture, light interception, water use and yield

FINAL REPORT to
Grape and Wine Research & Development Corporation

Project Number: **CSH 94/2**
Principal Investigators: Karl J Sommer, Ian Goodwin

CSIRO Plant Industry, Horticulture Research Unit, Merbein
Department of Natural Resources and the Environment, Tatura
Date: June 2000

Preface

This report was prepared by CSIRO and DNRE to meet reporting requirements to GWRDC. While it is not a general publication document, limited copies are being made available through GWRDC for extension purposes. *Information in the report must not be cited or reproduced without permission from CSIRO (Dr K. Sommer) or DNRE (Mr I. Goodwin).*

Table of Contents

List of Figures

List of Tables

1 Executive summary

This report comprises the results and analyses of two experiments conducted over a period of five growing seasons at Merbein in north-west Victoria on the Murray River and at Mt Helen near Tatura in Central Victoria. The experiments provided the baseline data for the development of vine-specific computer simulation procedures of VineLOGIC a computer simulation model that describes the development, growth and yield formation of a grapevine in response to its environment and to irrigation. Experimental sites at Merbein in north-west Victoria and Mt Helen in central Victoria were selected to be representative of respectively the hot, irrigated inland areas along the Murray River and the cool, mostly rain-fed areas of southern Australia. The Merbein site (elevation 60 m; annual rainfall 320 mm; MJT 23.9 °C) comprised minimal pruned and spur pruned Cabernet Franc vines grafted to Ramsey rootstocks in a randomised complete block design. The Mount Helen site (elevation 450 m, annual rainfall 700 mm and MJT 21.3 °C) comprised minimal pruned and Scott-Henry trained vines of the variety Pinot Noir with pre-veraison thinning and no thinning treatments as well as deficit and full irrigation treatments in a split split-plot design.

Detailed measurements of vine development, canopy growth, shoot growth, light interception, dry matter partitioning, leaf gas exchange, soil water content, yield formation, berry composition and wine quality were collected throughout the growing seasons.

1.1 Merbein experiment

1.1.1 Vine growth and development

In Merbein, the choice of pruning system resulted in large differences in vine morphology and vine performance. Minimal pruning caused an increase in bud number with around 1500 buds per vine compared to around 100 for spur pruned vines. The increase in bud number strongly reduced the rate of bud burst in minimal (50%) compared to spur pruned vines (95%). Because of a higher bud number per vine and despite a lower rate of bud burst, more shoots formed on minimal than on spur pruned vines. The greater shoot number of minimal compared to spur pruned vines led to a quicker canopy fill and a greater light interception during the early stages of canopy development (Sep. – mid-Nov.). Thereafter leaf area of spur pruned vines had caught up with that of minimal pruned vines and the former now intercepted more light.

1.1.2 Dry matter accumulation and vine morphology

The mass of single shoots of spur pruned vines at harvest was about 8 times that of minimal pruned vines. A greater proportion of shoot dry matter was partitioned into fruit as a result of minimal compared to spur pruning. About 25% of the leaf area of shoots from spur pruned vines arose from lateral shoots but there was no lateral shoot growth on minimal pruned vines. Leaves were smaller and thinner on minimal than spur pruned vines and there were fewer leaves on the main shoots of minimal than spur pruned vines. Leaves of minimal pruned vines had a lower rate of photosynthesis than leaves of spur pruned vines but differences were small.

1.1.3 Fruit set, yield, ripening and wine quality

Minimal pruning led to a 30% reduction in the number of flowers per bunch compared with spur pruning. Fruit set of minimal pruned vines (12.5%) was about half that of spur pruned vines (23.2%). Minimal pruned vines had 25% more yield than spur pruned vines and the former had more, but smaller bunches, with fewer and smaller berries. Ripening was delayed by about one week in minimal relative to spur pruned vines. In most seasons wine made from fruit that came from minimal pruned vines had higher acidity and lower pH than wine made from fruit that came from spur pruned vines. Tasting scores for wines that came from either minimal or spur pruned vines were similar.

1.1.4 Water extraction and water use

Minimal pruned vines extracted more water from the soil profile than spur pruned vines particularly during the early stages of canopy development when leaf area of minimal pruned vines was larger than that of spur pruned vines. Most of the water, regardless of pruning, was extracted between 0 and 80 cm soil depths. Water extraction from deeper in the profile was minimal.

1.2 Tatura Experiment

1.2.1 Vine growth and development

In Mt Helen, there were consistent and obvious differences between training systems in vine growth but no differences between irrigation or thinning treatments. Shoot length in minimal pruned vines was reduced by about 50% but leaf number was only reduced by 25% compared with Scott Henry indicating shorter internodes on minimal pruned vines. Leaf appearance was similar between training systems up to around 300 DDT. After the 4^{th} or 5^{th} leaf, leaves were smaller on minimal pruned shoots. Leaf area per shoot was therefore substantially less on minimal pruned vines. Total vine leaf area however was around 50% larger in minimal pruned vines due to a 3-fold increase in shoot number per vine.

Despite large differences in total vine leaf area between minimal pruned and Scott Henry vines for the entire season, canopy surface area around flowering and until canopy separation was similar. In minimal pruned vines the canopy surface area remained relatively constant for most of the season. Scott Henry vines had a similar canopy surface area as minimal pruned vines until the canopy of the former was re-arranged into a hedge when it increase by around 50%.

1.2.2 Dry matter accumulation, ripening and yield,

Annual shoot dry matter per vine was higher in minimal pruned vines and was attributable to a higher fruit dry weight. Berry fresh and dry weight was less on minimal pruned vines and differences arose prior to veraison. Deficit irrigation reduced berry fresh weight and dry weight post-veraison in minimal pruned vines probably due to increased water use compared to Scott Henry trained vines where there was no effect of deficit irrigation.

Minimal pruning appeared to reduce the accumulation of soluble solids although this was only obvious in 2 of the 5 years. At each sampling date from veraison to harvest in 3 of the 5 years, deficit irrigation of the minimal pruned indicated a reduction in total titratable acidity, an increase in pH and a reduction in soluble solids (Brix). There was no effect of bunch thinning on berry fresh or dry weight or berry composition.

Over the 5 years of the experiment total vine yield was 30% higher in minimal pruned vines attributed to a doubling in bunch number but a reduction in berry weight and number. Deficit irrigation reduced yield and the effect was greatest in minimal pruned vines. Thinning reduced yield in proportion to the number of bunches removed.

1.2.3 Water extraction and water use

Weekly measurements of soil water content were taken at 20 cm depth increments to 140 cm directly under the dripper, 45 cm from the dripper and mid row. Overall measurements indicated a wetted pattern to 80 cm depth and 45 cm radius from a 6 hour irrigation with 4 L/hr drippers. Changes in soil water content were highest at 20 cm depth directly under the dripper although changes mid row at 20 cm depth were also high probably due to non vine water use. Changes in soil water content decreased with depth and distance from the dripper. There was an alteration in the pattern of water extraction with both depth and position from the vine in the deficit treatments. Late in the season, as the topsoil dried, water extraction shifted to the lower depths.

Total soil water content to 160 cm depth was consistently less in the deficit treatments apart from the mid-row at 20 and 40 cm depth. A calculation of total vineyard water use based on rainfall, irrigation and changes in soil water content indicated a higher level of vineyard water use in minimal pruned vines.

Overall minimal pruned vines had the highest leaf area, water use and fresh and dry weight yield. Berry fresh weight was less and composition indicated slower maturity in minimal pruned vines. Deficit irrigation reduced berry fresh and dry weight, yield and delayed maturity in minimal pruned vines. Minimal pruned vines were probably more stressed under deficit irrigation compared with Scott Henry trained vines due to a higher water use.

2 Introduction

Increasingly, computer simulation modelling is being applied to optimise crop productivity and quality. Application of simulation models has been successful with most major field crops (Ritchie 1991). For the grapevine no comprehensive simulation models have been developed do date but would have many benefits to the viticultural industries including:

1. A better understanding of the relationship of vine growth and development with its environment.
2. Testing of new management systems, *e.g.* a wide array of trellising and spacing arrangements too costly to establish in field experiments.
3. Testing of management options with very long time scales *e.g.* salination, canopy architecture, nutrient leaching and water table movements.
4. Site evaluation with regard to irrigation requirements and climatic risk
5. A support tool for education, extension and decision support.

The current project was initiated to develop a dynamic simulation model of the grapevine suitable for the Australian environment. The project was a collaborative effort involving CSIRO Divisions of Plant Industry, the Department of Natural Resources and Environment (Agriculture Victoria).

3 Objectives

The development of a dynamic computer simulation model for the grapevine relies on suitable computational procedures that accurately describe vine behaviour in response to its environment and to irrigation. Suitable and reliable computational procedures can only be developed from long-term experimental data that accurately describe vine behaviour. At the outset of this project suitable experimental data was either not available or was deficient. Therefore, the first and major objective of this project was to:

A. Establish accurate and suitable baseline data for model development.

In turn the baseline data was used to:

B. Develop computer routines that describe vine development and growth in the Australian environment.

Two experimental sites were established to meet Objective A. Sites were chosen to be representative of the hot, irrigated inland areas along the Murray River (Merbein, Victoria) and the cool, mostly rain-fed areas of southern Australia (Mt Helen, Victoria). Trellising and irrigation treatments of the experiments were selected in accordance with standard viticultural practice. In addition, treatments were established to be representative a wide spectrum in the morphological and physiological behaviour of the vine in order to cover extremes of possible growth scenarios. Most of the resources available to the project were initially committed towards the establishment of detailed and comprehensive baseline data sets representative of the two experimental sites (Objective A).

This report provides a detailed description and analysis of the two baseline data sets from the Merbein and Tatura experiments which in turn were used to develop the vine specific computer routines of the VineLOGIC simulation model (Objective B). The description of these routines will be published elsewhere.

4 Experimental sites

Two sites were established, one representative of the hot irrigated inland wine growing regions along the Murray Valley (Merbein, Victoria) and the other representative of the cool mostly rain-fed areas of southern Australia (Mt Helen, Victoria).

4.1 Merbein site

The Merbein site was located at the experimental farm of CSIRO Plant Industry near Mildura in north-east Victoria (142° 4' E, 34° 10' S). The soil is classified as a Coomealla sandy loam (Northcote 1958). The site was planted to Cabernet Franc grafted to Ramsey at a row by vine spacing of respectively 3.1 by 2.4 m. Vines were 5 years old in the season of 1994/95 when the experiment was established and had been spur pruned to a quadrilateral cordon at a height

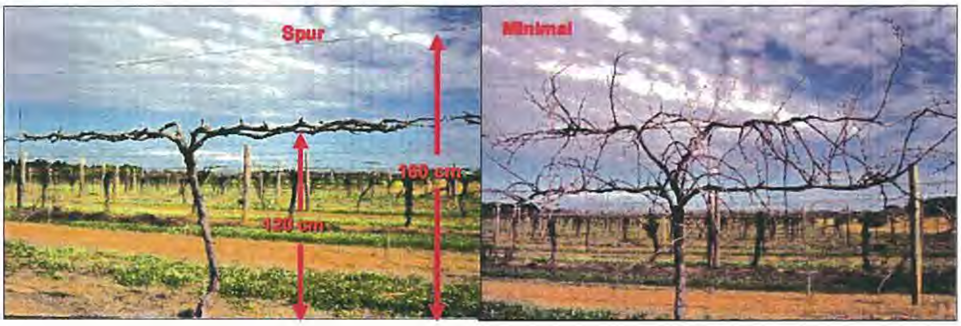

Figure 1. Spur pruned (left) and minimal pruned (right) Cabernet Franc experimental vines at Merbein, Victoria.

of 120 cm with a foliage wire at 160 cm (Figure 1). Three rows of vines were selected and were divided into 3 blocks each containing 36 vines. Each block was subdivided and half of each block was converted to minimal pruning in June 1994 by taking two of the four permanent cordons to the foliage wire at 160 cm. The pruning treatments were assigned randomly within each main block. Four adjacent vines from the centre row of each treatment were selected for continuous observations.

The site was irrigated with overhead sprinklers. The amount of water applied at each irrigation event was recorded. In the first season the amount was estimated from the duration of each irrigation event and in subsequent seasons flow meters were installed in the supply line to provide an estimate of the amount of irrigation water.

4.1.1 Vine morphology and vine growth measurements

The objective was to provide an accurate assessment of vine and shoot morphology throughout the growth period and in respect to the imposed pruning treatments. The following measurements were recorded.

4.1.1.1 Phenological records and per Cent bud burst

Major phenological events were recorded throughout each growth period according to the definitions adopted by Coombe (1995). The number of buds on selected vines was counted and recorded before bud burst. After bud burst, at approximately weekly intervals, the number of buds was recounted and the number of burst buds was recorded until no further bud burst was apparent. In addition, in seasons 3 to 5 buds were counted according to the Merbein Bunch Count Method as described by Antcliff (1972).

4.1.1.2 Monitoring of shoot growth

The purpose of this measurement was to obtain a detailed record of shoot leaf appearance and leaf area development on main and lateral shoots throughout the growth period. Two vines per block and per pruning treatment were selected from within the middle row and on each vine 8 shoots were selected and marked. Shoots were chosen systematically on either side of the trunk and trellis wire and from a proximal, medial and distal position on the cordon. From bud burst, the number of leaves that had emerged on each shoot as well as the length of each leaf and the length of the shoot was recorded. In the period between bud burst and flowering shoot measurements were recorded every week. Thereafter, until shortly before veraison, growth was recorded fortnightly and thereafter every four weeks. A final shoot record was obtained just before harvest. Estimates of area per leaf were calculated using a non-linear regression between area per leaf and leaf length. Different relationships were determined for leaves from minimal and spur pruned vines and were respectively as follows: $LA = 0.114729 * LL^{1.43}$; $R^2=0.983^{***}$ and $LA = 0.055103 * LL^{1.667}$; $R^2=0.984^{***}$, where LA is leaf area per leaf in cm^2 and LL is leaf length in cm.

4.1.1.3 Vine leaf area development

Leaf area development was assessed non-destructively using a LI-COR canopy analyser (LI-COR, Lincoln, Nebraska, USA) following a protocol specifically developed for grapevines (Sommer and Lang 1994). Measurements were recorded weekly until flowering and thereafter fortnightly or monthly until leaf fall.

4.1.2 Dry matter partitioning

Dry matter partitioning was estimated by destructively sampling entire shoots throughout the growing season. In seasons 1 to 3, shoots were sampled 4 times per season and in seasons 4 and 5 there were two additional sampling occasions. At each sampling 50 shoots of each training system were randomly selected from the outside rows. Care was taken to select only shoots that were not damaged. Shoots were immediately transferred to the cool room where they were stored in plastic bags for further processing. Shoot samples were processed according to the following procedure. The length of each shoot was recorded. Leaves on the main stem were removed by cutting the leaf petiole where it attaches to the leaf blade. Leaves were counted and the length of each leaf was recorded. In the first season each leaf was stored in a paper bag for drying. In subsequent seasons leaves of the main stem were bulked and stored in a paper bag for drying. Leaf petioles were always left attached to the stem. Leaves on lateral shoots were also removed and stored in paper bags for drying. Stems of the main and lateral shoots were separated and inflorescences were removed. If present, bunches were removed and their fresh weight was recorded. Subsequently the berries of each bunch were removed from the rachis and were counted. Berries from each shoot were stored in an aluminium tray and were reweighed before drying in an oven. After processing different shoot components were stored in paper bags and were immediately transferred to an oven for drying. Plant material was dried at a temperature of around 60-80C. After drying the samples were transferred to a desiccator and their weight was recorded.

4.1.3 Flower number per bunch, berry number per bunch and fruit set

Samples to determine flower numbers per bunch were collected shortly before cap fall. Fifty bunches per treatment were randomly selected from vines in outside rows. Each bunch was placed in a paper bag and was dried in an oven at 60 °C. Flowers of each bunch were counted manually. In the first and second seasons main and lateral branches of the rachis were counted separately according to the classification used by May (1986). In later seasons, 1996/97 to 1998/99, no such a distinction was made. Berry number per bunch was obtained from shoot samples shortly before harvest as part of the sampling procedure for the determination of dry matter partitioning (see 4.1.2). The mean of all samples was taken as the mean berry number per bunch. Per Cent fruit set was computed from the berry number per bunch over the mean flower number per bunch.

4.1.4 Light interception and light climate

The percentage of intercepted light is the amount of solar radiation recorded under the leaf canopy relative to the solar radiation above the leaf canopy. Light interception was measured fortnightly on clear days around solar noon using a ceptometer (Decagon, Oregon, USA). The instrument consists of a 80 cm long probe that is equipped with 80 light diodes spaced 1 cm apart. The instrument may be configured such that the reading of each diode is recorded and stored. Alternatively, the average from all sensor readings along the the probe may be stored. For the purpose of determining light interception the latter measuring mode was selected. Each light interception record per vine was based on 8 readings of the incident radiation below the leaf canopy and one reading above the leaf canopy. Readings below the canopy were taken according to a strict protocol to ensure that the average was representative of the area occupied by one vine.

The ceptometer was also used to record a profile of the light interception within the canopy. Readings were always obtained around one hour before or after solar noon. The ceptometer was configured such that the reading from each sensor was logged. This provided a record for each of the 80 sensors spaced at 1 cm increments along the probe. Readings were recorded at decrements of 30 cm ranging from 240 to 30 cm above the ground. To record a measurement the probe was pointing towards the vine row and the tip was level with the centre line of the trellis. The correct height for each recording was determined with a measuring rod. The ceptometer was levelled using the attached spirit level. Readings were obtained on either side of the vine row. Readings were stored in the logger attached to the ceptometer and were later downloaded to a computer for further analysis and plotting. Two vines per block and per pruning treatment were measured.

4.1.5 Leaf gas exchange

Leaf gas exchange was estimated diurnally using a LI-COR 6200 (LI-COR, Lincoln, Nebraska) portable gas exchange system. Readings were collected on clear days throughout the growth period at approximately monthly intervals. Well-exposed shoots were selected and, depending on their lengths and leaf number, gas exchange of between 3-14 leaves on the shoot were recorded, progressing from the base to the tip of the shoot. Immediately after measuring gas exchange three well-exposed leaves were selected from the vine and their water potential was determined using a pressure chamber. The procedure was repeated throughout the day alternating between pruning treatments and vine replicates.

4.1.6 Berry maturation

Monitoring of fruit maturation began at veraison. Weekly samples of 100 berries were collected from 6 vines per block and pruning treatment respectively. Samples were weighed and juice was extracted. Total soluble solids (°Brix) of juice were determined using an Type 302 Abbe refractometer (Atago Optical). Acidity and pH of the juice were measured by titrating with 0.1N sodium hydroxide to an end point of pH 8.3 using a GK2401C electrode, a VIT90 video titrator, an ABU91 autoburette and a SAC 80 sample changer (Radiometer Copenhagen).

4.1.7 Crop yield and other yield components

All vines were harvested when fruit was fully mature (>24 Brix). The number of bunches on each vine and the total weight of all bunches were recorded. A sub-sample comprising 100 berries was collected for determination of total soluble solids (°Brix), acidity and pH.

4.1.8 Wine quality

Wine was made from harvested fruit in the small scale wine making facility of CSIRO Plant Industry at Merbein and was analysed according to standard methods (Somers and Evans 1977).

4.1.9 Soil moisture monitoring

At the beginning of the first growth period sensing equipment was installed for soil moisture monitoring. Two sets of 20 cm long TDR (Time Domain Reflectometry) wave-guides (Soilmoisture Equipment, California) were installed per block such that 3 vines per pruning treatment could be monitored. A trench of about 1.4 m depth was excavated perpendicular to the vine row at a distance of around 1 m from the trunk. Buriable wave guides (20 cm long) were inserted horizontally into the side of the trench in a direction parallel to the vine row at 20, 40, 60, 80, 100 120 140 cm. The excavated soil was back-filled into the trench. Soil moisture was always monitored just prior to and after an irrigation or significant rainfall event.

In seasons 1 and 2 soil moisture was also monitored using a neutron probe. To that end 1.5 m long aluminium access tubes were installed parallel to the location of the TDR wave-guides but were offset by 50 cm towards the inter-row area. Direct comparison of TDR and neutron probe readings enabled cross-validation of the two methods. Neutron probe readings were recorded at fortnightly intervals throughout the growth period.

4.1.10 Drained upper limit and lower level of available soil moisture

A circular plot of about 10 m in diameter was set aside immediately adjacent to the experiment towards its north-western end. Four access tubes were installed in the plot, which then was irrigated for several days until the wetting front had reached 150 cm depth. The plot was then covered with plastic sheeting and was allowed to drain for two days. Subsequently, moisture content of the soil profile was recorded and was taken as the drained upper limit of the available soil moisture. The plot was then sown with a forage sorghum variety (***Sorghum bicolor*** spp) at a high planting density and was irrigated until plants were fully established. No further irrigation was applied thereafter until plants had desiccated, indicating depletion of the available soil water. At this point soil moisture was again recorded and was taken as the lower level of plant available soil moisture.

4.1.11 Soil particle analysis

Soil particle analysis was carried out to determine the percentage clay, silt, coarse sand and fine sand. Soil samples were obtained from 20, 40, 60, 80, 100, 120, 140 cm depth. Soil particle analysis was carried out in accordance with the method described by McIntyre and Loveday (1974).

4.1.12 Data analysis

The experiment was analysed as a randomised complete block design. Analysis of variance and plotting were carried out in SYSTAT (Wilkinson 1990).

4.2 Mt Helen site

The Mt Helen vineyard is located close to Avenel in the central Victorian highlands (145° 15' E, 36° 53' S) at an elevation of 450m. Average annual rainfall was 709mm, MJT was 21.3° C and heat sum (10° C base from October 1 to April 30) was 1489° C from July 1994 to July 1999. The soil is classified as a Boho sandy loam (Downes 1949). The site was planted in 1979 to Pinot Noir on own roots at 3.6 by 1.8 m spacing (Figure 2).

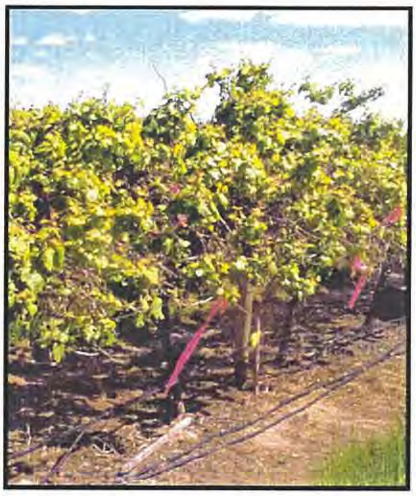

Figure 2. Scott Henry spur pruned (left) and minimal pruned (right) Pinot Noir experimental vines in November at Mt Helen, central Victoria.

Minimal pruned and Scott Henry trained vines were selected from a previous canopy management experiment established in the winter of 1989. Scott Henry trained vines were pruned to 4 bud spurs with approximately 175 buds per vine on two permanent cordons spaced at 30 cm with the lower cordon at 100 cm height. Two pairs of moveable foliage wires were positioned 30 cm below and 50 cm above the lower and upper cordons respectively when the canopy was separated in mid December. Canopy height and width of the minimal pruned vines was approximately 160 and 130 cm respectively. Minimal pruned vines were skirted in winter to a height of approximately 60 cm.

Three replicates of each training method consisting of 12 vines were split into two levels of water stress. Each water stress treatment was further split into two crop loads. Measurements were taken from two vine plots with two guard vines between each water stress treatment and a single guard vine between each crop load treatment. The experiment was thus a completely randomised split split-plot design.

Water stress treatments aimed to either minimise water stress by irrigating to meet evapotranspiration (referred to as Full) or to impose a moderate level of water stress (referred to as Deficit). In years 1 & 2 of the experiment the Deficit treatment was irrigated at approximately 10% of Full. In years 3 to 5 of the experiment the Deficit treatment was not irrigated. Vines were irrigated with two 4L/hr drippers spaced at 0.9m. Water meters were installed to monitor the amount of irrigation water applied.

Crop thinning treatments consisted of either removing 50% of bunches, approximately one month after berry set or leaving the crop unthinned. In year 3 no thinning was undertaken.

4.2.1 Vine morphology and vine growth measurements

The objective was to provide an accurate assessment of vine and shoot morphology throughout the growth period and in respect to the imposed pruning, thinning and irrigation treatments. The following measurements were recorded. Their description follows a chronological sequence in line with the course of the growing season.

4.2.1.1 Phenological records

Major phenological events were recorded throughout each growth period according to the definitions adopted by Coombe (1995).

4.2.1.2 Monitoring of shoot growth

The purpose of this measurement was to obtain a detailed record of shoot extension, leaf area development and leaf appearance on main and lateral shoots throughout the growth period. Four shoots from each vine within a plot were selected and marked. Shoots were chosen systematically on either side of the trunk, from a medial position and from the top and bottom cordons on Scott Henry trained vines. From approximately 4 weeks after bud burst shoot lengths were recorded weekly until veraison and less frequently thereafter until harvest. The number of leaves that had emerged on each shoot was also recorded apart from year 4 when no records were taken and year 5 when measurements were delayed by 4 weeks.

To calculate shoot leaf area the relationship between individual leaf length and area was established from destructive leaf samples during year 1. Eight leaves from each plot were sampled four times during the season. Different relationships were determined for leaves from minimal and Scott Henry trained vines and were respectively as follows: $LA = 1.7983 * LL^{1.6047}$; R^2=0.7712 and $LA = 1.4046 * LL^{1.7227}$; R^2=0.8266, where LA is leaf area per leaf in cm^2 and LL is leaf length in cm. In year 2 individual leaf length on the main shoot was measured in one replicate to determine the relationship between main shoot leaf area and shoot length. Different relationships were determined for shoots from minimal and Scott Henry trained vines and were respectively as follows: $SLA = 20.586 * SL$; R^2=0.8979 and $SLA = 17.387 * SL$; R^2=0.8856, where SLA is main shoot leaf area in cm^2 and SL is shoot length in cm. Total vine leaf area was calculated from shoot leaf area and shoot number per vine determined from Merbein bunch counts.

In years 3 and 5 total vine leaf area was calculated from measurements on main and lateral shoots. In year 3 individual leaf length measurements on main shoots and lateral shoots were taken on half the marked shoots weekly to veraison, then less frequently to harvest to calculate total shoot leaf area and vine leaf area. In year 5 lateral length was measured weekly from 2 weeks after flowering to veraison then less frequently to harvest. The position of senesced leaves along a shoot was also recorded. Shoot leaf area was calculated from main and lateral shoot lengths and senesced leaf area.

4.2.1.3 Vine leaf area development

The leaf area development was assessed non-destructively in year 3 using a DEMON following a protocol that was specifically developed for grapevines (Sommer and Lang 1994). Five measurements were recorded from bud burst to veraison.

4.2.1.4 Canopy dimensions

Canopy height and width on both sides of the trellis wire was measured at flowering and veraison for individual vines. In year 3 and 4 measurements were taken fortnightly. Canopy surface area and volume were calculated by assuming a half cylinder top with a radius equal to half the canopy width and a rectangular base. Both the minimal pruned and Scott Henry trained vines were calculated the same up to canopy lifting. After canopy lifting the Scott Henry trained vines were calculated assuming a rectangular shape.

4.2.2 Dry matter partitioning

Dry matter partitioning was estimated by destructively sampling entire shoots throughout the growing season. In year 2 shoots were sampled 2 weeks prior to flowering, at flowering, 2 weeks after flowering, 4 weeks after veraison and at harvest. In years 3 to 5 shoots were sampled at various times from 3 weeks prior to flowering to leaf fall. At each sampling 2 shoots from each plot were randomly sampled. Shoots that were marked for shoot length measurements were sampled at harvest in years 2 and 3 and at leaf fall in years 4 and 5. Shoot samples were processed according to the following procedure. Leaves and bunches were separated from the stem. Leaf petioles were always left attached to the stem. Leaves on laterals were also removed and stored separately. Berries were removed from the rachis and were counted. Leaves, stems and bunches were dried at a temperature of around 60C. After drying the samples were transferred to a desiccator and their weight recorded.

4.2.3 Seasonal changes in berry fresh and dry weight

Berry fresh and dry weight was measured from a 20 to 40 berry sample per plot taken weekly from post-flowering to harvest. Five berries were sampled per bunch from the apex, middle and shoulder of bunches. Bunches were randomly selected within a plot. Samples were collected into sealed plastic bags in the field. Samples were weighed on the same day as collection and oven dried at 60C for approximately one month. After drying the samples were transferred to a desiccator and their weight was recorded.

4.2.4 Seasonal changes in berry composition

Monitoring of fruit maturation began at veraison. 25 berries per plot were sampled weekly from post-veraison to harvest. Five berries were sampled per bunch from the apex, middle and shoulder of bunches. Bunches were randomly selected within a plot. Soluble solids concentration (°Brix) of juice was determined using a digital refractometer model PR-1 (Atago Optical). Acidity and pH of the juice were measured by titrating with 0.1N sodium hydroxide to an end point of pH 8.3 using an auto titrator model 719S Titrino (Metrohm).

4.2.5 Crop yield and other yield components

The number of bunches on each vine and the total weight of all bunches were recorded at harvest.

4.2.6 Soil moisture monitoring

Weekly measurements of total soil water content were taken with a neutron probe using a four second count duration. Seven access tubes per plot in two replicates were installed to 140 cm depth in a grid across and along the vine row. One tube was sited directly adjacent to the drip emitter, 4 tubes were 45 cm from the emitter along the vine row and towards the inter-row, and 2 tubes were sited 183 cm from the emitter in the mid inter-row. Total soil water content to 160 cm depth was calculated from a weighted average soil water content for position in relation to the emitter and depth.

The neutron probe was calibrated on site by sampling undisturbed soil cores (260 cm^3) at three positions around 9 spare access tube located close to the experimental site at 20 cm intervals to 140 cm depth immediately following a measurement. Cores were placed in sealed plastic bags, were later weighed and then dried to calculate volumetric water content. Water content readings from the three positions around an access tube were averaged. Calibration equation to convert raw counts was $VWC = 0.0024*C - 2.6837$ (R^2=0.7991) where VWC is the volumetric water content in cm^3/cm^3 and C is the raw probe counts.

EnviroScan sensors were installed in one replicate to measure soil water content every 30 minutes. Sensors were positioned adjacent to the emitters at 20, 40, 60 and 100 cm depths.

4.2.7 Root distribution and soil analysis

Two soil pits were dug to approximately 160 cm depth next to a vine and close to the experimental site to visually assess root distribution, soil profile changes and depths. Soil samples were taken within each profile for analysis of pH, EC, organic carbon and particle size analysis.

Soil cores (260 cm^3) at 20, 40, 60 and 80 cm depths were taken to determine the volumetric soil water content at saturation, field capacity (drained upper limit) and wilting point (lower limit).

4.2.8 Weather data

An automatic weather station was sited next to the experimental area. Solar radiation, wind speed, wet bulb temperature depression, dry bulb temperature and rainfall were recorded every hour for the duration of the experiment. Reference crop evapotranspiration (ET_0) was calculated every hour (Allen et al. 1998).

5 Description of baseline data

The following is a description of the data sets obtained from the Merbein and Tatura experimental sites. It follows the same sequence as the description of the methodology.

5.1 Merbein site

5.1.1 Phenological records and percent bud burst

5.1.1.1 Timing of bud burst

Results describe the sequence of bud burst beginning with the date when the first buds burst and the date when 50% of the buds that ultimately break, had broken (Table 1). The timing of 50% bud burst was determined graphically as illustrated in Figure 3. The horizontal lines represent 50% bud burst of minimal or spur pruned vines respectively. Two vertical dashed lines are drawn through the intersections of the horizontal lines with the line that represents the course of bud burst of the respective pruning treatments. The intersections of the vertical lines with the x-axis in turn denote the time of 50% bud burst. The time of first bud burst was determined by extending the line between the first and the second observation and determine its intercept with the x-axis when y = 0.

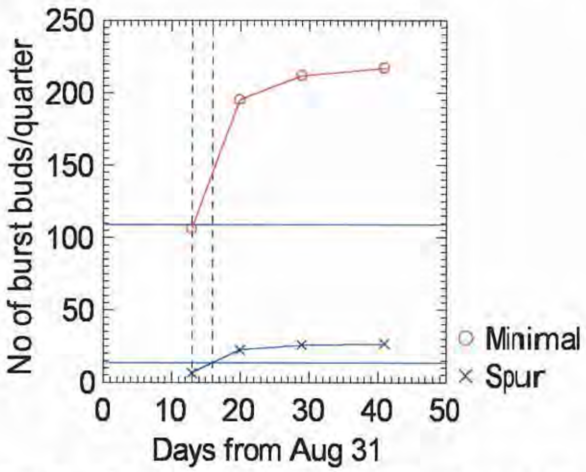

Figure 3. Time of 50% percent bud burst of minimal and spur pruned Cabernet Franc vines at Merbein in the season of 1995/96.

In the five seasons of the experiment the earliest bud burst was observed on 31 August and the latest on 17 September a range of 2 ½ weeks. Except in 1998/99, bud burst began always earlier in minimal than in spur pruned vines. Similarly, 50% bud burst was reached sooner in minimal than spur pruned vines but differences were small. Results suggest that spur pruning delayed bud burst in most seasons by around 5 days.

Table 1. Date of first bud burst and date of 50% bud burst in minimal and spur pruned Cabernet Franc at Merbein, Victoria between 1995/95 and 1998/99.

Event	Season	Minimal		Spur	
		First bud	50% burst	First bud	50% burst
Bud burst	1994/95	17 Sep	25 Sep	22 Sep	30 Sep
	1995/96	5 Sep	13 Sep	10 Sep	16 Sep
	1996/97	9 Sep	16 Sep	14 Sep	18 Sep
	1997/98	13 Sep	24 Sep	16 Sep	27 Sep
	1998/99	31 Aug	9 Sep	28 Aug	11 Sep

5.1.1.2 Other phenological events

Dates of other phenological events are shown in Table 2, Table 3 and Table 4. The dates of first flower appearance and of 50% flowering were similar between minimal and spur pruned vines (Table 2). Differences of up to 2 weeks in the timing of 'first flower' and '50% flowering' were observed over the five growing seasons. There was a time span of about 7 – 9 days between the appearance of the first flowers and 50% flowering. No differences as results of pruning were seen in the starting dates of veraison, except in the 1998/99 growing season, when veraison in minimal pruned vines was delayed by a few days (Table 3). The same was true for the date of 50% veraison, which occurred about 7 – 10 days later. Overall, regardless of seasonal influences and of pruning, the timing of veraison was remarkably uniform. Maturity dates are listed in Table 4 together with the total soluble solids (°Brix). Except in growing season five, fruit of both pruning systems was harvested at the same date. At a given harvest date maturity of minimal pruned vines was always delayed relative to spur pruned vines. The delay was equivalent to about two weeks except in the last season where fruit of minimal pruned vines remained on the vine for another 3 weeks and still was 3 Brix degrees lower than fruit from spur pruned vines.

Table 2. Date of flowering in minimal and spur pruned Cabernet Franc at Merbein, Victoria between 1995/95 and 1998/99.

Event	Season	**Minimal**		**Spur**	
		First	50%	First	50%
Flowering	1994/95	31 Oct	09 Nov	02 Nov	09 Nov
	1995/96	23 Oct	01 Nov	23 Oct	01 Nov
	1996/97	25 Oct	02 Nov	25 Oct	02 Nov
	1997/98	28 Oct	04 Nov	28 Oct	04 Nov
	1998/99	14 Oct	23 Oct	14 Oct	23 Oct

Table 3. Date of veraison in minimal and spur pruned Cabernet Franc at Merbein, Victoria between 1995/95 and 1998/99.

Event	Season	**Minimal**		**Spur**	
		Beginning	50%	Beginning	50%
Veraison	1994/95	12 Jan	19 Jan	12 Jan	19 Jan
	1995/96	09 Jan	19 Jan	09 Jan	19 Jan
	1996/97	08 Jan	20 Jan	08 Jan	20 Jan
	1997/98	09 Jan	21 Jan	09 Jan	21 Jan
	1998/99	07 Jan	07 Jan	07 Jan	15 Jan

Table 4. Date of harvest and soluble solids of fruit in minimal and spur pruned Cabernet Franc at Merbein, Victoria between 1995/95 and 1998/99.

Event	Season	**Minimal**		**Spur**	
			°Brix		°Brix
Harvest	1994/95	02 Mar	25.35	02 Mar	28.36
	1995/96	06 Mar	23.41	06 Mar	26.76
	1996/97	06 Mar	24.63	06 Mar	27.54
	1997/98	25 Feb	28.10	25 Feb	28.30
	1998/99	23 Mar	23.70	03 Mar	26.10

5.1.2 Per Cent bud burst

Bud counts provided an estimate of the percentage of bud burst based on the bud number retained during winter. A plot of the average percentage bud burst for the two pruning treatments over five seasons is shown in Figure 4. In spur pruned vines, regardless of season, percentage bud burst was consistently high, ie. > 90%. Conversely, in minimal pruned vines, on average just over half of the retained buds burst and the rate of bud burst was more variable from growing season to growing season. A much larger number of buds was retained on minimal than on spur pruned vines and this difference was probably the cause for the much lower percentage of bud burst in minimal relative to spur pruned vines. Carbohydrate and nutrient reserves per bud presumably were smaller for minimal than for spur pruned vines given the large differences in bud numbers. Minimal pruned vines adapted to this situation by reducing the number of buds that burst to ensure an adequate supply of reserves per bud.

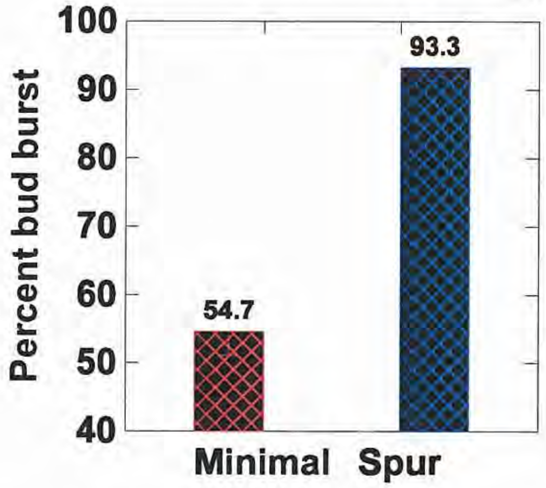

Figure 4. Average bud burst percentage of minimal and spur pruned Cabernet Franc at Merbein between 1994/95 and 1998/99.

5.1.3 Leaf appearance

Detailed records of leaf appearance of minimal and spur pruned vines were maintained to capture the influence of pruning on the rate of leaf appearance. Figure 5 shows the rate of leaf appearance of minimal and spur pruned vines in the growing seasons of 1994/95 to 1996/97 as a function of thermal time (heat sum, DDT). Shortly after bud burst leaf appearance rate between pruning treatments was similar but began to diverge after about 300 DDT because of a more rapid decline in leaf appearance on minimal than spur pruned vines. From around 700 DDT onward no more new leaves emerged on minimal pruned vines. Spur pruned vines followed a near constant rate of appearance until about 700 DDT and thereafter leaf appearance declined strongly but did not cease completely. The causes for this difference are probably related to the resources available for leaf growth. Leaves from minimal pruned shoots received less carbohydrate resulting in delayed leaf emergence compared with leaves from spur pruned vines.

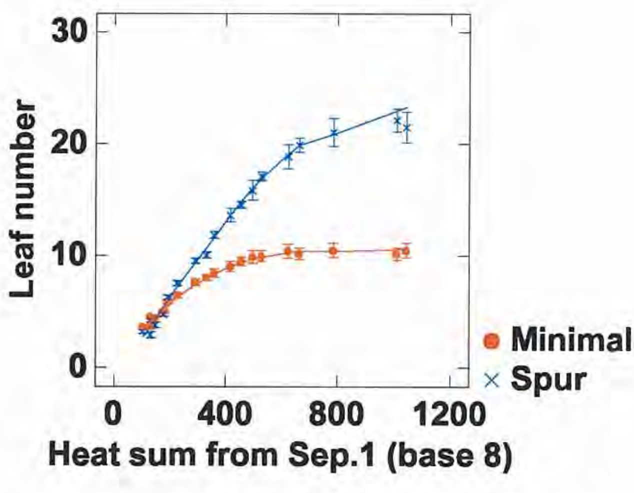

Figure 5. Leaf appearance as a function of heat sum (DDT) accumulated from Sep. 1 of minimal and spur pruned Cabernet Franc vines at Merbein in the growing seasons of 1994/95 – 1996/97

5.1.4 *Leaf size*

Large differences in the area of individual leaves along the shoot were observed between minimal and spur pruned vines (Figure 6). Leaves on shoots from minimal pruned vines were always much smaller than those from spur pruned vines. Regardless of pruning system leaf size increased steeply with leaf position, reaching a maximum at leaf 8 for spur and leaf 5 for minimal pruning. Beyond those positions leaf size declined on both pruning systems but more so for spur than for minimal pruned vines. Minimal pruned vines, on average had 14 leaves per shoot but spur pruned vines had up to 30 leaves per shoot. Differences in leaf size and number were again due to the relative lack of resources per leaf on minimal relative to spur pruned vines because of the substantial divergence in bud and hence shoot numbers between the pruning systems at the start of the growth period.

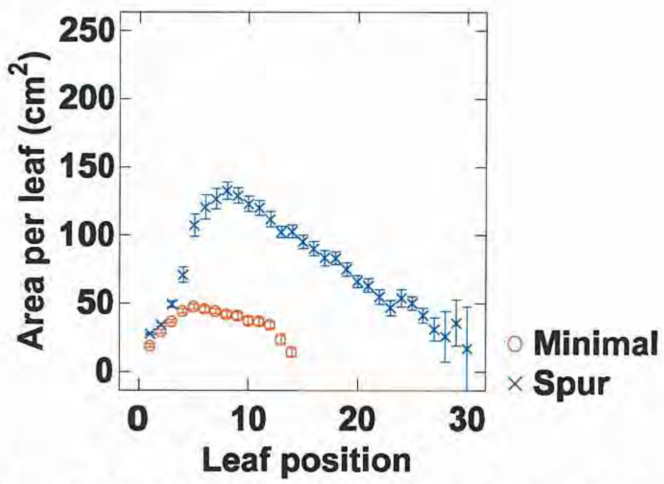

Figure 6. Maximum area per leaf (cm^{-2}) as a function of leaf position for minimal and spur pruned vines at Merbein in the growing season of 1995/96.

5.1.5 *Leaf area per shoot*

As expected from the size of single leaves, the area of all leaves on the shoot was much larger for shoots that came from minimal than from spur pruned vines (Figure 7). On average, leaf area per shoot of spur pruned vines was almost ten times that of minimal pruned vines. About one quarter of the total leaf area of shoots from spur pruned vines was due to lateral shoot growth. Conversely, no lateral shoots were found on minimal pruned vines. Shoot leaf area increased exponentially during the early growth period from around 25 days after August 31

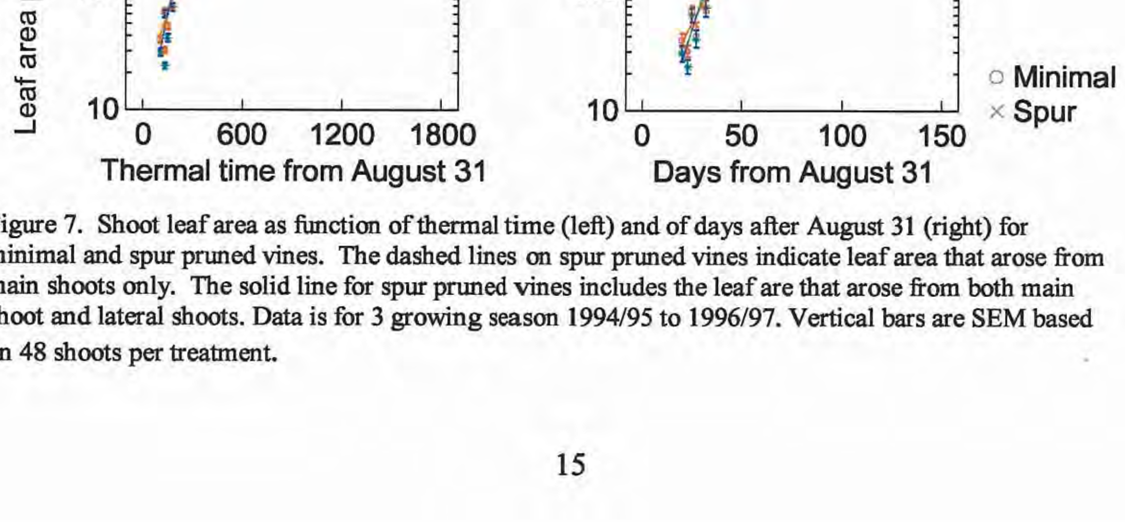

Figure 7. Shoot leaf area as function of thermal time (left) and of days after August 31 (right) for minimal and spur pruned vines. The dashed lines on spur pruned vines indicate leaf area that arose from main shoots only. The solid line for spur pruned vines includes the leaf are that arose from both main shoot and lateral shoots. Data is for 3 growing season 1994/95 to 1996/97. Vertical bars are SEM based on 48 shoots per treatment.

to around 60 days after August 31. Towards the end of that time span leaf growth ceased almost completely on minimal pruned vines but continued, although at a much lower rate, on spur pruned vines. Obviously there was greater competition for resources amongst the relatively large number of shoots on minimal, compared with the much smaller shoot number on spur pruned vines.

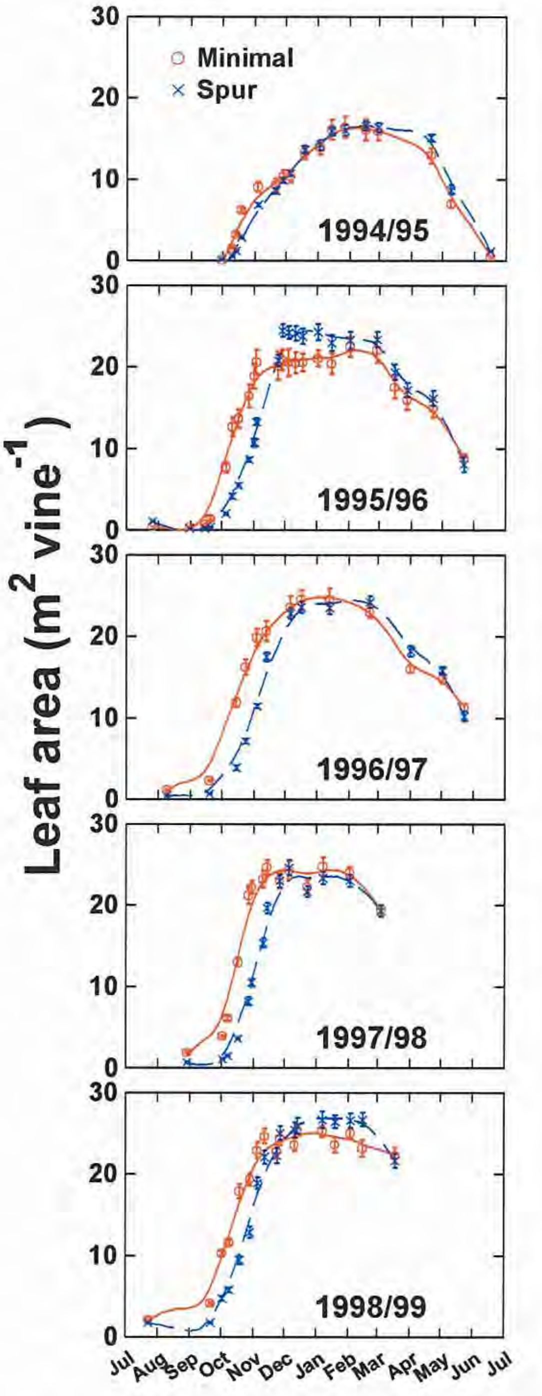

Figure 8. Leaf area index of minimal and spur pruned Cabernet Franc vines in the growing seasons of 1994/1995 through to 1998/99. Vertical bars are SEM.

5.1.6 *Leaf area per vine*

Leaf area development followed a distinct but similar pattern regardless of growing season (Figure 8). With the exception of the first season, leaf area development and canopy fill of minimal pruned vines was always ahead of that of spur pruned vines during the early part of the season. In the first season, shortly after converting vines from spur to minimal pruning, differences in vine leaf area development between pruning systems were small but became more apparent thereafter. The accelerated canopy fill of minimal relative to spur pruned vines was due to the larger bud and hence shoot number of the former in spring. During the early growth phase the larger number of emerging shoots on minimal compared to spur pruned vines resulted in a larger vine leaf area. The rate of leaf area expansion was largest shortly after bud burst from about mid September until around mid November when it began to decelerate for both pruning systems. By that time the leaf area of spur pruned vines had reached a similar size as that of minimal pruned vines and remained similar for the rest of the growing season. Both pruning systems attained their maximum leaf area around the middle of December. Over the duration of the experiment the maximum leaf area per vine increased strongly from the first to the second season but remained fairly constant from then on for either pruning treatment. Once leaf area had reached its seasonal maximum it decreased at a slow but relatively constant rate for the remainder of the growing season.

5.1.7 *Light interception and light climate*

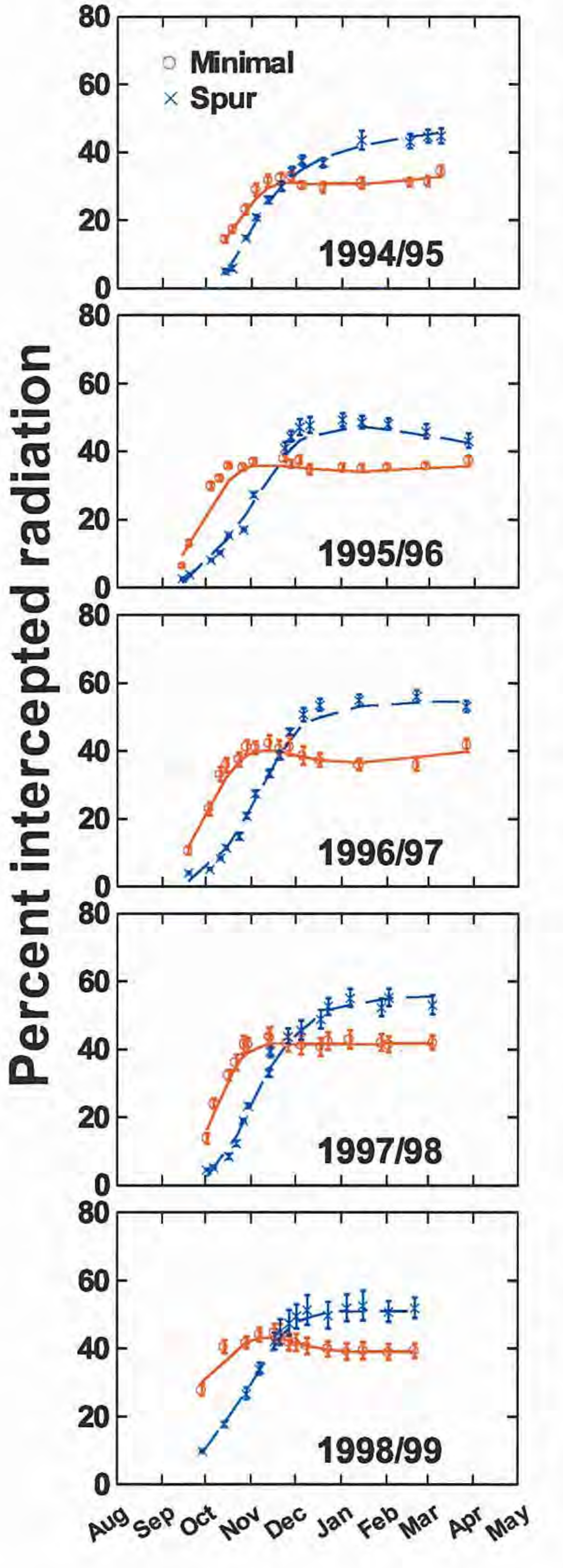

Figure 9. Light interception of minimal and spur pruned Cabernet Franc vines throughout the growing seasons of 1994/95 to 1998/99. Vertical bars are SEM.

Light interception is the percentage of the photosynthetically active radiation that is captured by the vine canopy. Light interception followed a similar pattern to leaf area development (Figure 9). Differences in light interception due to pruning system were apparent. Shortly after bud burst light interception of minimal pruned vines increased steeply and for a period of about 5 weeks minimal pruned vines intercepted significantly more light than spur pruned vines. The higher light interception was attributable to the larger leaf area on minimal relative to spur pruned vines during the period of early canopy development. Towards late November light interception of minimal pruned vines had reached its maximum and remained relatively constant until harvest in early March. Conversely, light interception of spur pruned vines continued to increase steeply until late December and overtook that of minimal pruned vines by the middle of November. Light interception of spur pruned vines reached its maximum in late December and remained unchanged until harvest in early March. During the period from mid November to harvest spur pruned vines always intercepted more light than minimal pruned vines. Spur pruned vines continued their shoot growth for longer than minimal pruned vines and although the leaf area of both pruning systems was similar the former appeared to intercept more light late in the season. The reason for this difference is due to differences in shoot morphology between the pruning systems. Spur pruned shoots were longer than minimal pruned shoots, extended further into the inter-row area and thus were able to capture a greater percentage of the incident solar radiation.

A plot of light interception and leaf area index is presented in Figure 10. The plot is an indication of the behaviour of light extinction for the two pruning systems. Results suggest that for every unit of leaf area, spur pruned vines intercepted more light, once leaf area had reached

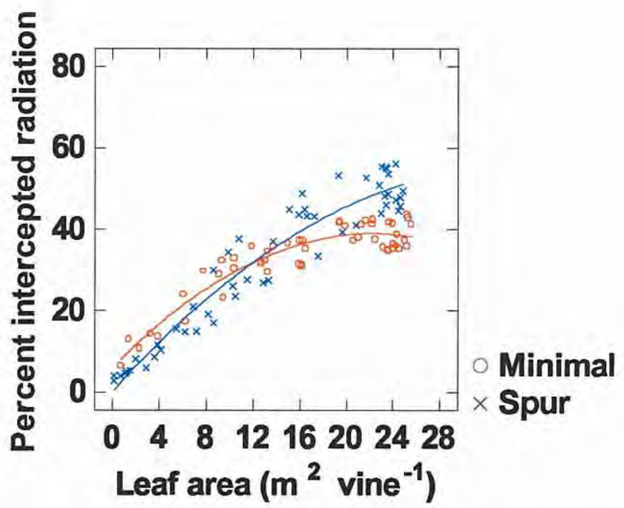

Figure 10. Relationship of percent light interception and leaf are per vine for minimal and spur pruned Cabernet Franc vines at Merbein, Victoria, between 1994/95 and 1998/99

values of between 14 – 16m^2. At low leaf areas (< 8m^2) extinction of both pruning systems was similar or slightly higher for minimal than spur pruned vines.

The differences are probably due to the shape of the vine canopy resulting in a distinct light interception profile for each of the pruning treatments. A profile of light interception of either pruning system is depicted in Figure 11. It shows the amount of photosynthetically active radiation (PAR) at different canopy heights and widths. The dark areas represent the degree of shading within the canopy. Distinct differences in the pattern of light interception within the leaf canopy are apparent for the two pruning treatments. In early spring minimal pruned vines at every canopy height intercepted more light than spur pruned vines and hence had a greater canopy light interception (see Figure 9). By early December this situation was reversed, spur pruned vines now intercepted more light at every level of trellis height (Figure 11, 4 December). The outline of the minimal pruned canopy hardly changed from the first (21 October) to the second (4 December) recording and little growth had occurred during that time. Conversely, by the second measuring date spur pruned vines had attained a greater canopy width compared with the first

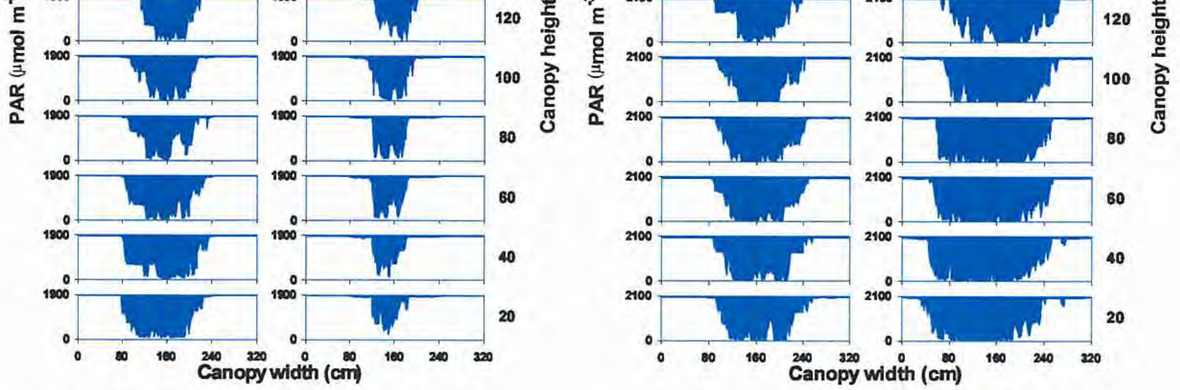

Figure 11. Light climate of minimal and spur pruned Cabernet Franc vines at different canopy heights and widths recorded on 21 October and December 4 1996

measuring date and relative to minimal pruned vines at either measuring date. The greater canopy width of spur pruned vines became apparent at the second measuring date. Readings also indicate that the solar radiation level in the canopy interior of either pruning treatment was low and more so in spur than in minimal pruned vines.

5.1.8 Dry matter partitioning per shoot

Shoot dry matter accumulation at distinct developmental events and the partitioning of shoot dry matter into the components of stem, leaf and fruit are depicted in Figure 12. The data was averaged across all growing seasons. The most obvious difference between the pruning systems was the much lower dry matter of minimal relative spur pruned single shoots. At harvest the mean mass per shoot of spur pruned vines was about 8 times that of single shoots

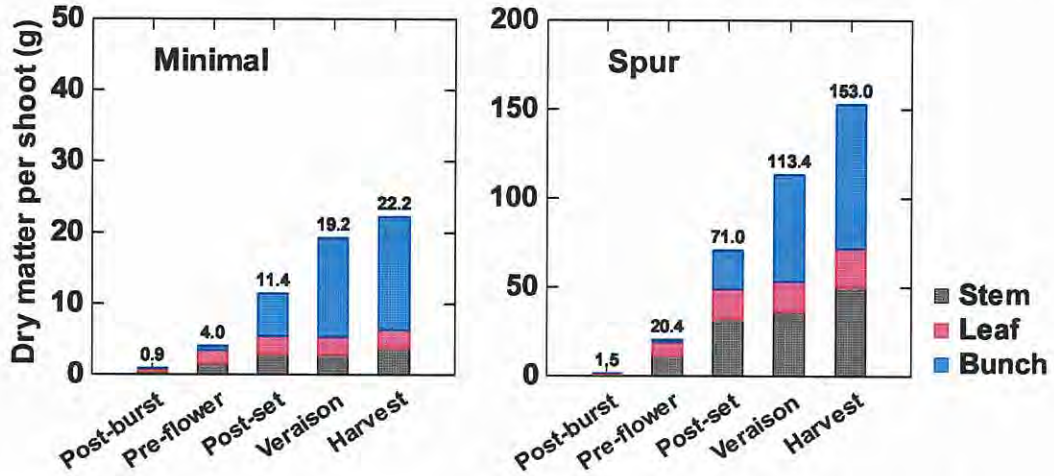

Figure 12. Shoot dry matter accumulation and partitioning into stems, leaves and bunches for minimal and spur pruned Cabernet Franc vines at Merbein , Victoria. Values represent means of 5 growing seasons.

from minimal pruned vines. The rate of dry matter accumulation per shoot throughout the season also was much larger for spur than for minimal pruned vines. Pre-flowering most of the dry matter was accumulated into stems and leaves. At that stage, differences in shoot mass due to pruning were already apparent but were small compared to later in the season. Shortly after set, fruit became the major sink for dry matter and now was the shoot component with the highest growth rate. As shoots continued to grow after set, the proportion of dry matter partitioned towards stems was becoming larger on spur than on minimal pruned vines. It

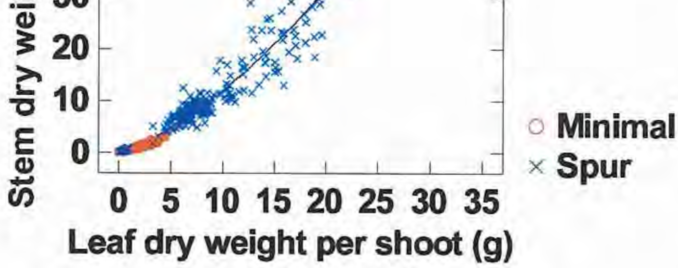

Figure 13. Partitioning of dry matter into leaves and stems for minimal and spur pruned shoot of Cabernet Franc shoots growing at Merbein.

appears that with increasing shoot mass spur pruned shoots required a higher proportion of biomass for structural support than the relatively small and much lighter minimal pruned shoots. The relationship between stem dry weight per shoot and leaf dry weight per shoot is illustrated in Figure 13. It demonstrates that as shoots grew bigger, an increasing proportion of the shoot dry matter was being partitioned towards growing stems rather than leaves. Shoots from spur pruned vines were much larger and therefore had a higher proportion of the shoot mass partitioned into stems rather than leaves.

5.1.9 Shoot dry matter partitioning per vine

Rather than looking at a population of single shoots, vine dry matter partitioning takes into account the whole vine. Because it was not possible to destructively harvest whole vines partitioning was estimated from destructive shoot sampling and vine shoot counts (Figure 14). The resulting graphs show a similar seasonal trend to those in Figure 12 but differences between pruning systems are now less apparent because the total shoot mass per vine rather than that of single shoots is taken into account. Total shoot dry matter per vine of minimal

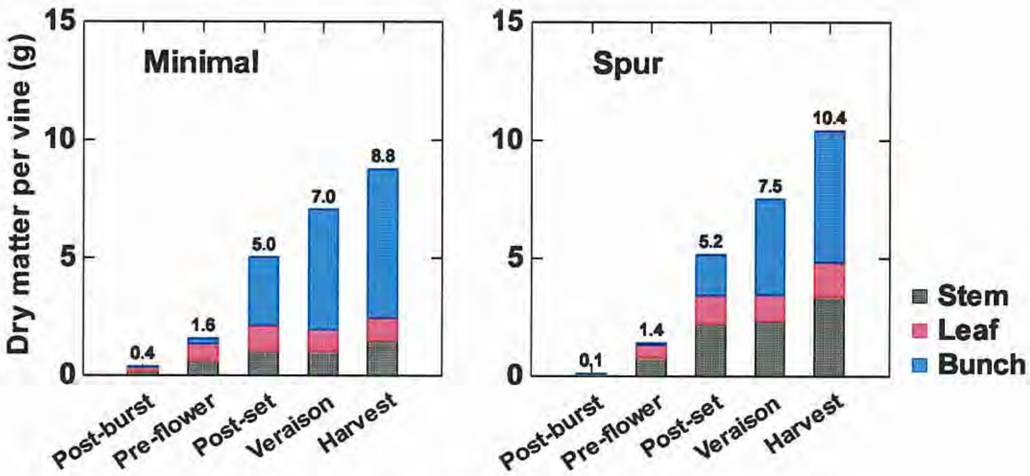

Figure 14. Vine dry matter partitioning of minimal and spur pruned Cabernet Franc into stems, leaves and fruit at Merbein. Values represent means of 5 growing seasons.

pruned vines at the end of the growing season was smaller than that of spur pruned vines but the fruit component was larger for minimal than for spur pruned vines. Pre-flowering, vine shoot dry matter was larger on minimal than spur pruned vines. This agrees with observations on vine leaf are development were minimal pruned vines always had larger canopies pre-flowering then spur pruned vines. The components of vine stem and leaf dry matter were always smaller on minimal than on spur pruned vines but the opposite was true with respect to fruit dry matter. Overall, dry matter production per vine over the five seasons was remarkably similar for the two pruning systems given the contrasting morphology with respect to shoot number and shoot size.

5.1.10 Flower number per bunch, berry number per bunch and fruit set

Minimal pruned vines on average had around 30% less flowers than spur pruned vines with the exception of the first season (Table 5). In the first season minimal pruned vines had significantly more flowers per bunch than spur pruned vines. Vines had only just been converted from spur to minimal pruning and the conversion resulted in higher flower numbers for the latter.

Table 5. Flower number per bunch for minimal and spur pruned Cabernet Franc vines at Merbein. Capital letters indicate differences for main effects year and pruning system. Small letters indicate differences of pruning within year; $p <= 0.05$; Tukey's multiple range test; $n = 50$.

Season	Minimal	Spur	Mean
1994/95	486 a	385 b	436 B
1995/96	467 b	681 a	574 A
1996/97	332 b	468 a	400 B
1997/98	296 b	579 a	438 B
1998/99	417 b	773 a	595 A
Mean	400 B	578 A	

Once minimal pruned vines had adapted to the conversion their flower number per bunch was always lower than that of spur pruned vines. There was also a seasonal effect on flower number with the second and fifth seasons being higher than other seasons. Flower number per bunch was more uniform in bunches from minimal than spur pruned vines (Figure 15). The majority of bunches from minimal pruned vines had between 300 and 600 flowers. In comparison spur pruned vines had a larger proportion of bunches with more than 500 flowers but flower number was more variable across the population. Bunches from spur pruned vines had always more berries compared with bunches from minimal pruned vines (Table 6). The differences were greater than would have been expected from the flower counts and were caused by a lower fruit set in minimal relative to spur pruned vines. Except for the first season berry number was consistent with the overall trend in flower number. Although flower number in the first season was higher on bunches from minimal pruned vines their berry number was lower, demonstrating the plasticity of the vines in adapting to the change in

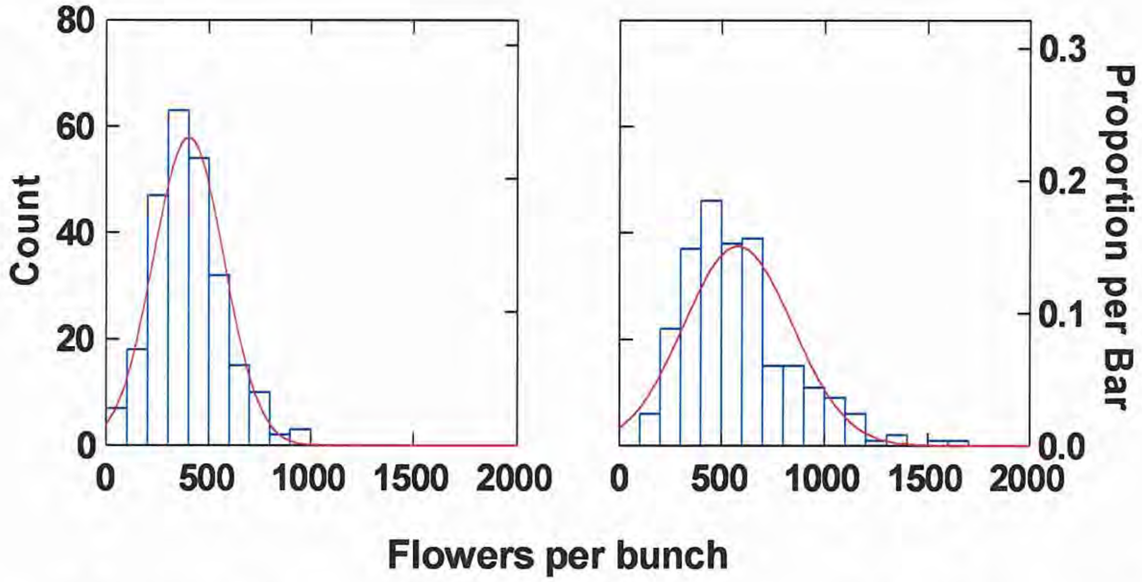

Figure 15. Density plot of flower number per bunch of minimal and spur pruned Cabernet Franc vines over five growing seasons at Merbein, Victoria.

pruning. Fruit set of minimal pruned vines was consistently lower and was about half that of spur pruned vines (Table 6).

Table 6. Berry number per bunch and percent fruit set for minimal and spur pruned Cabernet Franc vines at Merbein. Capital letters indicate differences for main effects season and pruning system. Small letters indicate differences of pruning within season. p=0.05 Tukey's multiple range test; n=50. Percent fruit set was calculated from treatment means of flower number per bunch and berry number per bunch therefore and no statistical analysis was possible.

	Berry number per bunch			Percent fruit set		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	55 b	110 a	83 B	11.4	28.6	20.0
1995/96	55 b	152 a	104 A	11.7	22.7	17.2
1996/97	48 b	117 a	83 B	14.5	24.9	19.7
1997/98	36 b	129 a	83 B	12.3	22.3	17.3
1998/99	53 b	137 a	95 A	12.8	17.7	15.3
Mean	49 B	129 A		12.5	23.2	

5.1.11 Berry maturation

Results of berry maturation and fruit quality are presented as time course measurements in Figure 16. The berry sugar content of minimal pruned vines always lagged behind that of spur pruned vines and differences were most pronounced in the 1998/99 season. In that year, beginning from around 148 days after August 31, no sugar was being accumulated in berries from minimal pruned vines for a period close to two weeks. Sugar levels in spur pruned vines continued to rise, although at a lower rate than in other years. Thereafter, from around 162 days after August 31, sugar accumulation continued at a similar rate in berries from either pruning treatment but still at a lower rate than in other years. Conversely, in the growing season of 1997/98 the course of sugar accumulation between pruning treatments was almost identical and the rate of accumulation was higher than in other years. The cropping level in 1997/98 was lower compared with other seasons and was similar between pruning treatments. The relatively low cropping level for either pruning treatment probably contributed to the steep increase in sugar accumulation.

Must acidity followed an inversely proportional course to must sugar accumulation. It declined steeply with time, following a similar course in every season. It behaved similarly with respect to pruning except in 1998/99, when minimal pruning caused a strong delay in the decline of must acidity relative to spur pruning.

Must pH was inversely proportional to must acidity and parallel to must sugar. Similar to sugar accumulation, minimal pruning delayed a rise in must pH relative to spur pruning. The delay was more obvious in 1998/99 relative to other growing seasons. As far as sugar accumulation is concerned the delay was probably caused by a period of heat stress the vines had to endure in early February of 1998/99.

Most of the observed differences in relation to pruning were attributable to the heavier crop in minimal relative to spur pruned vines. Minimal pruned vines carried a heavier crop in most years and therefore suffered from a delay in fruit maturation ranging from 7 days to almost 3 weeks.

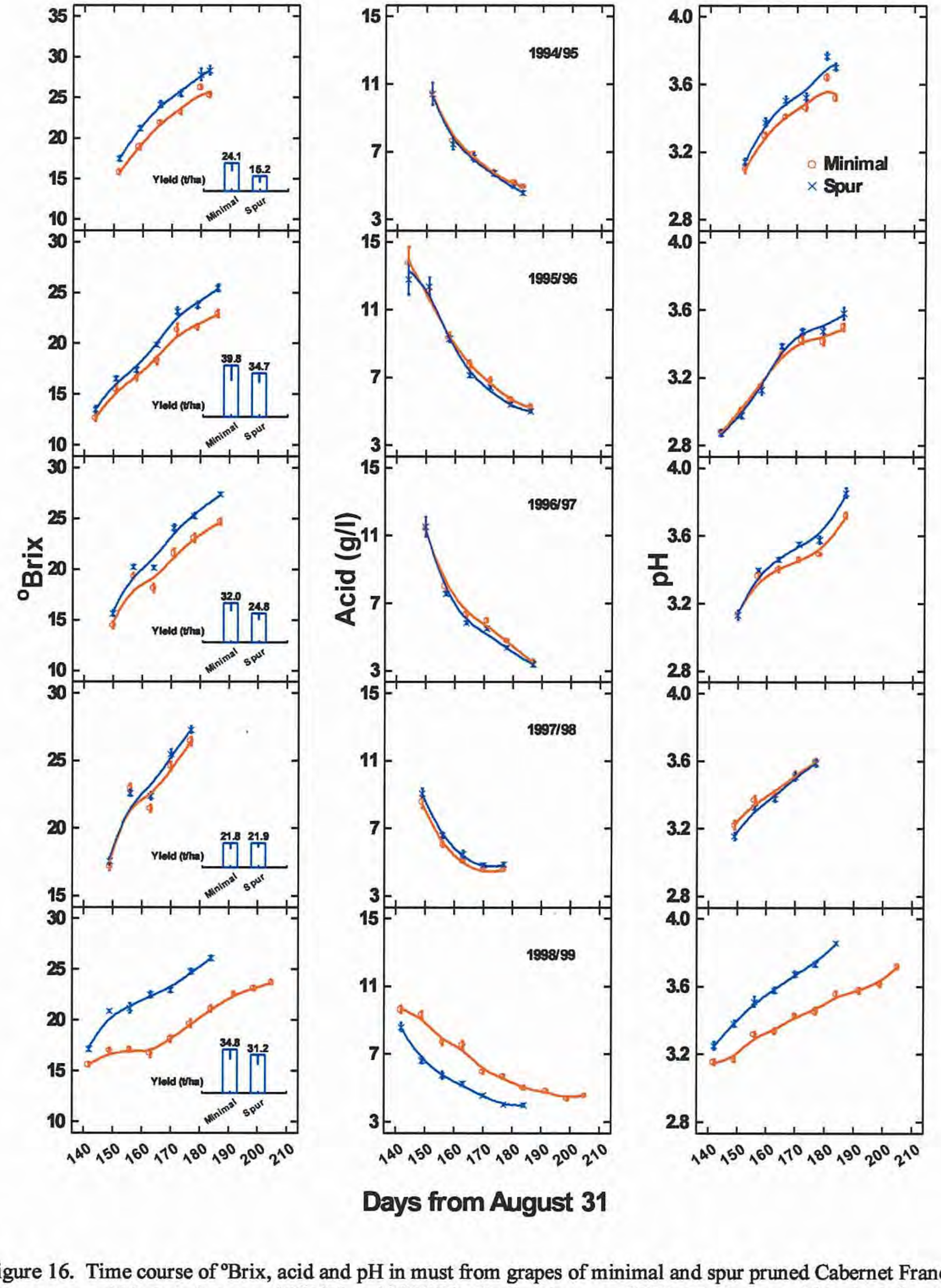

Figure 16. Time course of °Brix, acid and pH in must from grapes of minimal and spur pruned Cabernet Franc vines grown at Merbein between 1994/95 and 1998/99. Vertical bars are SEM. The inserts within the left column of graphs are bar charts showing the yield performance of minimal and spur pruned vines. Vertical bars on the charts represent –SEM.

5.1.12 Yield and yield components

Yield, measured in tonnes of fresh fruit per hectare and berry weight is shown in Table 7. Season had a strong influence on yield with a relatively low yield in the first year and very high productivity in the second and the final year.

Table 7. Grape yield and weight per berry of minimal and spur pruned Cabernet Franc vines at Merbein, Victoria. 'Mean' column headings denote seasonal effects across pruning treatments. 'Mean' row headings denote pruning effects across seasons. Values within 'Mean' columns or rows followed by the same or no capital letter are not significantly different p. Values within a row and season followed by a different small cap letter denote significant differences within season due to pruning ($p<=0.05$).

	Yield (t/ha)			Berry weight (g)		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	24.1 a	15.2 b	19.7 D	0.68	0.92	0.80 C
1995/96	39.8 a	34.7 b	37.3 A	0.93	1.12	1.02 A
1996/97	32.0 a	24.8 b	28.4 C	0.73	1.12	0.93 AB
1997/98	21.8	21.9	21.9 D	0.64	0.88	0.76 C
1998/99	34.8	31.2	33.0 B	0.73	0.98	0.86 BC
Mean	30.5 A	25.6 B		0.74 B	1.00 A	

Regardless of seasonal influences minimal pruned vines were always more productive and on average yielded around 27% more fruit than spur pruned vines. Berries from minimal pruned vines were significantly smaller than those from spur pruned vines, a reduction of around 25%. Season strongly affected berry weight but the reduction did not appear to be associated with high yields. Minimal pruned vines had around five times the number of bunches of spur pruned vines (Table 8). There was a strong seasonal influence on bunch number per vine with the number of bunches increasing over time particularly on minimal pruned vines. Minimal pruning consistently reduced the number berries per bunch by about two thirds of the number found on bunches from spur pruned vines. There was a significant seasonal effect on the berry number per bunch but the variation from season to season was relatively small.

Table 8. Bunches per vine and berries per bunch of minimal and spur pruned Cabernet Franc vines at Merbein, Victoria. 'Mean' column headings denote seasonal effects across pruning treatments. 'Mean' row headings denote pruning effects across seasons. Values within 'Mean' columns or rows followed by the same or no capital letter are not significantly different. Values within a row and season followed by a different small cap letter denote significant differences within season due to pruning ($p<=0.05$).

	Bunches per vine			Berries per bunch		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	587 a	142 b	365 C	44.6 b	87.2 a	65.9 AB
1995/96	916 a	226 b	571 B	38.6 b	103.0 a	70.8 A
1996/97	916 a	200 b	558 B	35.9 b	82.8 a	59.4 B
1997/98	1041 a	190 b	616 AB	24.6 b	99.0 a	61.8 B
1998/99	1117 a	233 b	675 A	31.9 b	102.7 a	67.3 AB
Mean	919 A	198 B		35.1 A	94.9 B	

Total soluble solids (°Brix) at harvest were always lower in fruit from minimal relative to that of spur pruned vines (Table 9). With the exception of the third season minimal pruned vines lagged behind spur pruned vines by about 3° Brix at the time of harvest. The fourth season was an exception in that both pruning systems had the same Brix level at harvest. Most of the delay in maturation under minimal pruning may be attributed to the higher fruit load relative to spur pruned vines (Table 7). During the first 4 growing seasons vines from both pruning treatments were harvested at the same date. At the end of year five the harvest of minimal pruned vines was delayed by about 3 weeks because ripening progressed very slowly relative to spur pruned vines. Despite the delayed harvest, the soluble solids of fruit from minimal pruned vines still lagged behind that of spur pruned vines by more than 3 °Brix. Acidity was inversely proportional to °Brix and was always higher in must from minimal relative to that of spur pruned vines because of a delayed ripening in the latter (Table 9). The trend in must pH was similar to that in soluble solids with lower values in must from minimal pruned vines due to a delay in ripening.

Table 9. Total soluble solids (°Brix), total acidity and pH at harvest in the must of minimal and spur pruned Cabernet Franc vines at Merbein, Victoria. 'Mcan' column headings denote seasonal effects across pruning treatments. 'Mean' row headings denote pruning effects across seasons. Values within 'Mean' columns or rows followed by the same or no capital letter are not significantly different. Values within a row and season followed by a different small cap letter denote significant differences within season due to pruning ($p<=0.05$).

	°Brix		
Season	Minimal	Spur	Mean
1994/95	25.4 b	28.4 a	26.9 B
1995/96	23.4 b	26.8 a	25.1 C
1996/97	24.6 b	27.5 a	26.1 B
1997/98	28.1	28.3	28.2 A
1998/99	23.7 b	26.1 a	24.9 C
Mean	25.0 B	27.4 A	
	Acid (g/l)		
Season	Minimal	Spur	Mean
1994/95	4.96 a	4.58 b	4.77 A
1995/96	4.86 a	4.33 b	4.59 A
1996/97	3.63	3.40	3.52 C
1997/98	3.94 b	4.21 a	4.08 B
1998/99	4.54 a	4.02 b	4.28 B
Mean	4.39 A	4.11 B	
	pH		
Season	Minimal	Spur	Mean
1994/95	3.52 b	3.70 a	3.62 C
1995/96	3.65 b	3.79 a	3.72 AB
1996/97	3.69 b	3.85 a	3.77 A
1997/98	3.70	3.68	3.69 B
1998/99	3.72 b	3.85 a	3.78 A
Mean	3.66 B	3.77 A	

5.1.13 Must and wine quality

Total soluble solids (°Brix) in free-run juice were mostly lower than in juice extracted from berry samples collected in the field (Table 9, Table 10). Acidity tended to be higher and pH tended to be lower in the first 3 seasons but not in the final two seasons when free- run juice and juice from berry samples are compared. Overall, pruning treatments and season had a similar effect on juice quality regardless if juice was free-run or was obtained from berry samples in the field. Acidity of free-run juice was very low in 1998/99 compared with preceding seasons. Therefore 2g of tartaric acid were added to the juice before fermentation. The addition of tartaric acid led to higher wine acidity than would have been expected from previous years when no acid adjustment was carried out (Table 10). Acidity in wine was always higher than acidity in juice from either free-run or berry samples but pH in wine and juice from either free-run or berry samples did not differ greatly. In most seasons wine made from fruit that came from minimal pruned vines had higher acidity and lower pH than wine made from fruit that came from spur pruned vines. This is probably so because berries from minimal pruned vines were smaller than those from spur pruned vines leading to a higher skin to pulp ratio in the former and hence a greater extraction of tartaric acid from the skin during fermentation. Tasting scores for wines that came from either pruning treatment were similar and no seasonal differences were apparent.

Table 10. Total soluble solids (°Brix), total acidity and pH in free-run juice (must) at harvest; tasting score, pH and total acidity of wine made from minimal and spur pruned Cabernet Franc vines at Merbein, Victoria. 'Mean' column headings denote seasonal effects across pruning treatments. 'Mean' row headings denote pruning effects across seasons. Values within 'Mean' columns or rows followed by the same or no capital letter are not significantly different. Values within a row and season followed by a different small cap letter denote significant differences within season due to pruning ($p<=0.05$).

	Brix (must)			Score (wine)		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	25.0 b	27.1 a	26.1 B	13.54	13.04	13.29
1995/96	22.2 b	26.0 a	24.1 D	-.-	-.-	-.-
1996/97	24.3 b	26.7 a	25.5 BC	14.48	14.69	14.59
1997/98	27.3	27.5	27.4 A	14.17	13.77	13.97
1998/99	23.7 b	25.7 a	24.7 CD	14.39	14.72	14.56
Mean	24.5 B	26.6 A		14.14	14.06	
	Acid (must)			Acid (wine)		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	5.99	5.94	5.97 A	6.23 a	5.63 b	5.93 A
1995/96	5.79	4.99	5.39 A	6.00 a	5.51 b	5.75 A
1996/97	3.76	3.72	3.74 B	5.65	5.75	5.70 AB
1997/98	3.29	3.48	3.39 B	5.40	5.33	5.37 B
1998/99*	2.99	3.23	3.11 B	5.95 a	5.53 b	5.74 A
Mean	5.92	5.82		5.85 A	5.55 B	
	pH (must)			pH (wine)		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	3.33 b	3.40 a	3.37 C	3.52 b	3.93 a	3.73 B
1995/96	3.57	3.59	3.58 B	3.58 b	3.83 a	3.71 B
1996/97	3.55	3.61	3.58 B	3.54 b	3.78 a	3.66 B
1997/98	4.02	3.97	4.00 A	3.99	4.09	4.04 A
1998/99*	4.02	4.00	4.01 A	3.35 b	3.52 a	3.44 C
Mean	3.70	3.71		3.60 B	3.83 A	

* In the 1998/99 season 2g/l tartaric acid was added to the must before fermentation

Strong seasonal differences were seen in wine colour density with the highest values being recorded in 1997/98 compared with relatively low values in 1994/95 and 1995/96 (Table 11). Wine made from fruit of minimal pruned vines had a lower colour density than wine made from fruit of spur pruned vines. An exception was the 1997/98 season when minimal pruning resulted in a higher colour density than spur pruning. Colour hue was also lower as a result of minimal compared to spur pruning and again strong seasonal differences with relatively high values in 1997/98 and 1994/95 were found. Anthocyanin levels were not different between seasons but across seasons spur pruning resulted in higher anthocyanin levels than minimal pruning with the exception of the 1997/98 season when both pruning systems were similar. Season also had a strong influence on ionised anthocyanins with low values recorded in the first and second seasons but no influence of pruning system on ionised anthocyanins was apparent. Total phenolics did not differ between pruning system but again there were pronounced seasonal differences.

Most colour related measurements in wine were strongly influenced by seasonal factors. Minimal pruning overall resulted in a reduction in colour density, colour hue and total anthocyanins. Delayed ripening as a result of a higher crop load on minimal as compared to spur pruned vines probably contributed to the reduced levels of colour density, colour hue and total anthocyanins in wine that came from minimal pruned vines.

Table 11. Colour density, colour hue, alpha, total anthocyanins, ionised anthocyanins and total phenolics of wine made from minimal and spur pruned Cabernet Franc vines at Merbein, Victoria. 'Mean' column headings denote seasonal effects across pruning treatments. 'Mean' row headings denote pruning effects across seasons. Values within 'Mean' columns or rows followed by the same or no capital letter are not significantly different. Values within a row and season followed by a different small cap letter denote significant differences within season due to pruning ($p<=0.05$).

	Colour density			Colour hue		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	2.29	2.69	2.49 D	0.84 b	0.94 a	0.89 A
1995/96	1.95 b	2.94 a	2.45 D	0.70	0.74	0.72 B
1996/97	3.66 b	4.52 a	4.09 C	0.71 b	0.78 a	0.75 B
1997/98	7.94 a	7.25 b	7.60 A	0.85	0.89	0.87 A
1998/99	5.80 b	7.60 a	6.70 B	0.62	0.60	0.61 C
Mean	4.33 B	5.00 A		0.74 B	0.79 A	
	Alpha			total Anthocyanins		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	6.07	4.11	5.09 C	403 b	477 a	440
1995/96	9.07	7.13	8.10 B	302 b	501 a	402
1996/97	11.09	9.06	10.08 A	390 b	479 a	435
1997/98	8.58	7.17	7.88 B	473	454	464
1998/99	10.29	9.96	10.13 A	378 b	456 a	417
Mean	9.02 A	7.49 B		389 B	473 A	
	Ionised anthocyanins			Total phenolics		
Season	Minimal	Spur	Mean	Minimal	Spur	Mean
1994/95	24.6	19.9	22.3 C	41.5	41.1	41.3 AB
1995/96	28.4	35.8	32.1 B	27.9 b	36.1 a	32.0 C
1996/97	43.4	43.4	43.4 A	45.5	48.9	47.2 A
1997/98	40.5	32.6	36.6 AB	43.1	38.1	40.6 B
1998/99	38.5	45.7	42.1 A	41.3	41.8	41.6 AB
Mean	35.0	35.5		39.9	41.2	

5.1.14 Leaf gas exchange

In the second and third year of the experiment regular diurnal measurements of leaf gas exchange were made in the field from early morning until late afternoon. Data from different measurements was combined to generate a light response curve of photosynthesis for minimal

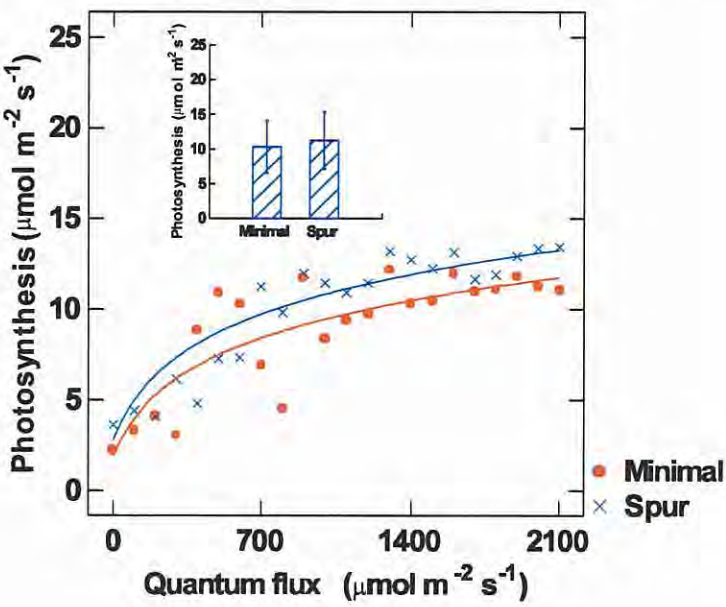

Figure 17. Rate of net photosynthesis in response to quantum flux of leaves from minimal and spur pruned vines. Insert is the mean rate of photosynthesis for minimal and spur pruned vines measured over a number of season.

and spur pruned vines. Figure 17 presents mean values of photosynthesis for the typical range of photon flux densities (PFD). Photosynthesis followed a classical light response curve with

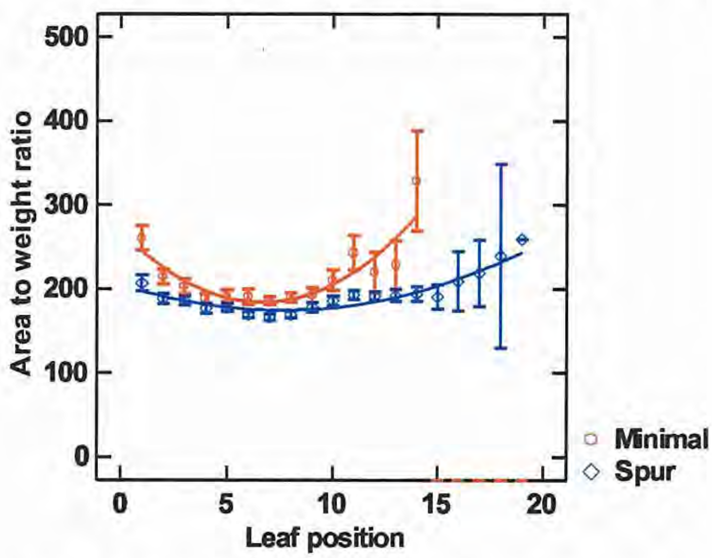

Figure 18. Area to weight ratio as a function of leaf position on shoots of minimal and spur pruned Cabernet Franc vines at Merbein.

an initial steep increase in net photosynthesis toward the compensation point and a further increase towards a saturation point of around 1000 µmol m^{-2} s^{-1} after which there was only a small increase in photosynthesis with quantum flux density. The response curve suggests that leaves of minimal pruned vines had a tendency toward a lower assimilation rate than leaves of spur pruned vines regardless of light intensity. However this difference was never statistically significant (see insert Figure 17). The difference in the rate of photosynthesis between pruning treatments probably resulted from the fact that leaves from spur pruned vines were thicker with a lower area to weight ratio than those from minimal pruned vines. Area to weight ratio is negatively correlated with the chlorophyll content per unit area of leaf. Therefore leaves from spur pruned vines probably had a greater potential for photosynthesis per unit of leaf area than those from minimal pruned vines.

A plot of the area to weight ratio (AWR) of single leaves along a shoot is depicted in Figure 18. The measurement confirms that leaves of spur pruned vines were thicker than those of minimal pruned vines. Leaves of minimal pruned vines always had a higher AWR and therefore were thinner than leaves from spur pruned vines. There was a trend along the shoot with leaves from node positions 6 to 7 having the lowest AWR and increasing values towards either end of the shoot. Differences in AWR between minimal and spur pruning were more apparent at either the proximal or distal end of the shoot.

We also assessed the influence of leaf age on photosynthetic rate in the field (Figure 19). Data from all measurement were pooled to express the rate of photosynthesis as a function of leaf age after unfolding. Only leaves fully exposed to the sun were considered for this function. The rate of photosynthesis was optimal when leaves were around 75 days from unfolding. Leaves that were either younger or older had a lower rate of photosynthesis. Again the rate of photosynthesis was always lower for leaves from minimal compared to spur pruned vines. It is interesting to note that Kriedemann (1970) in a pot experiment had found that leaf photosynthesis reached its optimum much earlier than in the present work, around 30 days from unfolding, and then declined quite steeply. The difference suggests that potted vines behave quite differently to field-grown vines and leaves of field-grown vines obtain their optimum capacity for photosynthesis much later in the season than leaves of potted vines.

Results further suggest that a considerable proportion of leaves would be operating at optimum rates of photosynthesis at around the time of veraison. The age response of photosynthesis seemed to be similar when leaves from minimal and spur pruned vines were compared. Again, the lower capacity for photosynthesis for leaves from minimal compared to spur pruned vines is apparent.

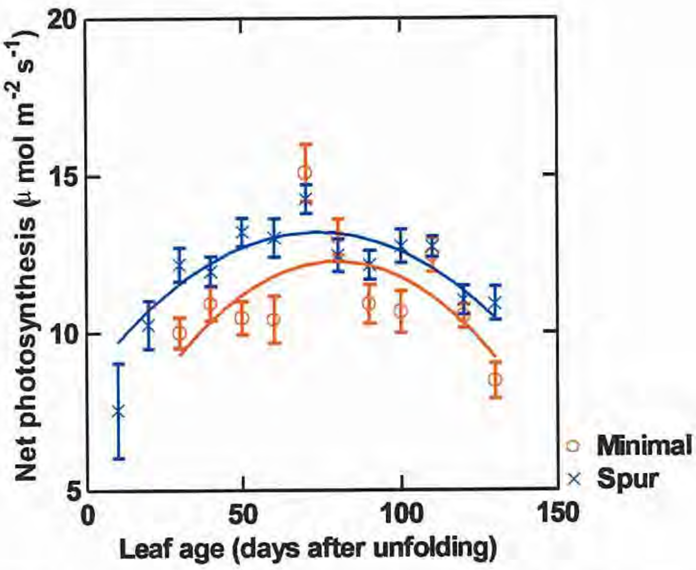

Figure 19. Rate of net photosynthesis of minimal and spur pruned Cabernet Franc as a function of leaf age (days after unfolding). Vertical bars are standard errors.

5.1.15 Water extraction and water use

Vines were irrigated using overhead sprinklers and irrigations were scheduled according to soil moisture level. When vines had depleted around 75% of the plant available soil water irrigation was applied to refill the soil profile to the drained upper limit. The time course of the soil moisture for minimal and spur pruned vines and the lower limit of plant available soil moisture at 20, 40, 60, 80 and 100 cm as well as the amount of irrigation and rainfall is shown in Figure 20 for the growing season of 1995/96. At soil depths of 20 and 40 cm the time course of soil moisture followed a distinct 'zig-zag' pattern due to repeated wetting and drying cycles following irrigation events. At 60 cm soil depth wetting and drying events were less pronounced compared with the 20 and 40 cm soil depths but were still obvious. At 80 and 100 cm no re-wetting after irrigation or rainfall events was apparent except for an initial irrigation in late September. Soil moisture at 60, 80 and 100 cm declined steadily from early October until leaf fall in mid to late May, indicating continuous water extraction. Water content at 60, 80 cm and 100 cm declined from around 30% in early October to just above 20% in late March. No re-wetting after irrigation events was apparent below depths of 60 cm, suggesting that infiltration was insufficient to penetrate beyond 60 – 80 cm or the vines extracted moisture before it reached depths below 60 – 80 cm. There was very little extraction from soil depths below 100 – 120 cm (data not presented) and this agrees with visual observations of rooting depth where few roots were found below 100 cm. After leaf fall there was a sharp increase in soil moisture at all depths after a final irrigation in mid May, indicating that water extraction had ceased. Soil moisture content was frequently lower for minimal than spur pruned vines especially during the early part of the growth period between

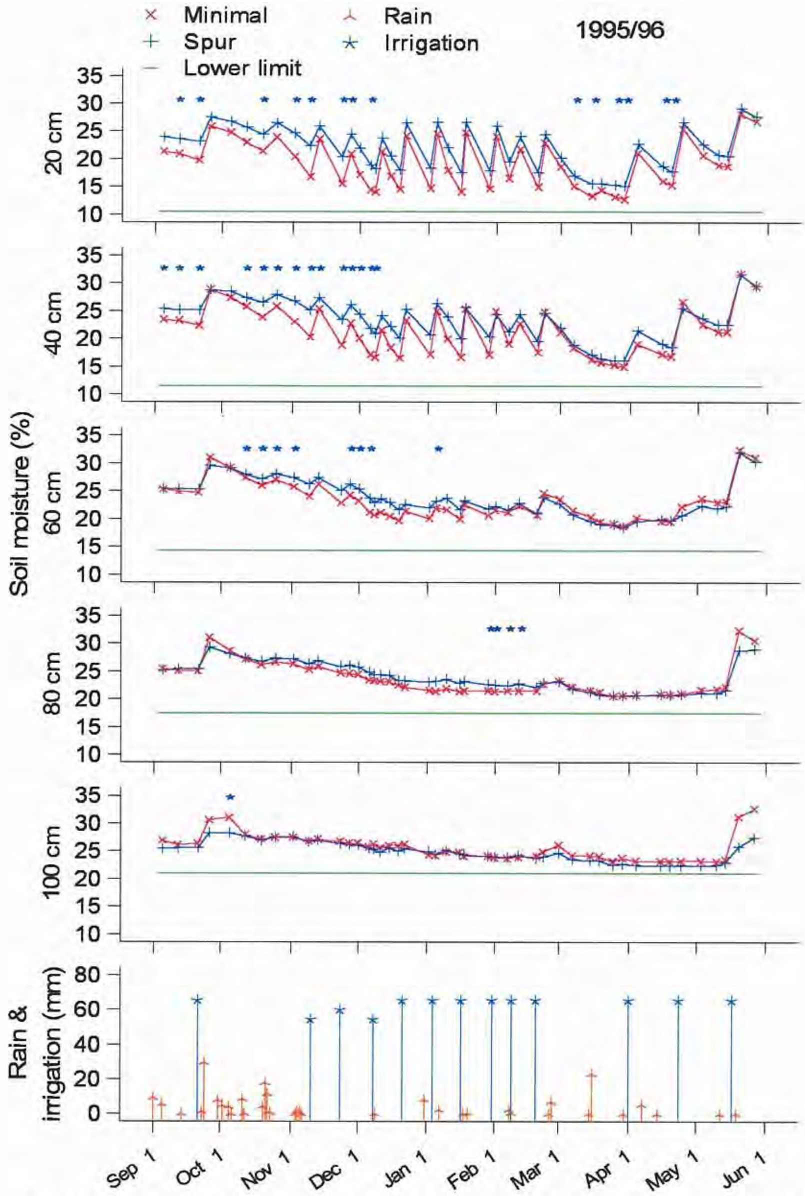

Figure 20. Percent soil moisture at 20, 40, 60, 80 and 10 cm depths during the 1995/96 growth period and amount of irrigation and rainfall. Stars indicate significant differences between pruning treatments (p<=0.05).

early September and late November. Differences between pruning treatments were most apparent at the 20, 40 and 60 cm soil depths. At 80 cm, no differences were observed except for a brief period between late January and early February. At 100 cm there was no difference between pruning treatments except on October 5 when soil moisture was higher in minimal than spur pruned vines. Minimal pruned vines left the soil profile drier than spur pruned vines at soil depths above 60 cm, during and shortly after the period when leaf area expansion was greatest. Below 80 cm soil moisture content was similar for spur and minimal pruned vines suggesting similar water extraction patterns regardless of pruning system. The soil moisture pattern of the 1995/96 season depicted in Figure 20 is typical for other seasons except the first season of 1994/95 when no differences in soil moisture were observed between pruning systems. This suggests that once pruning systems were fully established,

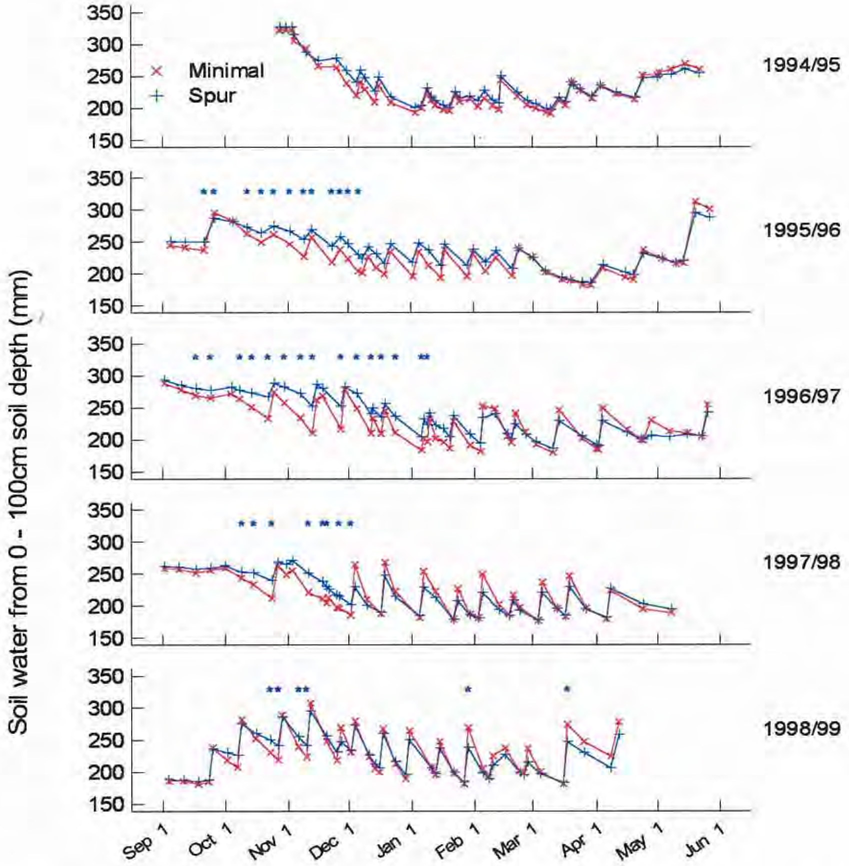

Figure 21. Time course of seasonal soil moisture between 0 – 100 cm soil depth for minimal and spur pruned Cabernet Franc at Merbein between 1994/5 and 1998/99.

after conversion from spur to minimal pruning at the end of the 1994/95 growing season, water extraction patterns remained similar.

The time course of the total amount of moisture stored in the soil profile between 0 and 100 cm is shown in Figure 21 for minimal and spur pruned vines during five growing seasons from 1994/5 to 1998/99. As for soil moisture content at shallow depths, graphs show a typical 'zig-zag' pattern as a result of frequent irrigation events. Soil moisture typically fluctuated between around 300mm in a full profile (drained upper limit) to just below 200mm when the available soil moisture was almost depleted (lower limit). At the beginning of each growing season total moisture was near its maximum because of winter rainfall. The exception was 1998/99 when winter rainfall and hence soil moisture were below average at the start of the growing season and an early irrigation had to be applied to fill the profile to the drained upper limit. The plant available soil moisture to a depth of 100 cm was around 125 mm. Differences in the amount of soil moisture stored between 0 and 100 cm that were attributable to pruning system were observed in every but the first growing season. Differences were only apparent in the early part of the season between late September and late November when vines under minimal pruning always extracted water to a lower level than vines under spur pruning. Differences in water extraction due to pruning coincided with differences in leaf area development between pruning treatments. This indicates that enhanced canopy fill of minimal relative to spur pruned vines during early growth led to greater water extraction in the former until both pruning systems had attained a similar leaf area in mid to late November. In 1994/95 the differences were not as obvious probably because this was the first growing season after vines had been converted from minimal to spur

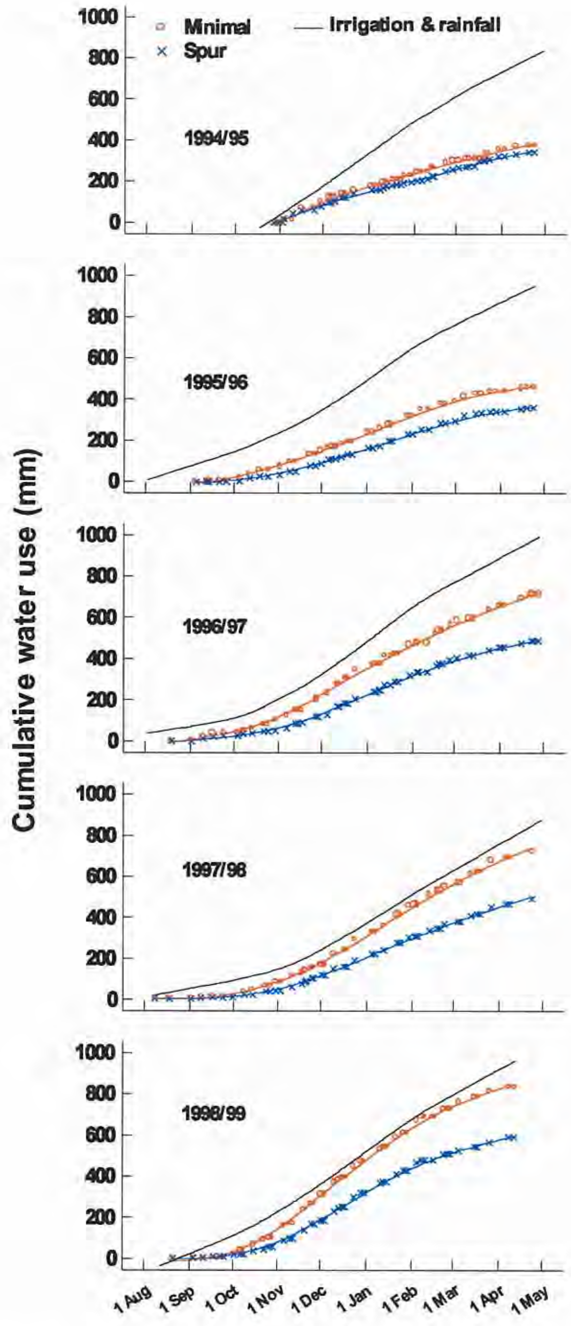

Figure 22. Seasonal cumulative water use of minimal and spur pruned Cabernet Franc from the 1994/95 to the 1998/99 growing seasons.

pruning. Small differences in total soil water between pruning systems were seen in 1998/99 compared with the 3 previous seasons. This was possibly so because of a dry winter resulting in a relatively low soil water storage at the beginning of the growing season. In turn during the early part of the growth period lack of water may have inhibited leaf area expansion and thus total water use of minimal relative to spur pruned vines. As result the observed differences in water extraction were less apparent than would have been expected from previous seasons.

Cumulative water use was calculated by subtracting soil moisture content recorded immediately before from that recorded shortly after an irrigation or significant rainfall event (Figure 22). Values were added for the growing season and represent the components of soil evaporation, drainage and vine transpiration. As expected from the time course of the percentage soil water at different depths (Figure 20) and soil water between 0 and 100 cm depths (Figure 21), more water was extracted by minimal than spur pruned vines. In the first growing season differences were small but in the second and in subsequent seasons water usage was considerably higher under minimal pruning than spur pruning. Differences in accumulated water use were in part due to minimal pruned vines using more water during the early stages of rapid canopy expansion between late September and late November. However there was also more use of water later in the season. The continuous line without symbols represents the amount of water that was received as either irrigation or rainfall. In the 1994/95 and to a lesser extent in the 1995/96 and 1996/97 seasons there was a discrepancy between the amount of water applied as irrigation or received as rain and the cumulative amount of water-use calculated from soil moisture readings. The discrepancy was largely due to the fact that in the first season readings of soil moisture were not always made immediately before or after an irrigation or rainfall event. Therefore not the whole differential in water use between two irrigations was captured and water use appeared to be less than would have been indicated by the irrigation amount. But even when soil moisture readings were taken immediately before or after irrigation there was still a difference between the amount of water applied and that recorded through soil moisture readings. This remaining difference is probably due to run-off or drainage. Soil moisture readings in Figure 20 suggest that there was little drainage out of the soil profile because irrigation applications never appeared to infiltrate beyond a depth of around 80 cm. Therefore, the remaining differential between the amount of water applied and that recorded as soil moisture was mostly the result of surface run-off.

5.2 Mt Helen site

5.2.1 Phenological records

Table 12 lists the main phenological dates. The latest bud burst occurred in year 1 and the earliest in year 2, a difference of one month. The start of flowering varied by 10 days and its duration was approximately one week. The length of time between bud burst and flowering varied from 42 days in year 1 to 77 days in year 2. Veraison varied by 22 days but the variation in length of time between the end of flowering and veraison was only 14 days. The harvest date varied by a month however, harvest was not based on a maturity index (eg. Brix) but rather the harvesting of the entire block by the vineyard manager. Average soluble solids (Brix) at harvest are indicated but it should be noted that there was considerable variation between treatments (see later). The highest harvest Brix (year 4) corresponded with the earliest harvest date (and earliest veraison date) and the equal lowest Brix (year 3) corresponded with the second latest harvest date and the latest veraison date.

Table 12. Phenological dates for Pinot Noir vines at Mt Helen, Victoria between 1994/95 and 1998/99.

	Bud burst (50%)	Flowering duration	Veraison (50%)	Harvest	Harvest (Brix)
1994/95	13 Oct	2 Dec - 9 Dec	7 Feb	15 Mar	21.2
1995/96	13 Sep	30 Nov - 7 Dec	8 Feb	8 Apr	22.8
1996/97	25 Sep	5 Dec - 12 Dec	20 Feb	10 Apr	21.2
1997/98	24 Sep	25 Nov - 4 Dec	29 Jan	12 Mar	23.9
1998/99	24 Sep	3 Dec - 10 Dec	15 Feb	23 Mar (SH)	23.5
				12 Apr (MP)	22.5

5.2.2 Vegetative growth

5.2.2.1 Leaf appearance and shoot growth

Leaf appearance rate was similar between minimal pruned and Scott Henry trained vines until about 400 DDT when the rate of leaf emergence in minimal pruned vines declined rapidly compared with Scott Henry vines, however leaf appearance ceased at similar DDT (Figure 23). Differences in shoot growth rates became apparent before differences in leaf emergence. Shoots stopped growing at similar DDT between treatments except for year 2, when Scott Henry trained vines continued to grow although this growth may not have been on the main shoot.

Final leaf number on the main shoot and total shoot length were consistently less on minimal pruned compared with Scott Henry trained vines. Shoot length was approximately reduced by 50 % on minimal pruned vines but leaf number was only reduced by 25%. Internode distance was therefore also reduced on the minimal pruned vines. There was no effect of irrigation or crop load.

5.2.2.2 Leaf size

Large differences in the area of individual leaves along the shoot were observed between minimal pruned and Scott Henry trained vines (Figure 24). Leaves on shoots from minimal pruned vines were always much smaller than those from Scott Henry trained vines. The size of the leaves increased steeply with leaf position, reaching a maximum at leaf 6 for Scott Henry and leaf 4 for minimal pruning respectively. Beyond those positions leaf size declined on both pruning system.

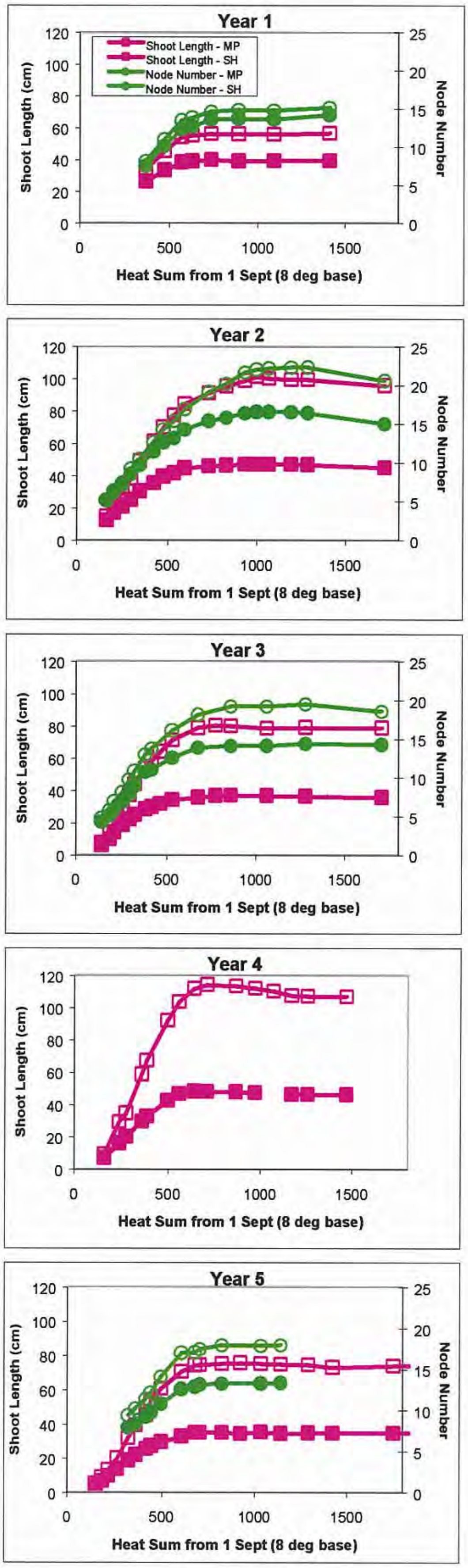

Figure 23. Average shoot length and node number on main shoots for minimal pruned and Scott Henry vines at Mt Helen, Victoria.

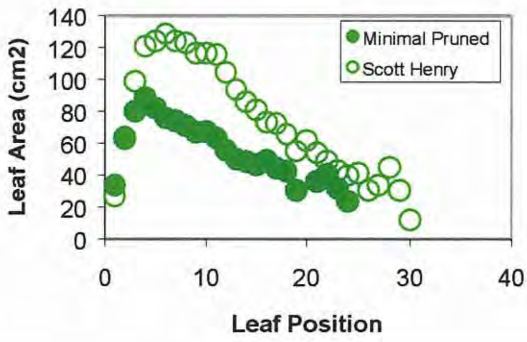

Figure 24. Individual leaf area as a function of leaf position for minimal pruned and Scott Henry vines in year 3 at Mt Helen, Victoria.

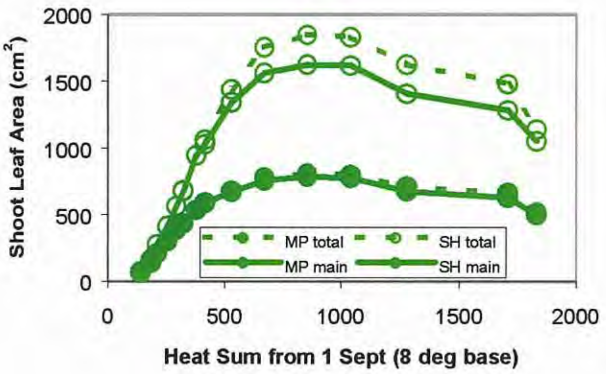

Figure 25. Main and total (including laterals) shoot leaf area as a function of heat sum for minimal pruned and Scott Henry vines in year 3 at Mt Helen, Victoria.

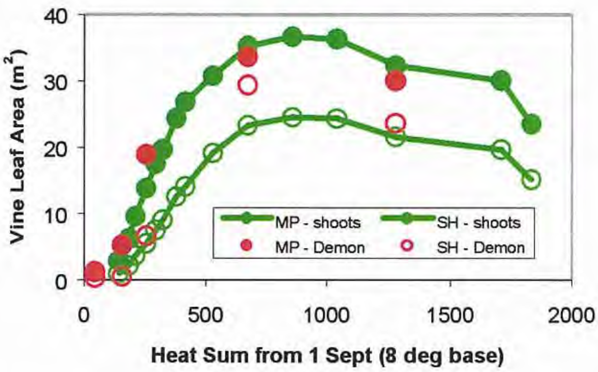

Figure 26. Total vine leaf area determined from shoot measurements and the Demon as a function of heat sum for minimal pruned and Scott Henry vines in year 3 at Mt Helen, Victoria.

5.2.2.3 Leaf area per shoot

Total leaf area per shoot was much larger for Scott Henry trained vines than minimal pruned vines (Figure 25 – year 3). The contribution from leaves arising from lateral shoots was approximately 15% for Scott Henry and was negligible for minimal pruned vines. There was very little leaf area developed after main shoots had stopped growing. Leaf area started to decline by the end of January due to basal leaf senescence.

5.2.2.4 Leaf area per vine

Estimates of leaf area per vine (Table 13) were calculated from main shoot length (Figure 23) and shoot number per vine for all years. Vine leaf area of minimal pruned vines was almost double that of Scott Henry for years 1 to 3. Differences were less in year 5 due to more shoots per vine in Scott Henry. Leaf area per vine was probably greater in Scott Henry vines because lateral leaves were not included (Table 13).

In year 3, more accurate estimates of total vine leaf area were taken by measuring leaf length of all leaves on a population of shoots (Figure 26). Leaf area was approximately 50% greater in minimal pruned vines. Indirect estimates of leaf area per vine based on the Demon instrument were similar to estimates based on leaf length measurements of a sample population of shoots (Figure 26). Higher leaf area per vine in minimal pruned vines was due to more buds and hence shoots per vine which more than compensated for less leaf area per shoot.

Table 13. Shoot number and maximum vine leaf area (estimated from main shoot length and shoot number) for Pinot Noir vines at Mt Helen, Victoria between 1994/95 and 1998/99.

	Minimal Pruned		Scott Henry	
	Shoot Number per Vine	Maximum Vine Leaf Area (m^2)	Shoot Number per Vine	Maximum Vine Leaf Area (m^2)
1994/95	368	31.8	166	16.3
1995/96	505	49.0	136	23.8
1996/97	452	34.7	133	18.6
1997/98	512	52.4	171	33.7
1998/99	438	32.5	208	27.0

5.2.2.5 Canopy surface area

Canopy surface area was similar between minimal pruned and Scott Henry vines at flowering (Table 14). After lifting and separating the foliage, canopy surface area was much higher in Scott Henry than minimal pruned vines.

Table 14. Canopy surface area in square metres (estimated from canopy height and width) close to flowering and post-veraison for Pinot Noir vines at Mt Helen, Victoria between 1994/95 and 1998/99.

	Minimal Pruned		Scott Henry	
	Approx. at Flowering	Post-Veraison	Approx. at Flowering	Post-Veraison
1994/95	5.2	4.9	5.6	6.5
1995/96	5.2	5.3	4.3	7.0
1996/97	5.8	5.5	5.0	7.4
1997/98	5.8	6.9	5.8	9.2
1998/99	5.4	6.4	4.5	8.6

5.2.2.6 Shoot dry matter partitioning

Shoot dry matter accumulation at distinct developmental events and the partitioning of shoot dry matter into stem leaf and fruit is depicted in Figure 27 for year 2. Total dry matter per shoot was much lower in minimal pruned vines compared with Scott Henry largely due to lower leaf and stem dry matter in the former. However, annual total dry matter per vine was much lower on Scott Henry vines due to lower fruit dry matter. As a proportion of the total, fruit dry weight was larger in minimal pruned vines. During the season fruit dry weight increase dramatically post-set.

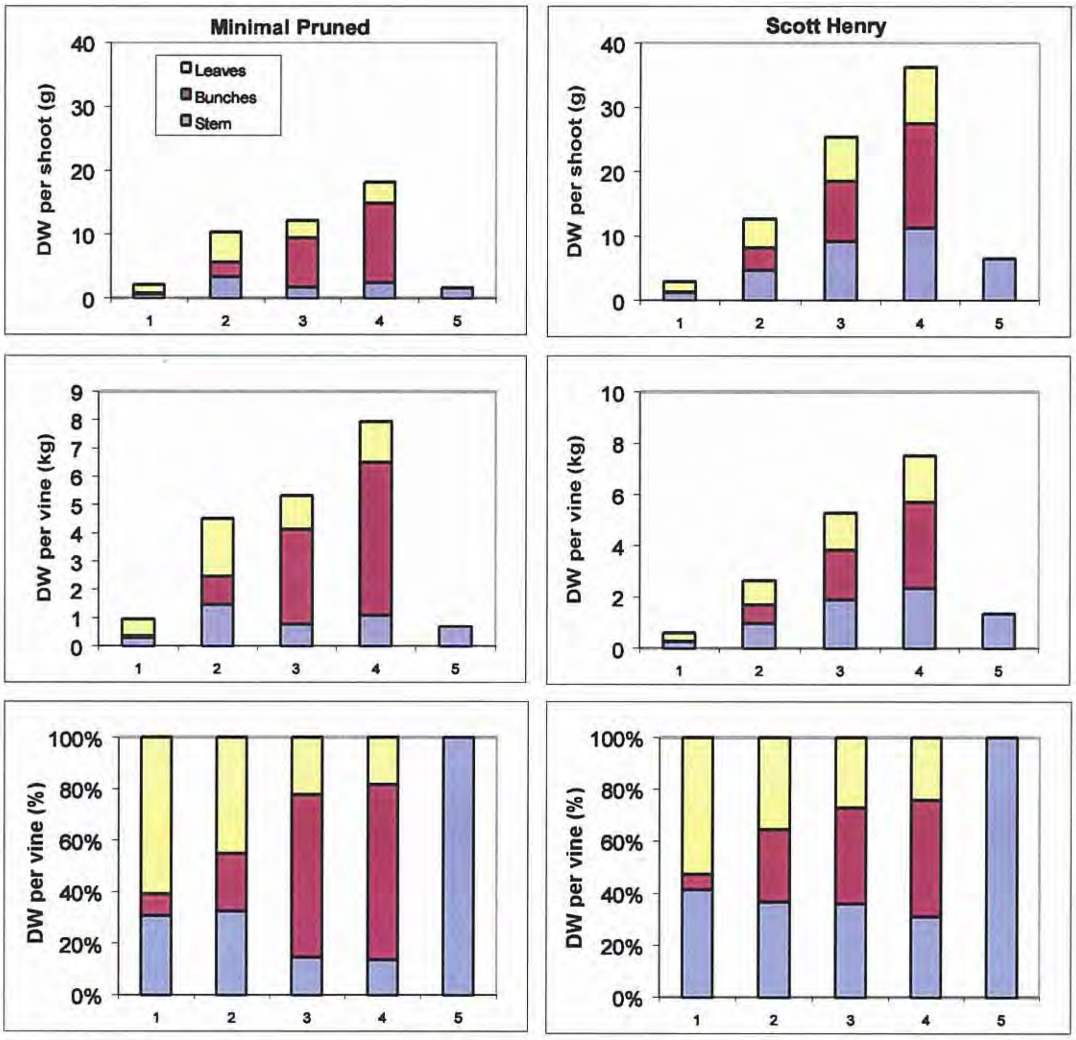

Figure 27. Dry weight of leaves, fruit and stems per shoot and per vine at; (1) 3 weeks pre-flowering, (2) midway between flowering and veraison, (3) at veraison, (4) at harvest and (5) at leaf fall, for minimal pruned and Scott Henry vines in year 2 at Mt Helen, Victoria.

5.2.2.7 Seasonal changes in berry fresh and dry weight

The pattern of berry fresh weight growth was double sigmoid showing an initial rapid growth followed by a lag in growth then a period of rapid growth and finally a period of no growth or a slight decline in berry fresh weight. The rate of change in fresh weight varied between years. For example, in year 5 after the lag, berry fresh weight increased at a much slower rate than in other years. The pattern of changes in berry dry weight was not the same as that in fresh weight. Initially there was a period of slow dry weight accumulation until the end of the lag in fresh weight growth, when dry weight increased rapidly to a maximum corresponding to the end of fresh weight growth.

Comparisons between treatments indicated a consistent decline in berry fresh weight in minimal pruned vines for years 3 to 5 (Figure 28). Differences were obvious well before veraison and probably occurred following berry set. Differences in dry weight between minimal pruned and Scott Henry vines were similar to fresh weight. Within each pruning treatment there was no consistent effect of bunch thinning on berry fresh or dry weight. There was however a difference between irrigation treatments. Berry fresh weight was consistently higher in all years in the minimal pruned Full treatment compared to the minimal pruned Deficit treatment (Figure 29). These differences occurred well before veraison. Differences in berry fresh weight between irrigation treatments in Scott Henry vines were not as marked as in minimal pruned vines probably due to the higher leaf area and water use in minimal pruned vines early in the growing season. Differences in berry dry weight between irrigation treatments within each pruning treatment were similar to fresh weight (Figure 30). Berry dry weight was consistently less in minimal pruned Deficit treatment however the differences were obvious only after veraison.

5.2.2.8 Seasonal changes in berry composition

There were no consistent differences in berry juice TTA or pH between minimal pruned and Scott Henry trained vines although in year 1 pH appeared to be higher in minimal pruned vines (Figure 31). In year 3 and 5 the concentration of berry juice soluble solids (Brix) in Scott Henry trained vines was higher at each sampling date despite an increase in berry fresh weight. In year 1, when yields were similar between minimal pruned and Scott Henry vines, the opposite was found. In year 5 harvest of minimal pruned vines was delayed until Brix was similar. There were no consistent effects of fruit thinning on berry composition, however, there were differences between irrigation treatments. Overall the Full treatment showed higher TTA, lower pH and lower soluble solids. In the minimal pruned Full treatment TTA was consistently higher, pH tended to be lower and the concentration of berry juice soluble solids (Brix) was higher in years 3 to 5 (Figure 32, Figure 33, Figure 34). In the Scott Henry Full treatment there were no differences in TTA in years 2 and 4 pH tended to be lower but there were no differences in the concentration of berry juice soluble solids (Brix), apart from year 1 when the Full treatment was lower which may have been due to the higher crop load.

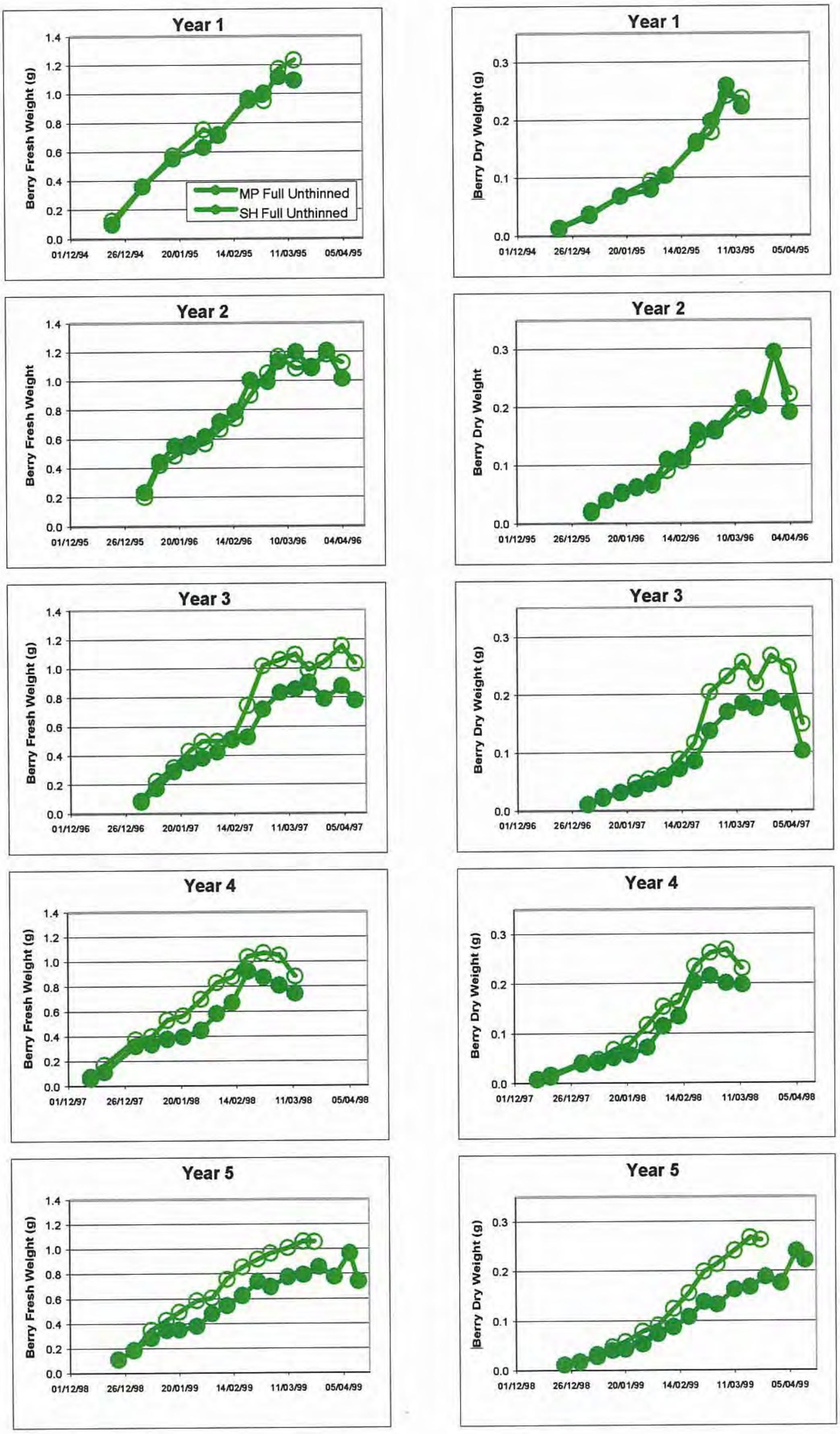

Figure 28. Berry fresh and dry weight as a function of time during the season for minimal pruned and Scott Henry vines at Mt Helen, Victoria.

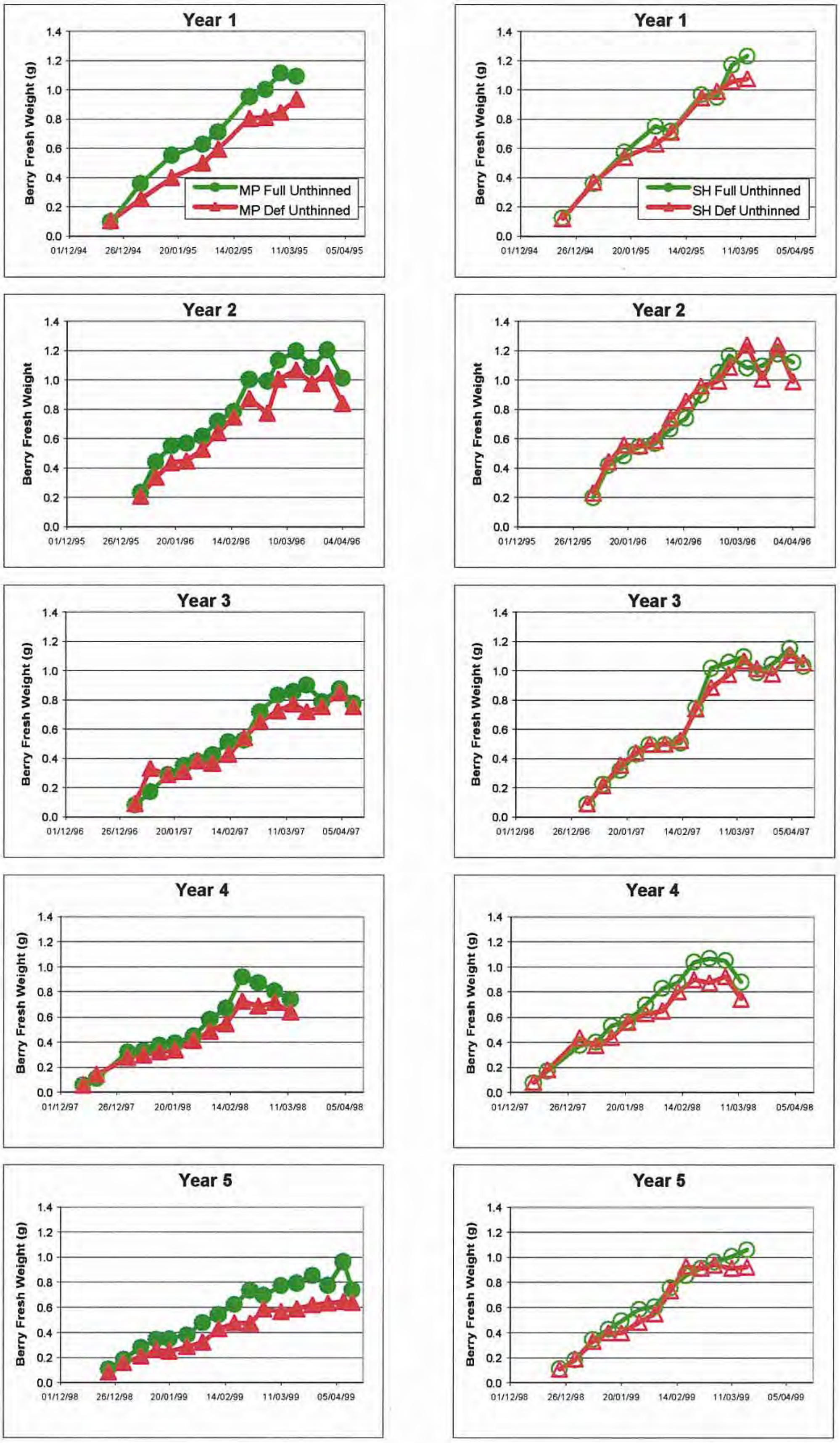

Figure 29. Berry fresh weight comparing Full and Deficit treatments as a function of time during the season for minimal pruned and Scott Henry vines at Mt Helen, Victoria.

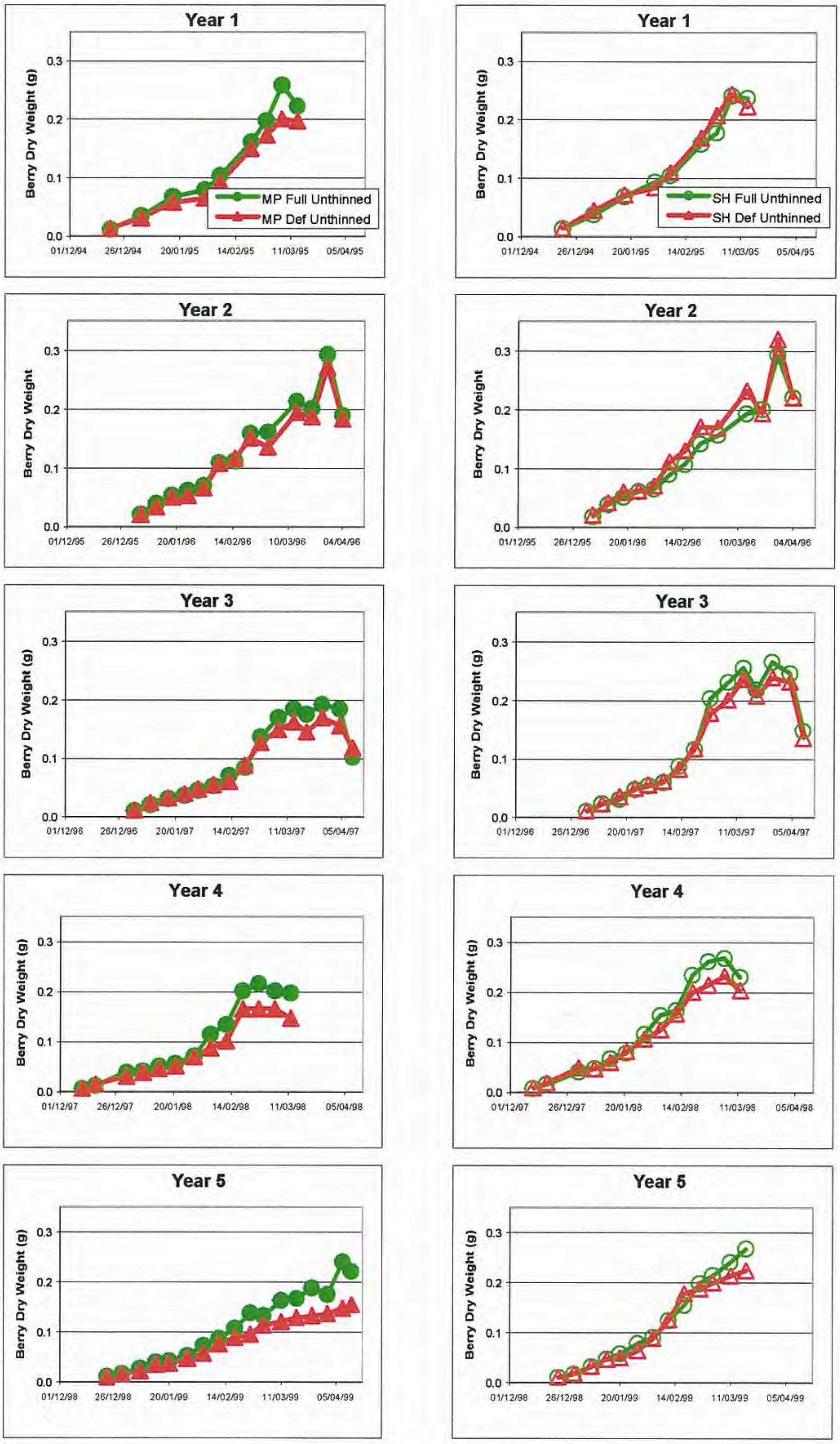

Figure 30. Berry dry weight comparing Full and Deficit treatments as a function of time during the season for minimal pruned and Scott Henry vines at Mt Helen, Victoria.

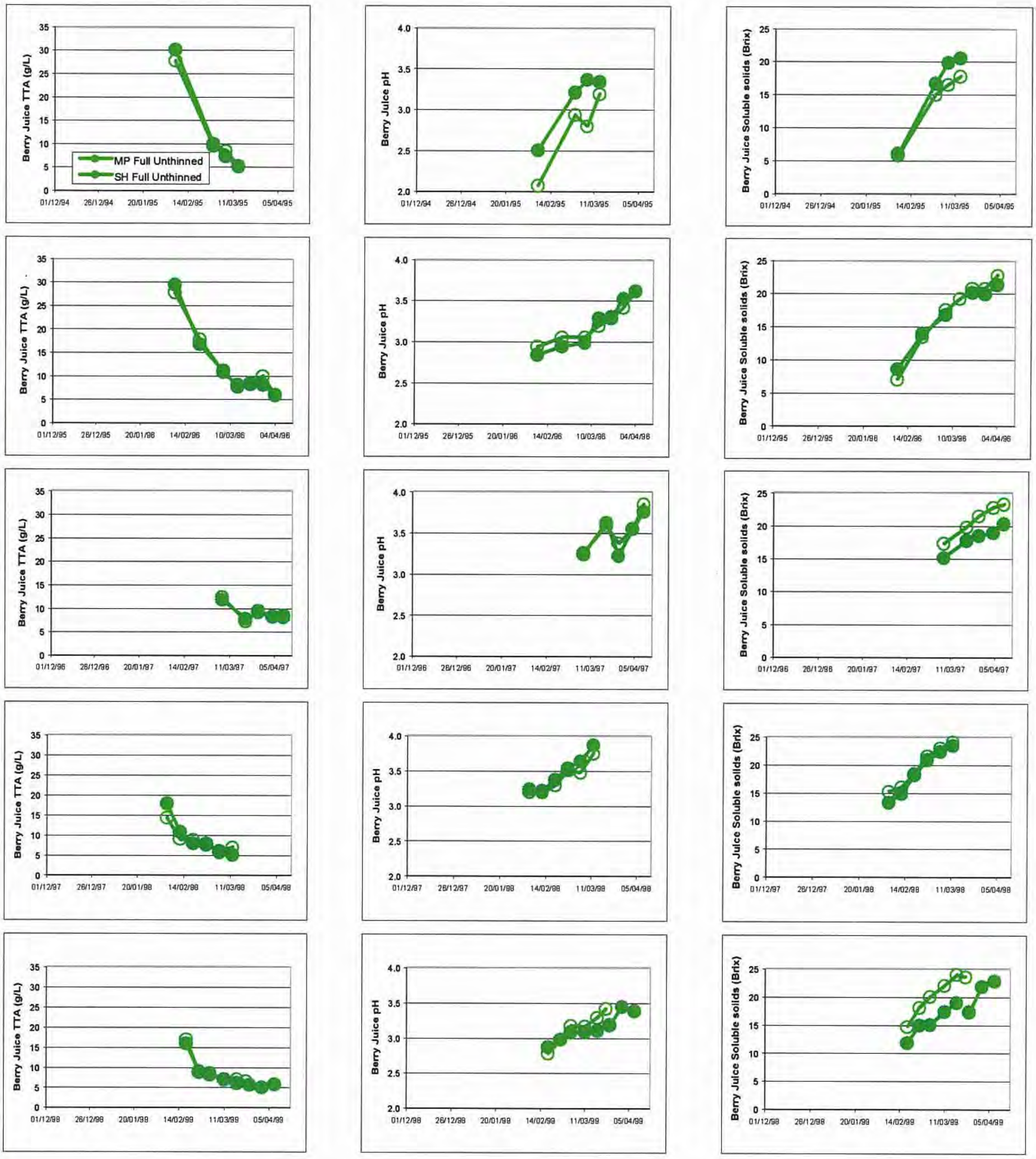

Figure 31. Berry juice total titratable acid (TTA), pH and soluble solids (Brix) comparing minimal pruned and Scott Henry vines as a function of time during the season at Mt Helen, Victoria.

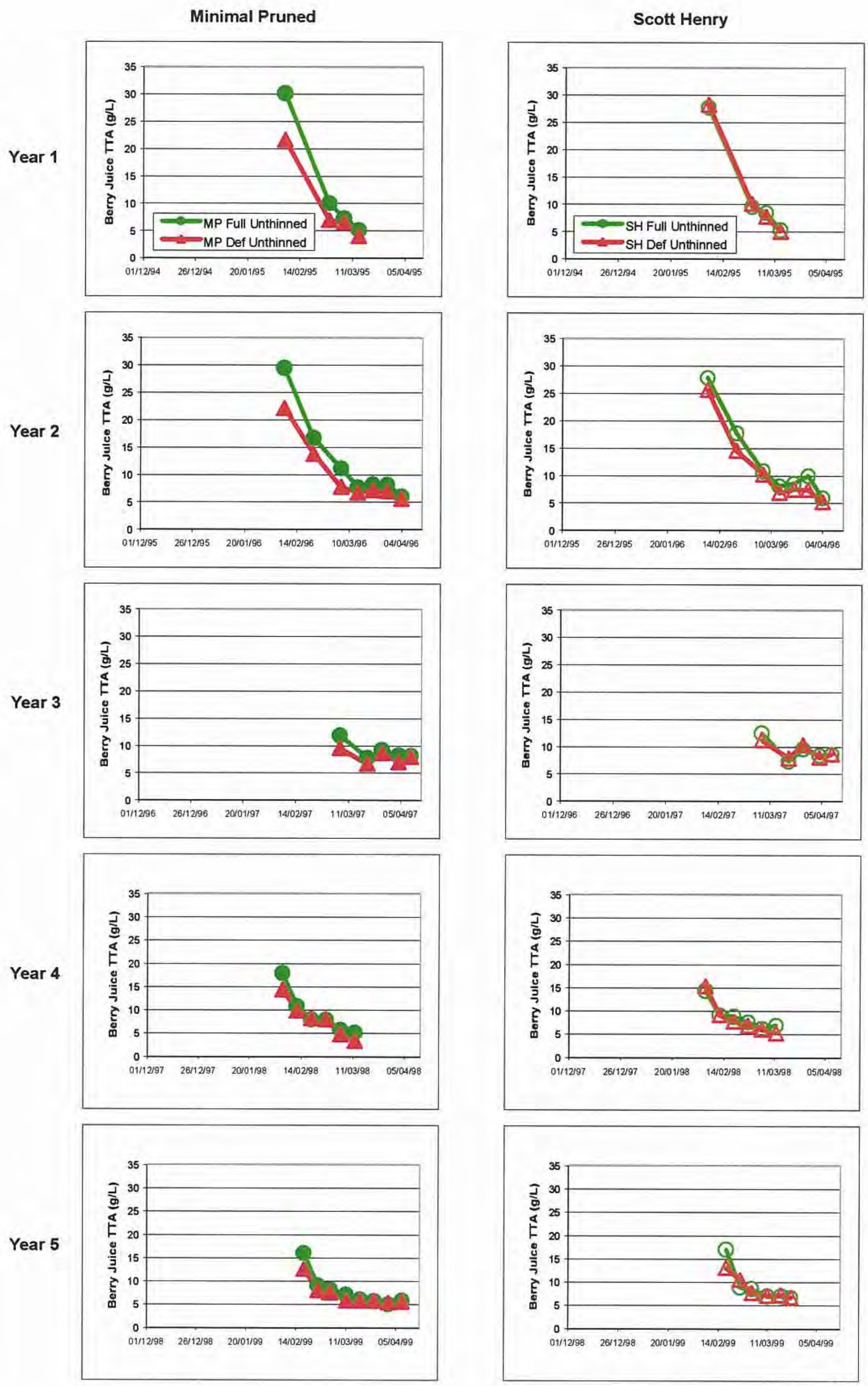

Figure 32. Berry juice total titratable acid (TTA) comparing Full and Deficit treatments as a function of time during the season for minimal pruned and Scott Henry vines at Mt Helen, Victoria.

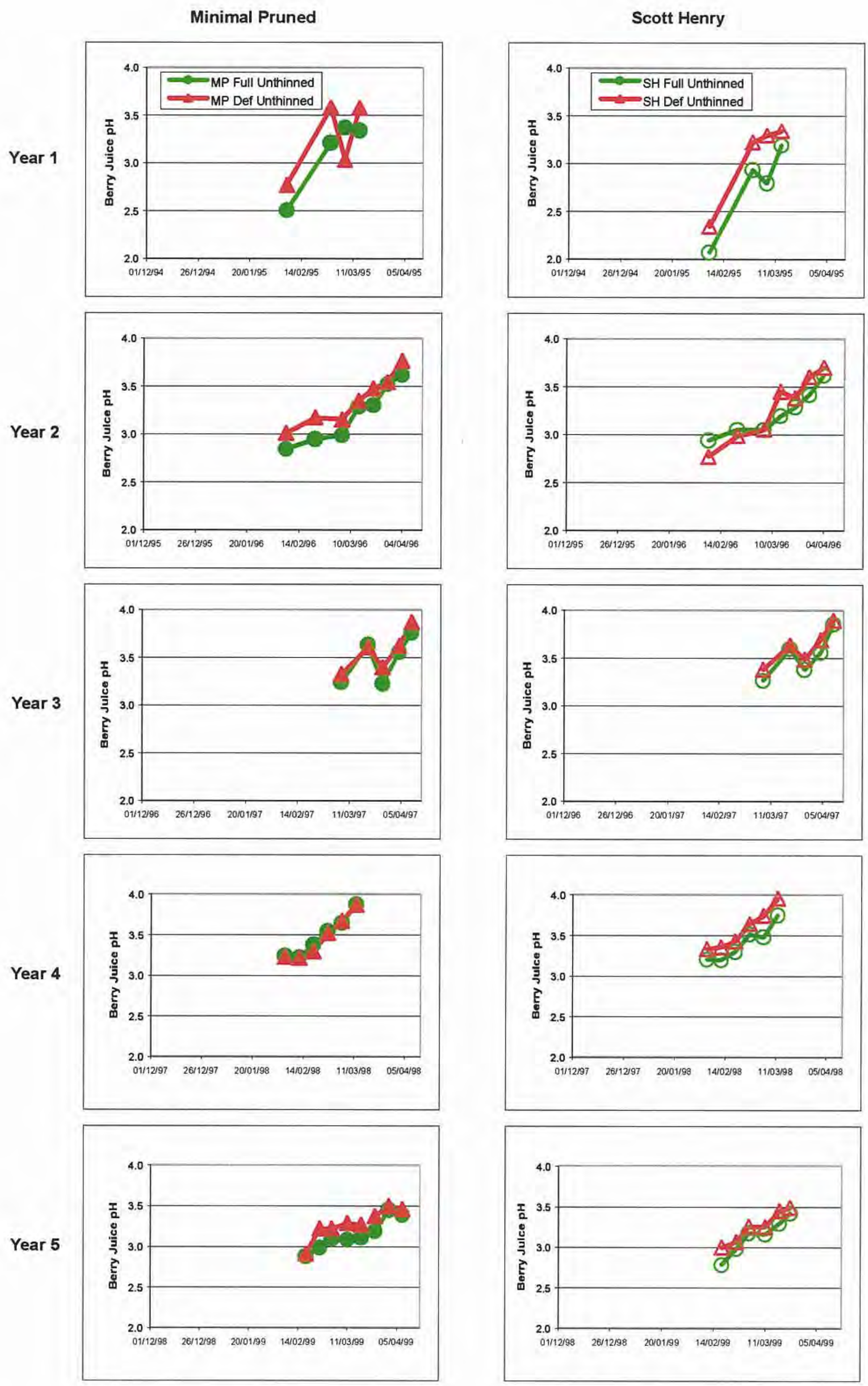

Figure 33. Berry juice pH comparing Full and Deficit treatments as a function of time during the season for minimal pruned and Scott Henry vines at Mt Helen, Victoria.

Year 1

Year 2

Year 3

Year 4

Year 5

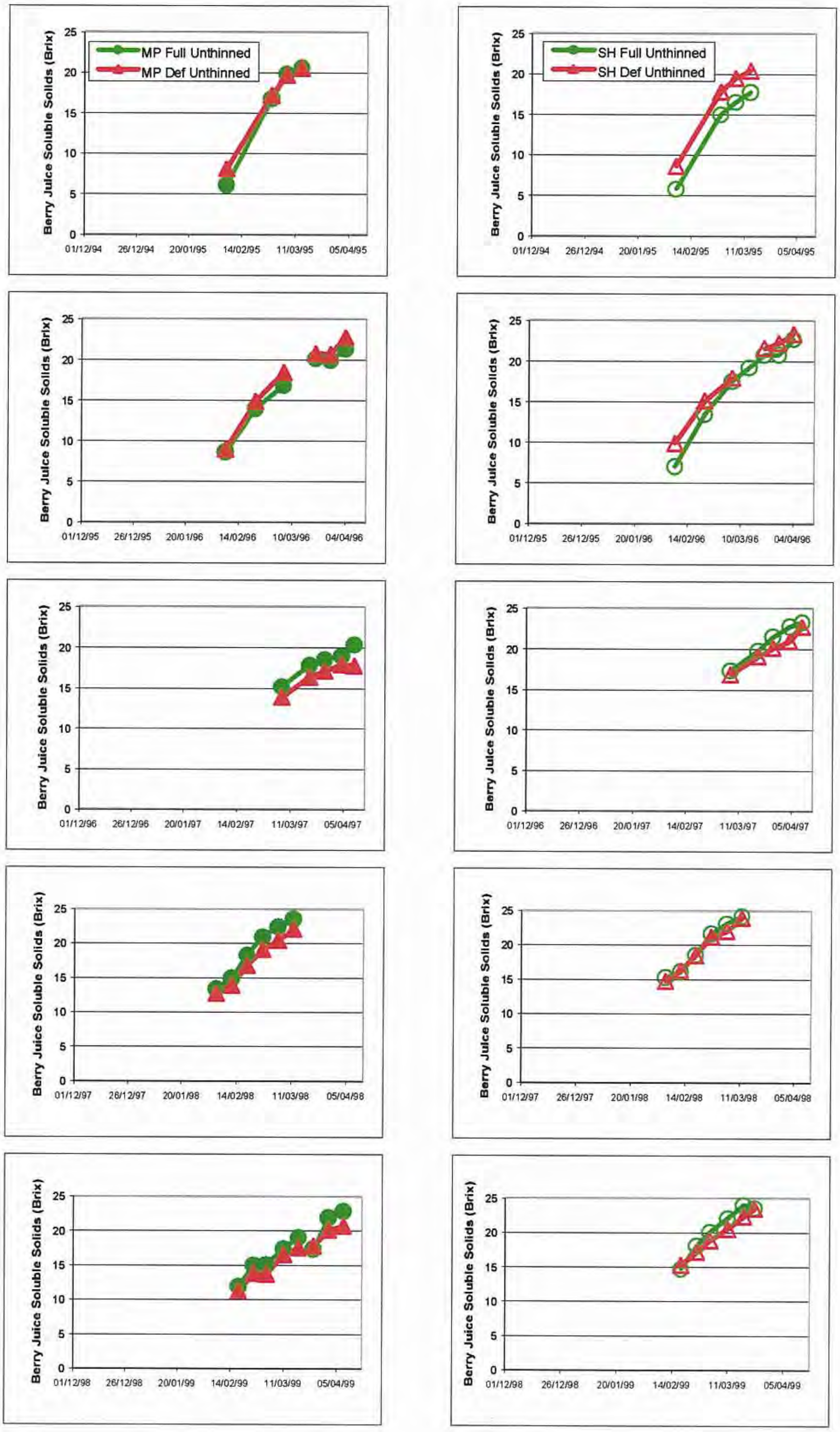

Figure 34. Berry juice soluble solids (Brix) comparing Full and Deficit treatments as a function of time during the season for minimal pruned and Scott Henry vines at Mt Helen, Victoria.

5.2.2.9 Yield and yield components

Average total yield over the 5 years indicated a 30% increase in minimal pruned vines compared with Scott Henry trained vines across both irrigation and thinning treatments (Table 15). In year 1 there were no differences in yield between pruning treatments. Deficit irrigation reduced yield although the reduction was greater in minimal pruned vines compared with Scott Henry trained vines. The yield reduction from the Deficit treatment was attributed to a lower berry weight. Bunch thinning reduced yield by the proportion of bunches thinned – there was no compensatory berry growth or increase in fruitfulness.

Table 15. Harvest yield (kg per vine) for Pinot Noir vines at Mt Helen, Victoria between 1994/95 and 1998/99.

Year	Minimal Pruned				Scott Henry			
	Deficit		Full		Deficit		Full	
	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned
1994/95	13.3	7.0	16.1	7.6	11.9	7.9	16.9	11.4
1995/96	7.5	6.9	11.0	9.8	4.5	5.0	8.1	4.0
1996/97*	15.1	14.7	15.8	12.2	6.5	7.7	7.0	7.4
1997/98	10.2	8.3	10.2	8.7	6.9	6.6	9.7	4.3
1998/99	13.2	7.0	16.3	10.4	7.1	6.0	11.1	7.3
Average	11.9	8.8	13.9	9.7	7.4	6.6	10.6	6.9
(t/ha)	(17.8)	(13.2)	(20.8)	(14.5)	(11.1)	(9.9)	(15.9)	(10.3)

* no thinning was undertaken in 1996/97

Bunch number per vine was consistently higher in minimal pruned vines although in year 1 bunch number was only marginally higher in minimal pruned vines (Table 16). Bunch number from thinning was less each year apart from year 2 and 3 when there was no thinning. Thinning in year 1 may have increased fruitfulness the following season although this was not observed in year 3 or 5.

Table 16. Bunch number per vine for Pinot Noir vines at Mt Helen, Victoria between 1994/95 and 1998/99.

Year	Minimal Pruned				Scott Henry			
	Deficit		Full		Deficit		Full	
	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned
1994/95	289	166	286	161	166	107	212	146
1995/96	192	205	234	243	86	94	117	71
1996/97*	433	406	434	313	139	172	163	170
1997/98	233	180	225	186	120	105	136	74
1998/99	472	272	459	260	165	134	196	141
Average	324	246	328	233	135	122	165	120

* no thinning was undertaken in 1996/97

Bunch weight was consistently less each year in minimal pruned vines (Table 17). Bunch thinning did not affect bunch weight. Deficit irrigation consistently reduced bunch weight in minimal pruned vines but not in Scott Henry trained vines.

Table 17. Average bunch weight (g) for Pinot Noir vines at Mt Helen, Victoria between 1994/95 and 1998/99.

	Minimal Pruned				Scott Henry			
Year	Deficit		Full		Deficit		Full	
	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned
1994/95	46.0	42.2	55.0	48.0	69.6	73.5	80.9	78.3
1995/96	39.7	33.3	44.6	39.0	51.9	53.3	66.5	57.2
1996/97*	34.9	36.1	37.4	39.3	46.5	44.7	43.0	44.7
1997/98	43.4	47.3	46.3	48.0	57.1	62.5	72.5	57.5
1998/99	27.9	25.7	36.7	40.6	42.3	44.4	56.4	52.0
Average	38.4	36.9	44.0	43.0	53.5	55.7	63.9	57.9

* no thinning was undertaken in 1996/97

Berry number per bunch was calculated from average bunch weight and harvest berry fresh weight (Table 18). In years 1 and 2 there were fewer berries per bunch in minimal pruned vines compared with Scott Henry. In years 3 to 5 the differences between minimal pruned vines and Scott Henry were inconsistent. There was no effect of thinning or irrigation treatment on berry number per bunch.

Table 18. Average berry number per bunch calculated from bunch weight and berry weight for Pinot Noir vines at Mt Helen, Victoria between 1994/95 and 1998/99.

	Minimal Pruned				Scott Henry			
Year	Deficit		Full		Deficit		Full	
	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned	Unthinned	Thinned
1994/95	49.1	42.0	50.4	42.4	66.4	60.5	63.4	66.0
1995/96	47.1	39.1	44.9	41.5	51.6	51.8	58.0	51.9
1996/97*	46.4	51.2	48.1	48.1	41.7	44.9	41.0	43.4
1997/98	67.3	78.4	62.0	65.6	70.9	74.5	83.8	64.9
1998/99	45.3	35.9	39.6	46.6	48.1	48.6	51.9	55.6
Average	51.0	49.3	49.0	48.8	55.7	56.0	59.6	56.3

* no thinning was undertaken in 1996/97

5.2.2.10 Soil moisture monitoring

Soil moisture measurements (neutron probe) at 20, 40, 60, 80, 100 and 140 cm depth directly under the dripper, 45 cm from dripper and mid row for pruning and irrigation treatments for year 3 are shown in Figure 35. Changes in soil moisture were greatest at 20 cm depth. Mid row changes in soil moisture were notably high at 20 cm depth probably due grass water use. Changes in soil moisture mid row below 20 cm were still relatively high but were less than directly under the dripper indicating some water extraction mid row at depth. Irrigation generally wetted the soil to 80 cm depth and 45 cm width from the dripper.

Soil moisture was consistently higher directly under the dripper and at 45 cm from the dripper, at all depths in the Full treatments of both pruning treatments. Soil moisture at 20 and 40 cm depth mid row was similar between irrigation treatments but below 40 cm depth, Full treatments had higher soil moisture levels. This suggests that grass water extraction mid row to 40 cm depth probably accounted for the majority of soil moisture changes as irrigations did not extend to mid row. Below 40 cm mid row changes in soil moisture were probably from vine water extraction.

Changes in soil water content decreased with depth and distance from the dripper, however, in the deficit treatment changes in soil water content for the season were similar from 40 to 140cm depth. The pattern of soil water content altered during the season in the deficit treatment. At 20 and 40 cm depth soil water content decreased to a minimum towards the end of December. At greater depths changes in soil water content did not occur until January or later. This indicates an alteration in the pattern of water extraction with both depth and position from the vine

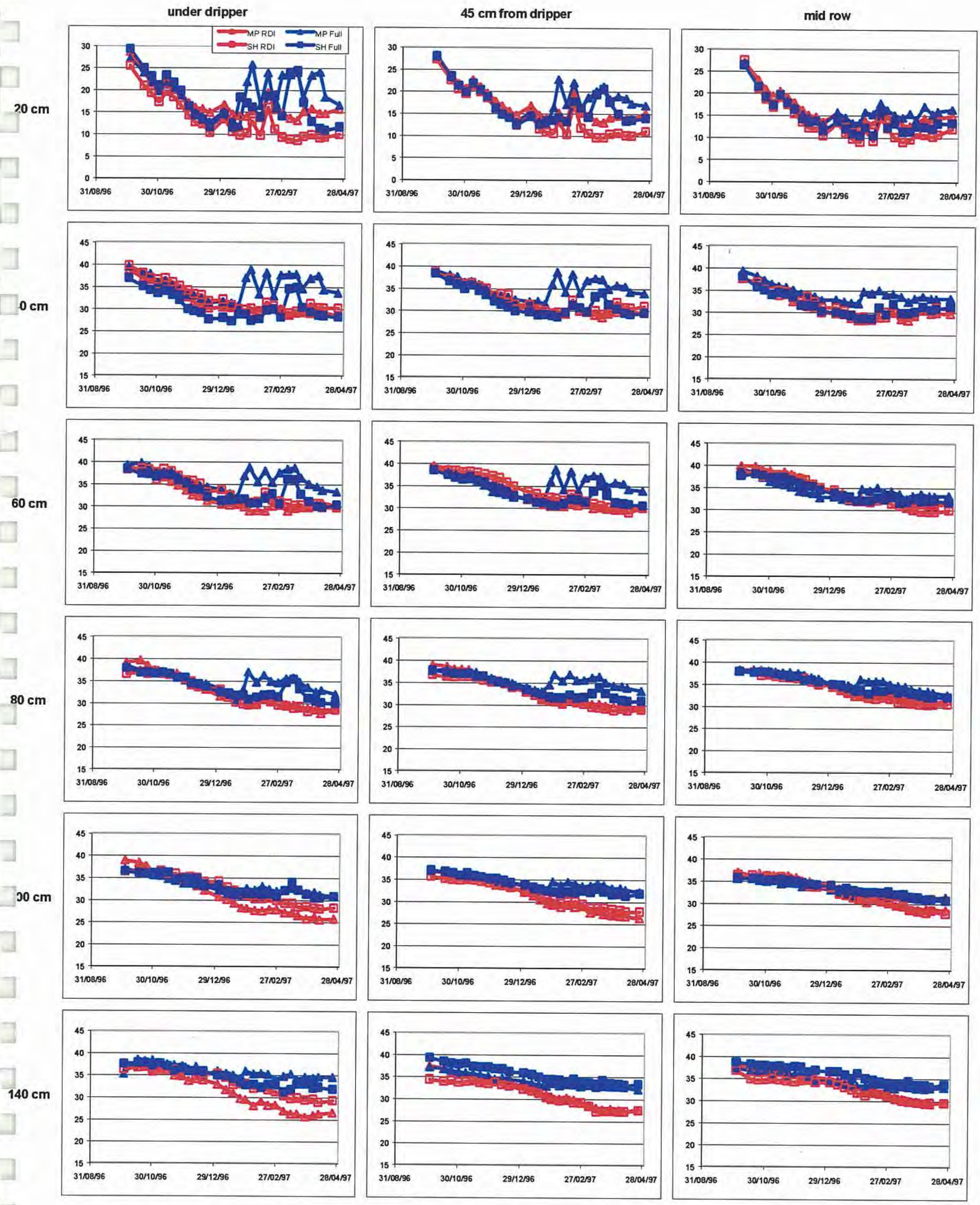

Figure 35. Soil water content (%v/v) measured with a neutron probe comparing Full and Deficit treatments in minimal pruned and Scott Henry vines in year 3 at Mt Helen, Victoria.

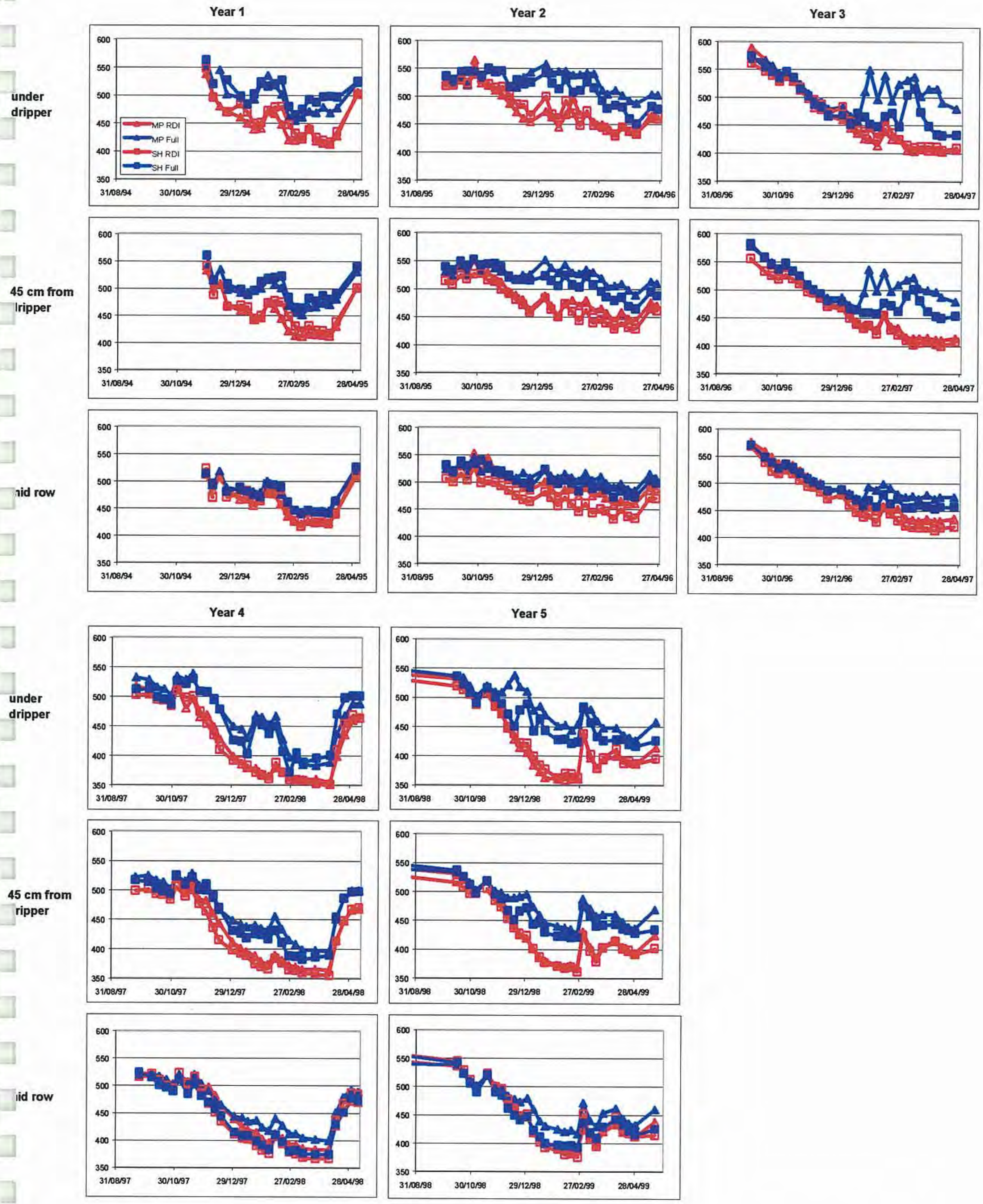

Figure 36. Total soil water content to 160 cm depth (mm) measured with a neutron probe comparing Full and Deficit treatments directly under dripper, 45 cm from dripper and mid row in minimal pruned and Scott Henry vines at Mt Helen, Victoria.

Total water content to 160 cm depth at each position in relation to the emitter is shown in Figure 36. Within each year there was a similar pattern of change in soil water content for the Deficit treatments at each position although in mid row the magnitude of the change was less. This result supports the suggestion that inter-row water use could be substantial from a combination of cover crop and vine water use.

In all years the Full treatment at each position, apart from year 4 and 5 mid row, had the highest total soil water content. In year 2 the water content was higher in all treatments compared with other years and in year 4 and 5 water content was lower in both the Full and Deficit treatments compared with other years. The Full treatment did not maintain a constant soil water content to 160 cm depth during the season at any position although in year 2 moisture was relatively constant until late February.

Soil moisture data from the EnviroScan supported the above findings from the neutron

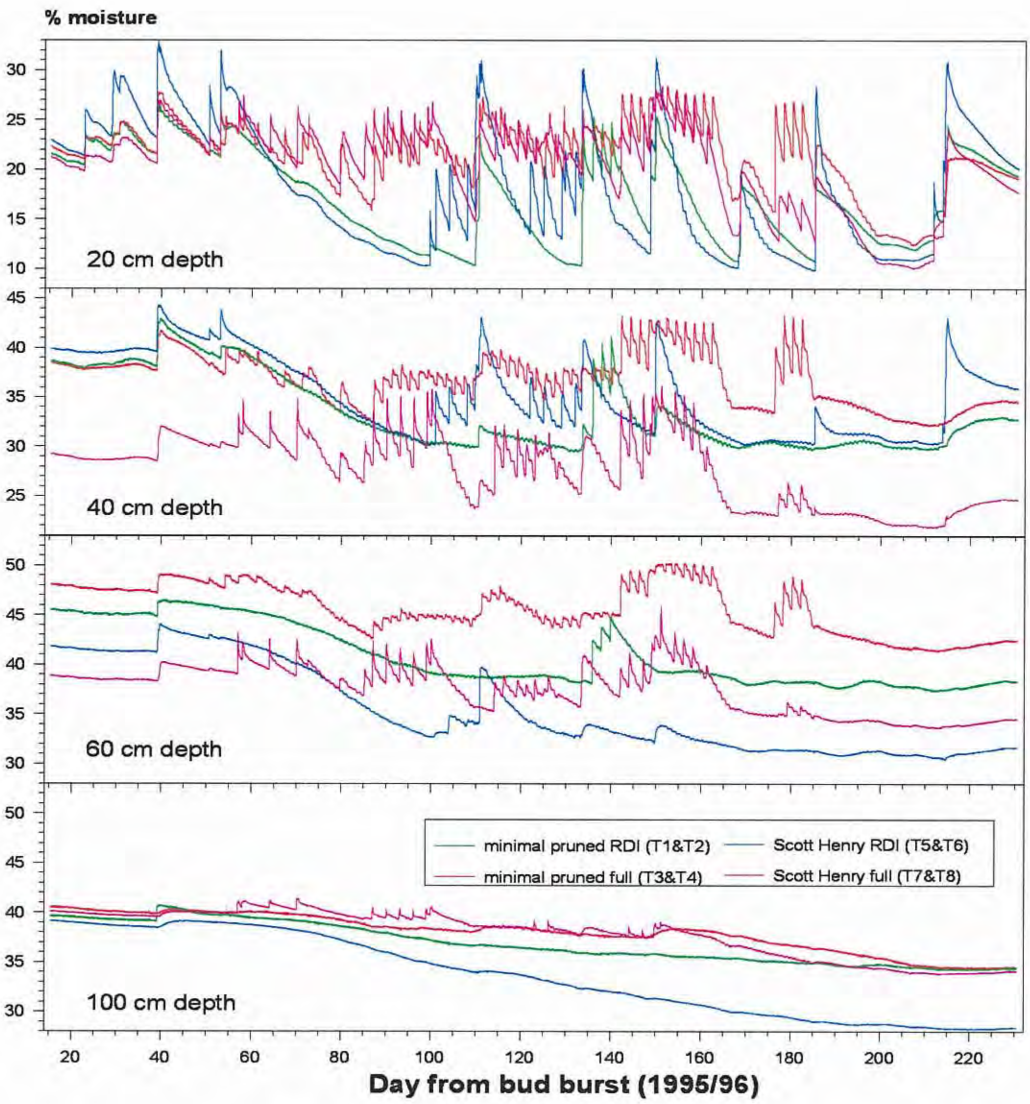

Figure 37. Soil water content (%v/v) measured with the EnviroScan comparing Full and Deficit treatments in minimal pruned and Scott Henry vines in year 2.

probe (Figure 37). Firstly, the largest change in soil moisture was in the top 20 cm and was especially noted in the Deficit treatments. Secondly, irrigation wetted the soil to somewhere between 60 and 100 cm depth. Thirdly, moisture was maintained relatively constant in the Full treatments for much of the season. In addition the EnviroScan showed a much higher level of daily water use at 20 cm depth which declined to a non-detectible level at 100 cm depth.

Total water use was calculated by water balance for irrigation and pruning treatments and was compared with ETo calculated by the standard Penman Monteith equation for grass (Figure 38). Water use was highest in the minimal pruned Full treatment.

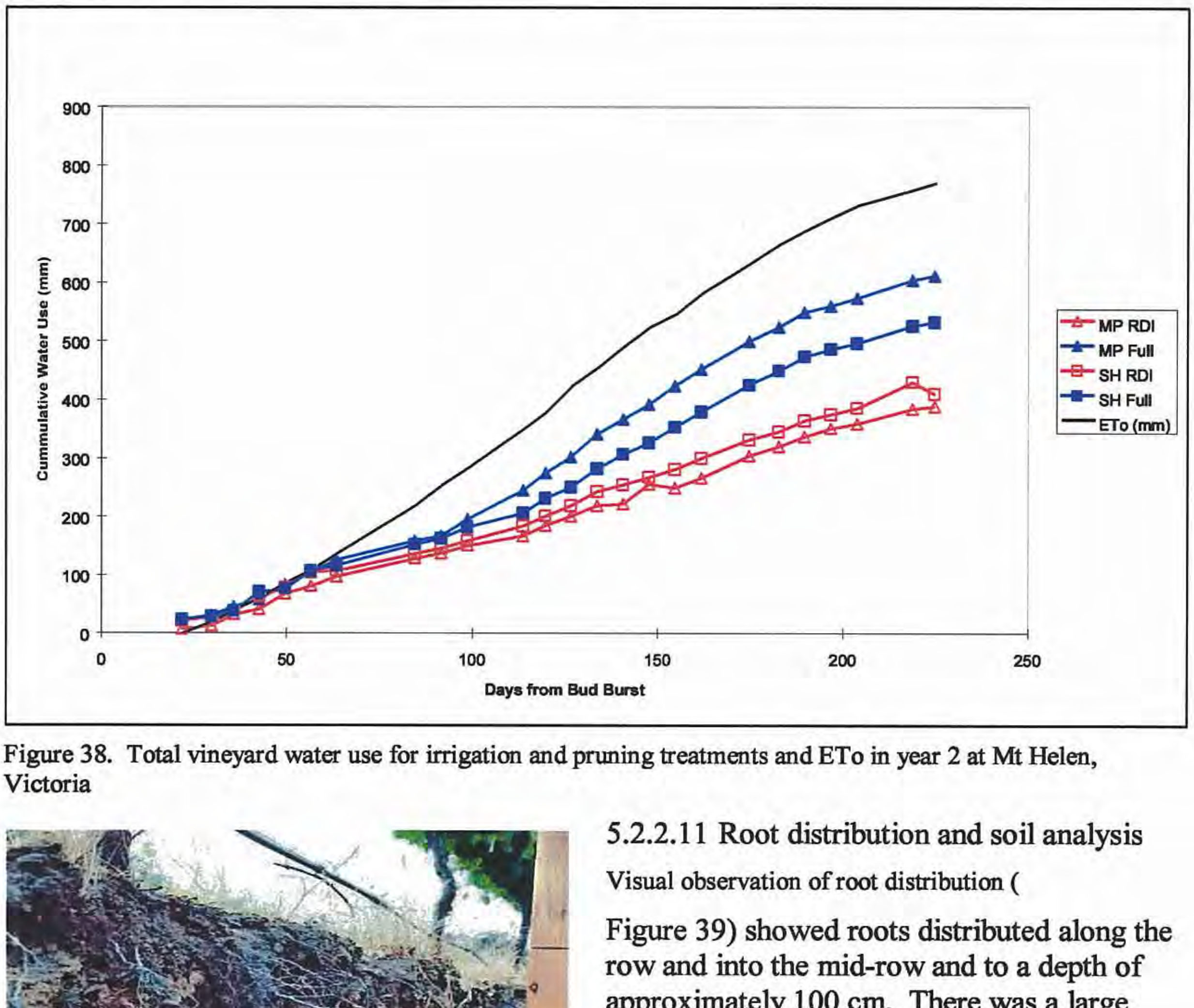

Figure 38. Total vineyard water use for irrigation and pruning treatments and ETo in year 2 at Mt Helen, Victoria

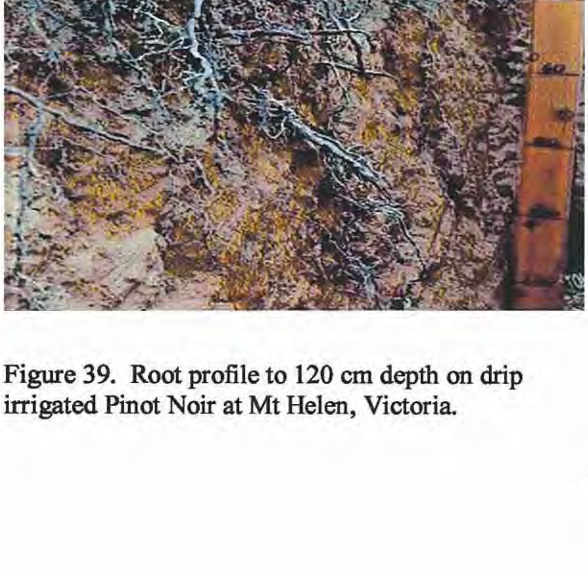

Figure 39. Root profile to 120 cm depth on drip irrigated Pinot Noir at Mt Helen, Victoria.

5.2.2.11 Root distribution and soil analysis

Visual observation of root distribution (

Figure 39) showed roots distributed along the row and into the mid-row and to a depth of approximately 100 cm. There was a large decrease in root density with depth. The majority of roots were in the top 40 cm. There was no obvious concentration of roots in the soil directly below the emitter.

Soil analysis showed an acid soil and increasing acidity with depth with low salt and organic carbon levels (Table 19). Particle size analysis classified the soil as a loamy sand in the top 10 cm changing to loam between 10 and 38 cm and then to a clay as the sand content declined and the clay content

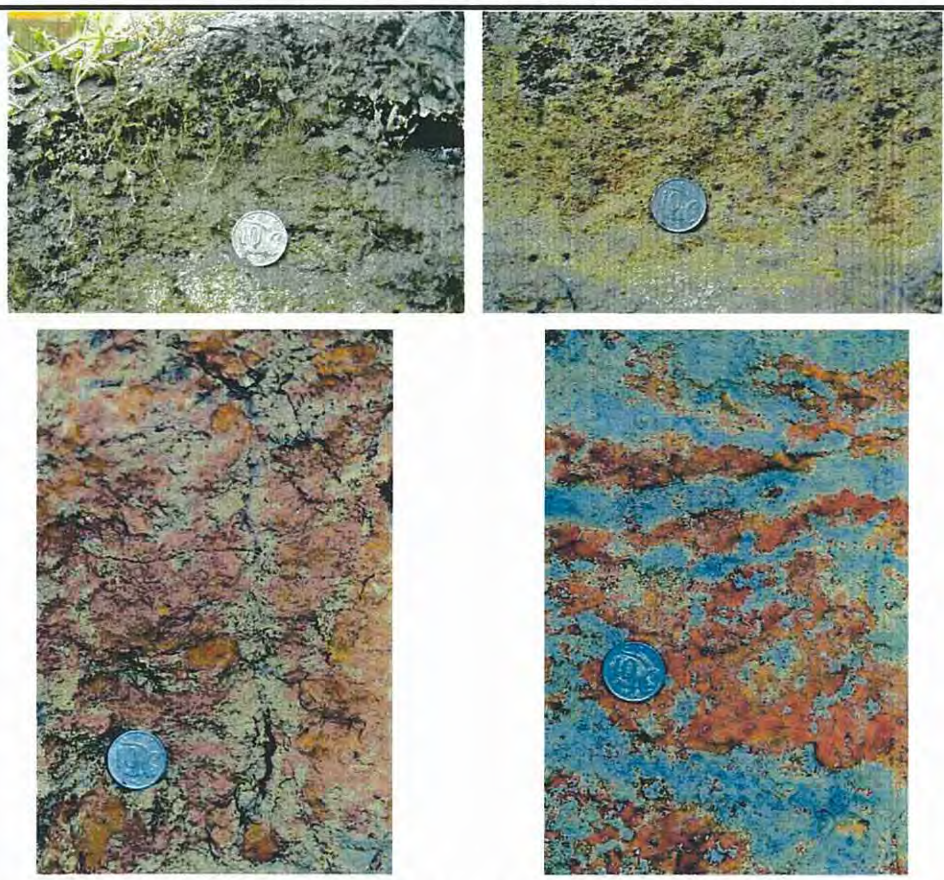

Figure 40. Soil profile at Mt Helen, Victoria. Top to bottom profile depths are 0 to 10 cm, 10 to 38 cm, 38 to 85 cm and below 85 cm.

increased. Photos of the profile are shown in Figure 40.

Table 19. Soil analysis and particle size analysis for soil profile at Mt Helen, Victoria.

Depth (cm)	PH water	pH $CaCl_2$	$EC_{1:5}$ (dS/m)	Organic C (%)	Particle Size Analysis (%) Coarse sand	Fine sand	Silt	Clay
0 – 10	5.60	4.90	0.09	1.1	54.6	24.4	15.3	5.8
10 – 38	5.40	4.80	0.09	0.5	47.3	26.4	15.1	11.3
38 – 85	4.90	4.40	0.12	0.2	23.3	16.7	12.4	47.7
> 85	4.73	4.30	0.17	0.1	24.7	21.4	15.6	38.3

Intact soil cores to determine moisture characteristics showed an increase in water content at saturation, field capacity and wilting point with depth (Table 20). Total plant available water ranged from 14% at 20 and 40 cm depth to just 8% at 60 and 80 cm depth.

Table 20. Soil moisture characteristic (% water content v/v) for soil profile at Mt Helen, Victoria.

Depth (cm)	Saturation	Field Capacity (10 kPa)	Wilting Point (1500 kPa)
20	42	24	10
40	47	34	20
60	48	40	32
80	50	40	32

5.3 References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop evapotranspiration – Guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper, 56. FAO, Rome.

Antcliff, A.J., May, P., Webster, W.J. and Hawkes, J. (1972) The Merbein bunch count, a method to analyze the performance of grape vines. Hortscience **7**, 196-197.

Coombe, B.G. (1995) Adoption of a system for identifying grapevine growth stages. Australian Journal of Grape and Wine Research **1**, 100-110.

Downes, R.G. (1949). A soil, land-use, and erosion survey of parts of the counties of Moira and Delatite, Victoria. Bulletin No. 243, CSIRO, Melbourne.

Kriedemann, P.E., Kliewer, W.M. and Harris, J.M. (1970) Leaf age and photosynthesis in *Vitis vinifera*. Vitis **9**, 97-104.

May, P. (1986) The grapevine as a perennial, plastic and productive plant. In: 'Proceedings of the Sixth Australian Wine Industry Technical Conference'. Ed. . (Australian Wine Research Institute: Glen Osmond, SA) pp. 40-49.

McIntyre, D.S. and Loveday, J. (1974) Particle-size analysis. In: 'Methods for Analysis of Irrigated Soils; Technical Communication No. 54'. Ed. J. Loveday. (Commonwealth Bureau of Soils: .

Northcote, K.H. (1958) A pedological study of the soils occurring at Coomealla, New South Wales. CSIRO Bulletin No 264

Ritchie, J.T. (1991) Specifications of the ideal crop model for predicting crop yields. In: 'Climatic risk in crop production: Models and management for the semi-arid topics and subtropics. Proc. Intnl. Symposium, St Lucia, Brisbane, Queensland'. Eds. R.C. Muchow. and J.A. Bellamy. (C.A.B. International: Wallingford, UK) pp. 97-122.

Somers, T.C. and Evans, M.E. (1977) Spectral evaluation of young red wines: Anthocyanin equilibria, total phenolics, free and molecular SO_2, "chemical age". Journal of the Science of Food and Agriculture **28**, 279-287.

Sommer, K.J. and Lang, A.R.G. (1994) Comparative analysis of two indirect methods of measuring leaf area index as applied to minimal and spur pruned grape vines. Australian Journal of Plant Physiology **21**, 197-206.

Wilkinson, L. (1990) 'SYSTAT: The System for Statistics' (SYSTAT Inc.: Evanston, Illinois).

Disclaimer