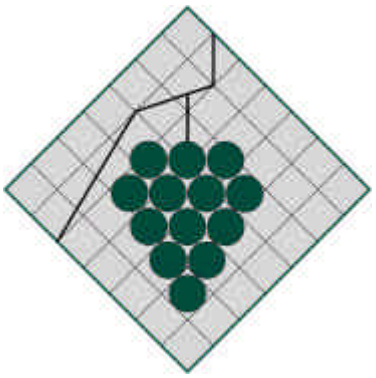


Physiological factors influencing vine response to minimal pruning and optimisation to enhance yield and wine quality

FINAL REPORT to

GRAPE AND WINE RESEARCH & DEVELOPMENT CORPORATION

Project Number: CSH 6GW

Principal Investigator: P R Clingeleffer
Karl J Sommer

Research Organisation: CSIRO Division of Horticulture

Date: February 1991 – January 1994

Final Report

Project Title	**Physiological factors influencing vine response to minimal pruning and optimization to enhance yield and wine quality.**
Project Number	**CSH 6GW**
Organisation	**CSIRO Division of Horticulture**
Location	**Merbein, Victoria**
Supervisors	**P.R Clingeleffer** **K.J Sommer**
Time Span	**February 1991- January 1999**

Objective

Determine relationships between physiological factors influencing the carbohydrate economy of minimally pruned vines and the various components of shoot and crop development, including shoot and vine morphology, yield, grapejuice and wine quality.

Table of contents

1. Introduction 1

2.Materials and Methods 1

2.1 Experimental sites 1
2.1.1 Irrigated inland district (Sunraysia) 2
2.1.2 Cool climate district (Coonawarra) 3
2.2 Canopy growth measurements 4
2.3 Leaf physiological measurements 5
2.4 Wood sampling for carbohydrate analysis 5
2.4.1 Carbohydrate extractions 6
2.5 Fruit maturation, crop yield, fruit and wine quality 7

3. Results 8

3.1 Leaf canopy development 8
3.1.1 Irrigated inland district (Sunraysia) 8
3.1.2 Koorlong 8
3.1.3 Nangiloc 9
3.1.4 Cool climate district (Coonawarra) 9

3.2 Leaf physiological performance, shoot and leaf size 10
3.2.1 Irrigated inland district (Sunraysia) 10
3.2.2 Cool climate district (Coonawarra) 13

3.3 Yield, must and wine quality 15
3.3.1 Irrigated inland district (Sunraysia)15
3.3.2 Cool climate district (Coonawarra) 18

3.4 Carbohydrate economy (Irrigated inland district; Sunraysia) 22
3.4.1 Carbohydrate content and composition: Seasonal trends 23
3.4.2 Wood dry matter and carbohydrate storage 24
3.4.3 Pruning weight 26

4. Discussion 27

4.1 Leaf canopy development 27
4.2 Leaf physiology 28
4.3 Crop capacity and wine quality 28
4.3.1 Irrigated inland district (Sunraysia) 28
4.3.2 Cool climate district (Coonawarra) 29
4.4 Carbohydrate storage 30

5.Conclusions 31

6.Publications arising from the study 32

7. Bibliography 33

Introduction

In recent years traditional spur and cane pruning systems in many vine-growing areas of Australia have been increasingly replaced by either mechanical hedging or minimal pruning techniques (May and Clingeleffer 1977; Clingeleffer 1983; Clingeleffer and Possingham 1987). Minimal pruning techniques reduce the need for manual pruning, are suited to mechanical harvesting, and therefore reduce costs. In Australia minimal pruning systems are being used with traditionally grown varieties such as Cabernet Sauvignon, Shiraz, Grenache and Semillon. The systems are being used commercially in a wide range of environments i.e., the irrigated inland districts along the Murray Valley and in the cool climate districts of Coonawarra and Padthaway (Kidd 1986; Clingeleffer 1989).

Minimal pruning profoundly changes the morphology of grapevines resulting in a large, permanent vine structure. Generally these changes seem to be similar for different wine grape varieties. Compared with traditional systems the canes of minimal pruned vines are smaller in diameter, shorter in length, have fewer nodes and shorter internode spaces (Clingeleffer and Possingham 1986; McCarthy and Cirami 1990). In spring a larger number of buds burst in minimal pruned vines and canopy development is faster than under traditional pruning (Downton -and Grant 1991). The cropping level of minimal pruned vines is often found to be higher than for traditional systems (Clingeleffer 1984; Clingeleffer 1989). This may be related to the speed of canopy development, particularly early in the season, its size and/or the photosynthetic capacity of individual leaves.

The aim of this project was to compare growth and cropping performance of vines under traditional and minimal pruning systems. The comparative study focussed on four major areas of interest which were thought to be crucial in evaluating and characterising vine responses to minimal pruning.

1. Leaf canopy development

2. Leaf physiological performance

3. Yield, must and wine quality

4. Carbohydrate economy

Following is a description of the experimental methods applied in this study and its main findings. Experimental results are presented in accordance with the four main areas just outlined.

2. Materials and Methods

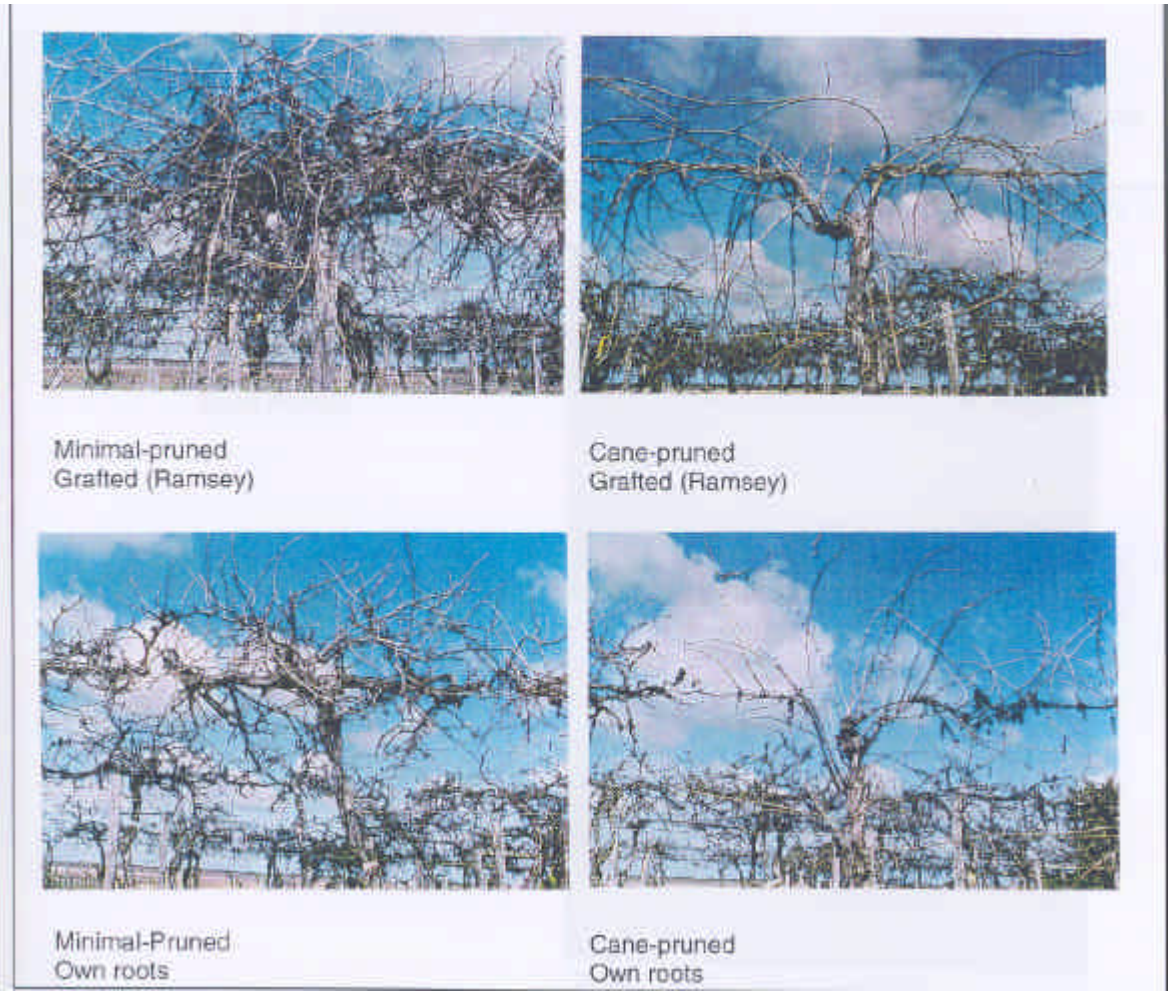
2.1 Experimental sites

A number of experiments were carried out at Coonawarra in the south east of South Australia and in Sunraysia in north western Victoria near the border with New South Wales. The regions represent two distinct climatic zones. Sunraysia is representative for many of the irrigated inland districts with an HDD of 2244°C[1] whereas Coonawarra, with an HDD of 1432°C, in comparison represents a relatively cool and mostly rain fed coastal district.

2.1.1 Irrigated inland district (Sunraysia).

In Sunraysia, the main study site, Cabernet Sauvignon vines were grown at the irrigated Koorlong research vineyard of the CSIRO Division of Horticulture near Mildura, Victoria.

Figure 1: Minimal and cane pruned Cabernet Sauvignon either grafted to Ramsey rootstocks or growing on their own roots before winter pruning at Koorlong, Sunraysia, Victoria.



The vineyard was established in 1968 in a soil classified as a Coomealla sandy loam (Northcote 1958). Half the vines in the experiment were growing on their own roots and half were grafted to Ramsey rootstocks. Row by vine spacing was 3.0 by 1.8mand trellis height was 1.8 m. Originally all vines were cane pruned. Cane pruned vines were pruned to six canes each and canes were wrapped on a single high wire at 1.8m. In 1980 half the vines were converted to minimal pruning (Clingeleffer 1989).

---

[1]HDD°C is the heat summation of mean temperature >10°C during Oct. – Apr.

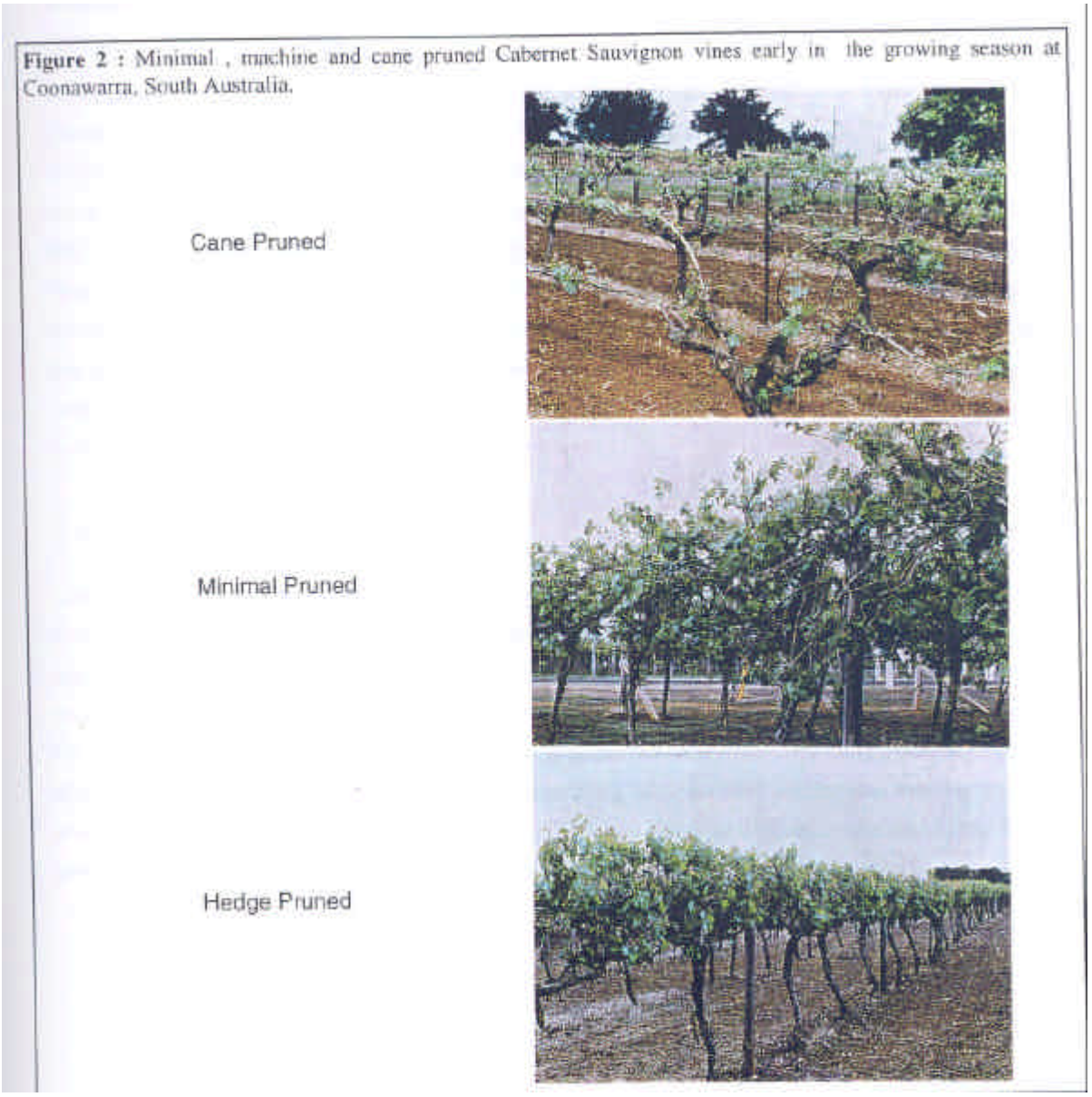
This was achieved by selecting plots consisting of 6 vines of which half were converted to minimal and the other half were cane pruned. There were three replicate vines from each rootstock by pruning treatment combination.

In addition to the CSIRO site, vine canopy development and crop yields were also monitored in two commercial vineyards near Nangiloc Sunraysia One site, planted to Cabernet Sauvignon, provided a comparison between traditionally cane pruned vines trained to on wide T-trellis and minimal pruned vines. Vineyards were planted at a row by vine spacing of 3.35*2.44m (11' * 8'). A second vineyard with similar spacing was planted to Chardonnay. It had originally been spur pruned and trained to a two wire vertical trellis but most of it was subsequently converted to minimal pruning and therefore was an ideal site for comparing the two pruning methods.

2.1.2 *Cool climate district (Coonawarra)*

Vines from two commercial vineyard sites, one planted to Cabernet Sauvignon and the other to Shiraz

Figure 2 : Minimal , machine and cane pruned Cabernet Sauvignon vines early in the growing season at Coonawarra, South Australia.



were studied in Coonawarra. The aim was to compare the growth development, crop yield and leaf physiological performance of traditionally cane pruned vines with those of mechanically hedged and minimal pruned vines.

The main site under investigation was a 25 year old vineyard planted with ungrafted Cabernet Sauvignon in a Coonawarra loam (Terra Rossa) overlying lime stone (Northcote 1988). Three rows of the vineyard were converted to minimal pruning in 1979 and the remainder was mechanically hedged. Minimal pruned and mechanically hedged vines were trained to a high wire of about 1.8m with a row by vine spacing of 3.0 by 1.8m (Figure 2). There was no inter-row cultivation because weeds were controlled by slashing and vines received supplementary irrigation during the summer period. An adjacent vineyard of similar age, also planted to Cabernet Sauvignon on own roots, was used as a cane pruned control treatment. Row by vine spacing was 3.0 by 1.8m, with a 1.0 m high, 2 wire vertical trellis. Weed control under the traditional system was by cultivation and vines relied on natural rainfall for their water supply. Ten of each, minimal pruned, hedged and cane pruned vines were randomly selected for regular estimation of leaf area index and estimation of leaf water potential, leaf photosynthesis and conductance.

A second experimental site was selected in a vineyard, which was established in 1969 when it was planted with ungrafted Shiraz at a row by vine spacing of 3.05 by 1.52m (10' by 5'). The soil was similar to that just described above. Vines were originally trained to a 2 wire vertical trellis but in 1978 were re-trained on a high wire (1.8m) and thereafter were hedge pruned by machine. In 1984 half of the vines were converted to minimal pruning and have been minimal pruned ever since. An adjacent vineyard of similar age and vine spacing also planted to ungratted Shiraz was used as a cane pruned control treatment with vines trained to a height of 1.5 m on a 2 wire vertical trellis. Weed control under the traditional system was by cultivation and vines relied on natural rainfall for their water supply. Ten vines were randomly selected from each treatment, their seasonal canopy development was monitored and their yield parameters were determined.

2.2 Canopy growth measurements

Leaf area index of experimental vines was estimated regularly at the various sites during the 1991/92 and 1992/93 growth periods using a Li-Cor LAI-2000 canopy analyser. The instrument calculates the leaf area index (LAI) from radiation measurements with a fish eye lens. A measurement per vine consisted of 1 reading above and 3 below the canopy. Below canopy readings were collected close to the ground along the centre line of the row directly under the vine. Readings were collected during late afternoon or early evening in order to minimus scattering of direct sunlight from the foliage. The leaf area per vine was calculated using a relationship between direct and indirect measurements of leaf area index obtained from a validation study using the LAI-2000 instrument (Sommer and Lang 1994).

2.3 Leaf physiological measurements

Leaf gas exchange was measured with the aim to compare the photosynthetic performance of single leaves as influenced by the pruning regime. Readings were obtained throughout the 1991/92 and 1992/93 growth periods. Selected Cabernet Sauvignon vines were monitored at the main study sites at Koorlong, Sunraysia and in Coonawarra; Measurements were obtained with a Li-Cor 6200 portable gas exchange system. A set of diurnal readings on a particular day consisted of approximately 120 leaf measurements recorded between morning and late afternoon alternating between treatments. Readings were always recorded on a pre-selected shoot whereby, early in the season, every leaf on that shoot was measured, whereas later, as shoots grew longer, every second or third leaf was measured. Diurnal readings were recorded six times during the 1991/92 and five times during the

1992/93 season at Koorlong and twice in each season (January and February) in Coonawarra. Readings were taken on clear days and from shoots whose leaves were fully exposed to the sun. Immediately after measuring gas exchange a well-exposed leaf on an adjacent was removed and its water potential was determined by using a pressure chamber.

Prior to measuring gas exchange, the shoot length, leaf number and length of every leaf on the shoot was recorded. Leaf area was estimated from leaf length measurements using the equation $A=5.63-0.\ 712L+\ 1.138L^2$ ($R^2=0.92^{**}$) where L is leaf length and A is leaf area. In addition, the greenness of each leaf on the shoot was measured using a SPAD-501 portable leaf greenness meter. It has been shown that the greenness of a leaf, measured with the instrument, closely correlates with its chlorophyll content (unpublished results).

2.4 Wood sampling for carbohydrate analysis

Vine wood for carbohydrate analysis was obtained from Cabernet Sauvignon vines of the irrigated Koorlong research vineyard described above. Vine wood was sampled from three vines of each pruning treatment by rootstock combination. Wood was sampled on three occasions during 1991/92 (Aug. 22, Nov. 11, Mar. 3) and 1992/93 (Aug. 5, Dec. 8, Apr. 20). In addition, on the first sampling date (Aug. 22 1991) three whole vines per pruning treatment and rootstock combination were cut at ground level and removed. Soil around the root system was excavated using shovels and a tractor mounted backhoe. Roots were separated from the soil and, together with above ground plant parts, were transported to the laboratory for further processing. Roots were washed, dried with plotting paper and weighed. Above ground plant parts were separated into trunk, old wood and new wood and were also weighed. Sub-samples from roots, trunks, old and new wood were retained for later biochemical analysis. Sub-samples were obtained with a pair of secateurs by cutting chips of wood from shoots, canes and permanent cordons. Wood sub-samples from the medium and upper part of the vine trunk were obtained from shavings by boring a small hole through the trunk using a hand held brace and bit (22 mm). Fresh sub-samples were weighed immediately and dried in an oven (24 h, 60º C). After drying, they were re-weighed and the water content used to calculate the dry matter content of the destructively sampled vine parts. Sub-samples were then stored for later analysis of their carbohydrate content.

On the remaining sampling dates vines were left intact and samples for carbohydrate analysis were collected in the field. Wood samples from different plant parts were obtained as described above and their fresh and dry weight recorded. Prior to biochemical analysis all dry wood samples were ground pass a 80 µm mesh using a Rotor-Speed mill (Fritsch GmbH, Germany).

2.4.1 Carbohydrate extractions

2.4.1.1 Sugar

Before processing, ground samples were dried over-night (60°C) and allowed to cool to room temperature in a desiccator. Approximately 500mg of sample material was weighed into 50 ml polypropylene centrifuge tubes. After adding 15ml of water, samples were homogenised for 2 mins using an Ultraturax and were placed in a boiling water bath for 20 min. After cooling, tubes were centrifuged for 15 min at 10,000 revolutions per minute (12,000 x g) and the supernatant was transferred to a 50 ml volumetric flask. The remaining pellet was twice extracted with 15ml of water and all extracts were combined and brought to volume. From the extract, glucose, fructose and sucrose were analysed enzymatically. All reactions involved were carried out in semi-micro 2.5ml cuvettes. Two replicates were analysed from each sample.

The concentration of glucose and fructose were determined before and that of glucose again after enzymatic hydrolysis of sucrose and were based on the following principles (ANONYMOUS 1989) Glucose and fructose phosphorylated to glucose-6-phosphate (G-6-P) and fructose-6-phosphate (F-6-P) by the enzyme hexokinase (HK) and adenosine-5'-triphosphate (ATP). In the presence of the enzyme glucose-6-phosphate dehydrogenase (G-6-P-DH), G-6-P was oxidised by nicotineamide-adenine dinucleotide phosphate (NAPD) to gluconate-6-phosphate with the formation of reduced nicotineamide-adenine dinucleotide phosphate (NADPH). The amount of NADPH formed in this reaction is stoichiometric with the amount of glucose. NADPH was determined spectrophotometrically by means of its absorbance at 340 nm. On completion of this reaction involving G-6-P from glucoseF-6-p was converted to G-6-P by the enzyme phosphoglucose isomerase (PGI). In turn G-6-P originating from fructose was again determined in the same way as G-6-P from glucose. Subsequently sucrose was hydrolysed (pH 4.6) by the enzyme β-fructosidase (invertase) to glucose and fructose. The determination of glucose after inversion was carried out in the same assay according to the principles outlined above. The sucrose content was calculated from the difference of the glucose concentrations before and after enzymatic inversion.

2.4.1.2 Starch

The remaining pellet from the sugar extraction was dried in the centrifuge tubes overnight (70°C). After cooling to room temperature in the desiccator, samples were reweighed and 25ml of 8M HCI and 10ml dimethyl sulfoxide were added. Sample pre-treatment with dimethyl sulfoxide and hydrochloric acid was necessary to convert the starch into a soluble form. Subsequently, tubes were sealed with parafilm and incubated for 30 min in a reciprocating water bath at 60º C. After cooling, 20ml of water was added and the solution was adjusted to between pH 4 - 5 using 5 M NaOH. The solution was filtered into a 50 ml volumetric flask and brought to volume. Starch content of the solution was analysed enzymatically according to the following principle (Anonymous 1989). In the presence of the enzyme amyloglucosidase (AGS) starch was hydrolised to glucose at pH 4.6. The concentration of glucose formed was determined using the same steps as outlined for the determination of glucose above. Two replicates were analysed from each sample.

2.5 Fruit maturation, crop yield, fruit and wine quality

The development of fruit maturation was monitored in the vines of the main trial site near Koorlong, beginning five weeks prior to maturity. Weekly samples of 100 berries were collected from 12 minimal and 12 cane pruned half of which were either grafted or ungrafted. Samples were weighed and berry weight was calculated. Juice was extracted from the berry sample and sugar concentration (ºBrix) was determined using a Type 302 Abbe refractometer (Atago Optical). Acidity and pH of the juice were measured by titrating with 0.1 N 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).

In all experiments crop yield was measured by removing and weighing fruit from whole vines. In all but the main trail vineyard at Koorlong, all bunches from ten selected vines per pruning treatment were removed by hand, counted and weighed. A sub-sample of 100 berries was collected from each vine, their juice was extracted and its sugar concentration acidity and pH were determined as described above. Fruit from the Koorlong site (Cabernet Sauvignon) and from both trial sites at Coonawarra were combined into three lots, which were then used for small scale winemaking (Kerridge 1983). Wine quality was evaluated according to standard methods (Somers and Evans 1977).

3. Results

3.1 Leaf canopy development

3.1.1 *Irrigated inland district (Sunraysia)*

In Sunraysia leaf canopy development was monitored at three sites during the 1991/92 and 1992/93 growth period comprising a range of training/pruning methods. All measurements relating to leaf area development were carried out using a non-destructive indirect optical method as was outlined earlier.

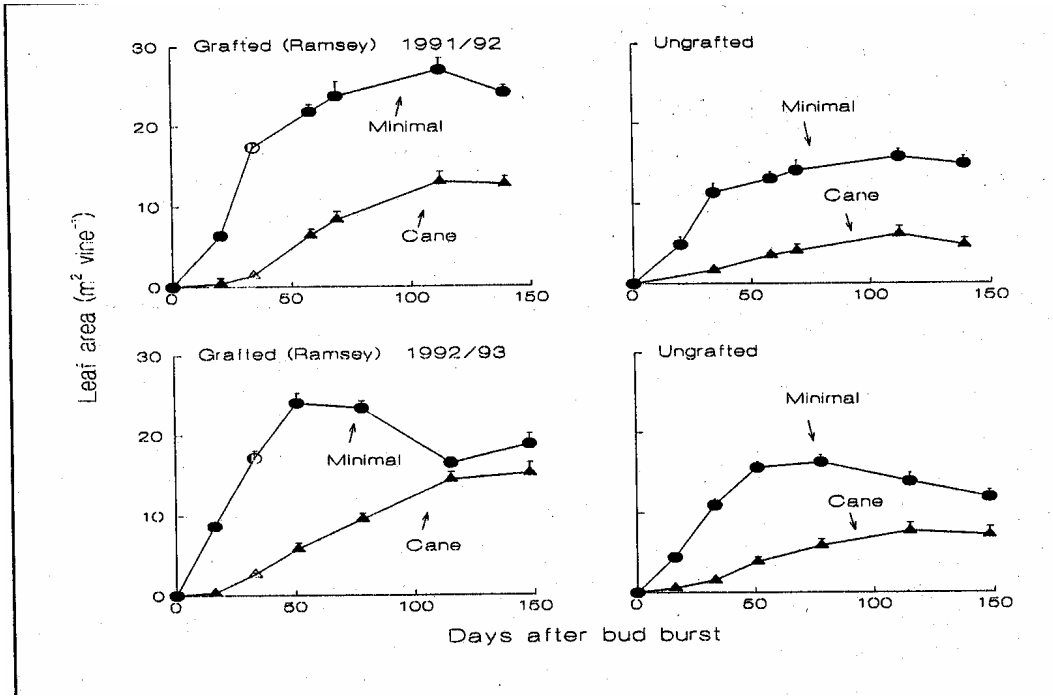


Figure 3 Seasonal leaf area development of grafted (Ramsey) and ungrafted Cabernet Sauvignon at Koorlong, Victoria during the 1991/92 and 1992/93 growth periods. Vertical bars are +standard error of the mean (n=6)

(Sommer and Lang 1994).

3.1.2 Koorlong

At Koorlong, the main site, leaf area development of minimal and cane prune vines, either grafted or ungrafted, was compared during the seasons of 1991/92 and 1992/93. Results showed that in both years early season leaf canopy development of minimal pruned vines was accelerated over that of cane pruned vines regardless of the influence of rootstock **(Figure 3).** Consequently, minimal pruned vines filled their canopies sooner and had a longer leaf area duration than cane pruned vines. Minimal pruned vines developed approximately twice the leaf area of cane pruned vines. Regardless of pruning method, grafted and ungrafted vines followed a similar growth pattern but grafted vines always grew more leaf area than ungrafted vines. It is interesting to note that in the 1992/93 season leaf area of grafted and ungrafted minimal pruned vines ceased to expand from about 50 days after bud burst and from then on continued to declined strongly.

This was a result of wet weather conditions during spring leading to infection with downy mildew and loss of leaf area. During the same time span leaf area of cane pruned vines continued to increase. Obviously, cane pruned vines were not as strongly affected by the infection probably because of better penetration of preventative fungicidal sprays in cane than minimal pruned vines.

3.1.3 Nangiloc

A similar overall pattern of leaf area development to that of Koorlong was observed in the commercial vineyards near Nangiloc **(Figure 4**). In both years and regardless of the variety early season leaf canopy development of minimal pruned vines was always accelerated over that of traditionally cane or spur pruned vines. Differences between the pruning treatments were not as large as those measured at the Koorlong site. Except during the 1992/93 season when minimal pruned Cabernet Sauvignon vines developed much more quickly

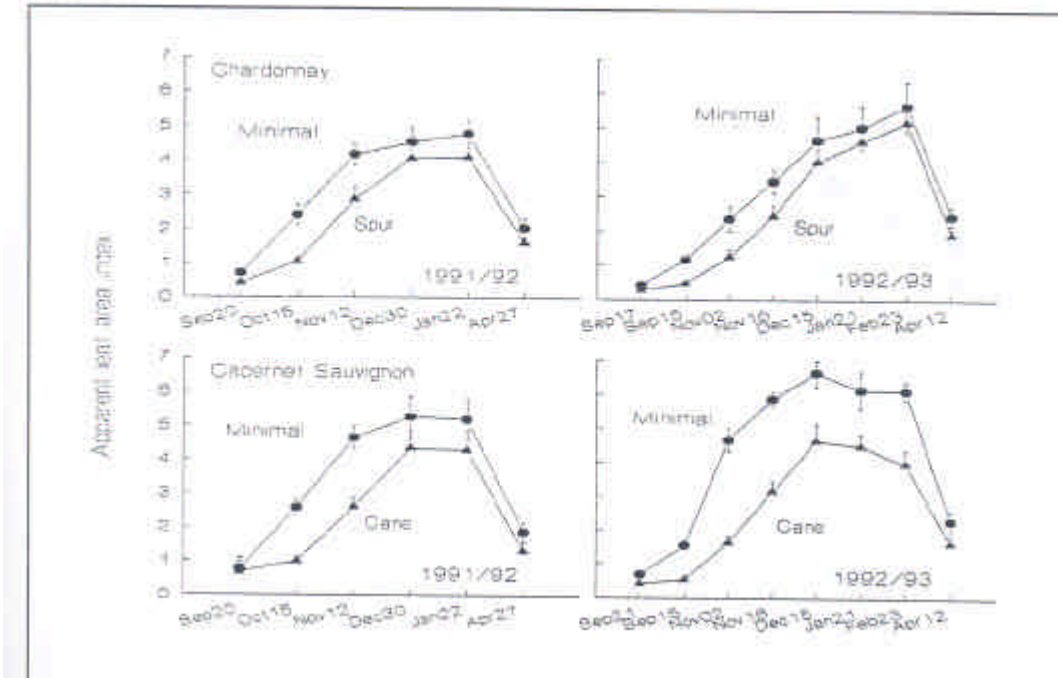


Figure 4 (above) Seasonal development of apparent leaf area index of minimal and cane pruned Carbernet Sauvignon and of minimal and spur pruned chardonnay during the 1991/92 and 1992/93 growth periods at Nanglioc, Victoria. Vertical bars are =/- standard error, (n=10).

and grew considerably larger leaf canopies than cane pruned vines.

3.1.4 Cool climate district (Coonawarra)

In Coonawarra leaf canopy development was monitored at two commercial vineyard sites during the 1991/92 and 1992/93 growth period comprising minimal pruned, mechanically hedged and cane pruned Shiraz and Cabernet Sauvignon vines **(Figure 5**).

As was observed in Sunraysia, minimal pruned vines developed more quickly than hedged and cane pruned vines.

Consequently, they filled their canopies sooner, attained a larger maximum leaf area and a longer leaf area duration than vines from other pruning regimes. With regard to development speed and magnitude of leaf area, mechanically hedged vines, regardless of variety, always occupied an intermediate position relative to the minimal and cane pruning treatments. However, for the variety Shiraz the differences in development speed and total leaf area between minimal pruned and mechanically hedged vines were quite small compared with Cabernet Sauvignon.

Not surprisingly, supplementary irrigation accelerated leaf area development and size in cane pruned Cabernet Sauvignon vines. In 1992/93, with supplementary irrigation (Cane+), cane pruned Cabernet Sauvignon developed almost twice the leaf area of cane pruned vines without supplementary irrigation (Cane-). In contrast, with no supplementary irrigation (Cane-), leaf area development of cane pruned Cabernet Sauvignon and Shiraz (Cane-) always lagged behind minimal pruned or hedged vines regardless of variety.

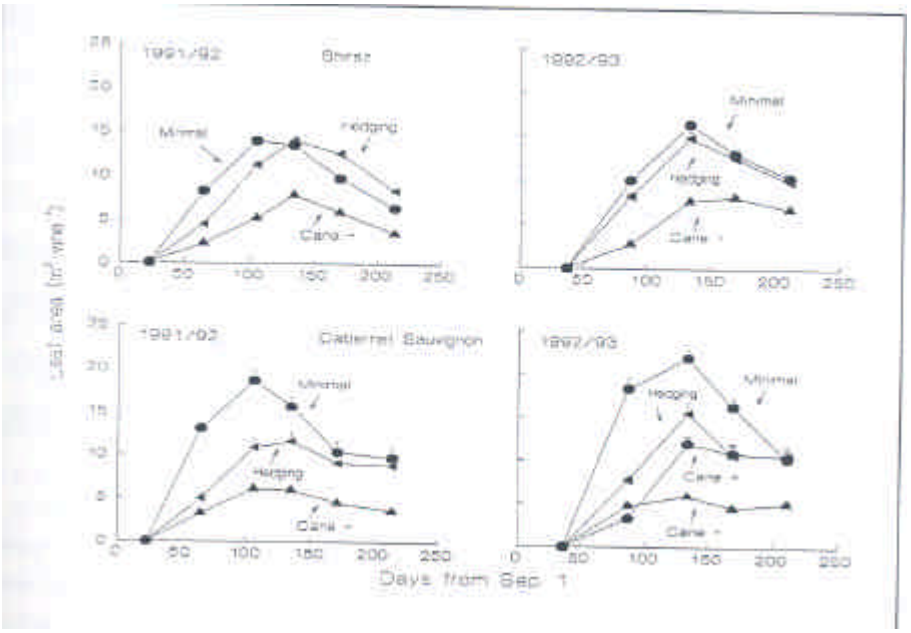


Figure 5 (above) Seasonal leaf area development of cane pruned, minimal pruned and mechanically hedged Cabernet Sauvignon and Shiraz at Connawarra, South Australia during 1991/92 and 1992/93. The minus sign indicates that vines under this treatment received no supplementary irrigation. Vines under the remaining treatments did receive supplementary irrigation. Vertical bars are +standard error of the mean (n=10.)

3.2 Leaf physiological performance, shoot and leaf size
3.2.1 Irrigated inland district (Sunraysia)

At the Koorlong site, the diurnal course of leaf assimilation rate, stomatal conductance, leaf water potential and leaf greenness were monitored regularly throughout the 1991/92 and 1992/93 seasons. The performance of single leaves of minimal and cane pruned Cabernet Sauvignon, either grafted (Ramsey) or ungrafted (Own) was compared. Shoots length development and the number and size of leaves of selected shoots from the respective rootstock by pruning combinations were also regularly recorded. Results will be presented as seasonal averages because they reflect reasonably well the observations made on particular days.

3.2.1.1 Leaf performance

Table 1 Average photosynthesis, stomatal conductance, leaf temperature, leaf water potential, leaf greenness, leaf area and shoot length of minimal and cane pruned Cabernet Sauvignon growing on own roots or grafted to Ramsey rootstock. Averages are mean values calculated from six daily readings during 1991/92 and 1992/93 at Koorlong, Victoria. Values followed by the same letter or by no letter are not significantly different (LSD; $p<0.05$).

Koorlong			Minimal		Cane		Minimal	Cane		
1991/92			Own	Ramsey	Own	Ramsey			Own	Ramsey
	Photosynthesis	µmol m^{-2} s^{-1}	9.6	11.4	10.9	11.6	10.6	11.3	10.3 B	11.5 A
	Stom. Conductance	mmol m^{-2} s^{-1}	194	268	212	275	234	245	204 B	272 A
	Leaf temperature	°C	30.3	31.9	32.3	33.4	31.1	32.9	31.5	32.7
	Leaf water potential	MPa	-0.95 ab	-0.85 ab	-1.02 a	-0.89 b	-0.95	-0.95	-0.99	-0.91
	Leaf greenness	SPAD	30.3	31.9	32.3	33.4	31.1	32.9	31.5	32.7
	Leaf area	cm^2 $leaf^{-1}$	53	54	71	76	55 B	76 A	64	66
	Shoot length	cm	36	42	65	79	39 B	72 A	51	60
1992/93	Photosynthesis	µmol m^{-2} s^{-1}	8.9	8.3	10.3	9.7	8.6	10.0	9.6	9.0
	Stom. Conductance	mmol m^{-2} s^{-1}	151	161	160	172	156	166	155	167
	Leaf temperature	°C	31.5	31.3	32.3	31.4	31.4	31.9	31.9	31.3
	Leaf water potential	MPa	-1.04	-0.85	-1.09	-0.85	-0.96	-0.98	-1.04A	-0.85B
	Leaf greenness	SPAD	29.7 b	30.7 b	29.9 b	34.1 a	30.2 B	32.0 A	29.8 B	32.4 A
	Leaf area	cm^2 $leaf^{-1}$	58 d	65 c	73 b	100 a	61 B	86 A	65 B	82 A
	Shoot length	cm	39 c	65 b	77 b	133 a	52 B	105 A	58 B	99 A

3.2.1.1. 1 Pruning effect:

A comparison between pruning treatments showed that variables related to leaf physiological performance such as the rate of photosynthetis, stomatal conductance, leaf temperature, water potential and leaf greenness were similar in both years except for leaf greenness which, on average, was higher for leaves of cane than minimal pruned vines during the second growth period (**Table 1**).

3.2.1.1.2 Rootstock effect

Photosynthetic rate and stomatal conductance were higher for leaves from grafted than ungrafted vines in the first but not in the second season (**Table 1**). Conversely, leaves of ungrafted relative to grafted vines were of similar greenness in the first but were significantly less green in the second season. Temperature recorded for leaves from grafted and ungrafted vines was similar in both years. In contrast, leaf water potential in the first season was similar but was significantly more negative for ungrafted than grafted vines during the second season.

3.2.1.1.3 Interactions

No significant interaction effects between pruning and grafting treatments were recorded with regard to leaf photosynthesis, stomatal conductance and leaf temperature. Leaf water potential of cane pruned ungrafted vines during the first season was significantly lower that that of grafted vines **(Table 1).** A similar trend, although not statistically significant, was seen in the second season. Moreover, in the second season leaves from cane pruned and grafted vines were significantly greener than those from ungrafted and cane pruned vines.

Variations in leaf photosynthetic performance from season to season were largely attributable to climatic differences. The 1991/92 season was a very fruit full with a high fruit set and a large crop. The high cropping potential represented a strong sink resulting in a high demand for photosynthate. Consequently, throughout the 1991/92 growth period, relatively high photosynthetic rates were recorded, particularly on grafted vines. Conversely, in the second season, characterised by an unusually wet spring, the more vigorous grafted vines became strongly infected with downy mildew, severely reducing the potential crop and sink strength. In comparison with the preceding season the reduced demand for photosynthate was reflected in an overall lower photosynthetic rate and stomatal conductance but the decline was particularly severe for grafted vines. The much higher photosynthetic performance of grafted relative to ungrafted vines recorded in the first season completely disappeared; instead a tendency toward a slightly lower rate of photosynthesis was recorded for grafted as compared to ungrafted vines.

3.2.1.2 Leaf and shoot size

3.2.1.2.1 Pruning effect

The average area of single leaves and the average length of shoots of minimal pruned vines was always significantly smaller and shorter respectively than the corresponding measurements of cane pruned vines (**Table 1**).

3.2.1.2.2 Rootstock

In the first season average leaf size and shoot length were similar between rootstocks. However, in the second season leaves and shoots of grafted vines on average were larger than those of ungrafted vines.

3.2.1.2.3 Interaction

No significant interactions due to grafting and pruning were observed in the first season with regard to the average area or size of individual leaves. In contrast, in the second growth period leaf size was strongly affected by the combined effects of pruning and grafting. Cane pruned and grafted vines, on average, had the largest leaves followed by cane pruned ungrafted, minimal pruned grafted and minimal pruned ungrafted leaves.

Differences in average leaf size and shoot. Length for the two consecutive seasons was mostly attributable to climatic variations. The severe downy mildew infection in the second year of the experiment resulted in leaf loss particularly in grafted vines.

As a compensation mechanism, new leaves appearing after the infection grew to a relatively large area. Furthermore, because of crop loss and hence loss of sink strength on grafted vines, more assimilate was allocated towards additional vegetative growth resulting in the development of larger leaves and longer shoots.

3.2.2 Cool climate district (Coonawarra)

At Coonawarra, the diurnal course of leaf physiological variables, leaf and shoot size were monitored twice in mid January and mid February of the 1991/92 and 1992/93 seasons. A comparison was made between minimal pruned, mechanically hedged and traditionally cane pruned Cabernet Sauvignon in a commercial vineyard. Results are presented as annual averages of the two diurnal observations made in each season.

Vines under traditional management in the Coonawarra district, historically were cane pruned and had to rely on inter-row cultivation for weed control and on natural rainfall for their water supply (**Figure 2**). The conventional cane pruning treatment is always marked with a minus sign (Cane(-);**Table 2**) in order to indicate that vines received no supplementary irrigation. In contrast, under modern management, minimal and mechanically hedged vines did receive supplementary irrigation. In order to obtain a valid comparison of the pruning systems *per se* an additional cane pruned treatment (Cane(+)), with a plus sign to indicate supplementary irrigation, was introduced in the second season of the experiment (1992/93).

3.2.2.1 Leaf performance

During the 1991/92 and 1992/93 seasons, leaf photosynthetic rate and stomatal conductance recorded for traditionally cane pruned vines were lower when compared with vines of the other treatments.

Table 2 Average photosynthesis. stomatal conductance and water potential of leaves of cane pruned, hedged and minimal pruned Cabernet Sauvignon in Coonawarra. Values are means of diurnal records obtained twice in 1992 and 1993 respectively. The minus sign indicates that vines received no supplementary irrigation.

	Coonawarra		Cane(-)	Cane(+)	Hedge	Minimal	SE
1992/92	Photosynthesis	$\mu mol\ m^{-2}\ s^{-1}$	6.4		8.4	8.8	0.4
	Stomatal conductance	$mmol\ m^{-2}\ s^{-1}$	92		134	134	8
	Leaf temperature	°C	30.1		29.1	29.6	0.5
	Leaf water potential	MPa	-1.20		-1.39	-1.38	0.03
	Leaf greenness	SPAD	28.6		29.0	28.5	0.3
	Leaf area	$cm^2\ leaf^{-1}$	73		85	83	3
	Shoot length	cm	81		79	54	2
1992/93	Photosynthesis	$\mu mol\ m^{-2}\ s^{-1}$	8.1	10.6	10.7	11.0	0.6
	Stomatal Conductance	$mmol\ m^{-2}\ s^{-1}$	104	206	200	205	15
	Leaf temperature	°C	36.4	35.1	35.1	35.6	0.7
	Leaf water potential	MPa	-1.51	-1.46	-1.45	-1.53	0.04
	Leaf greenness	SPAD	26.6	27.4	27.9	26.6	0.3
	Leaf area	$cm^2\ leaf^{-1}$	65	82	96	66	19
	Shoot length	cm	72	100	111	60	6

(**Table 2).** This was probably because the traditionally cane pruned vines, without supplementary irrigation, suffered from temporary water deficits, followed by stomatal closure and a rise in leaf temperature. The average leaf water potential of un-irrigated cane pruned vines in 1991/92 was less negative compared with the other treatments because of stomatal closure as a result of water deficits. Leaf greenness of vines in both seasons was similar between treatments suggesting similar leaf chlorophyll content and potential for photosynthesis.

In the second year (1992/93), additional cane pruned vines with supplementary irrigation displayed a similar behaviour as minimal pruned and hedged vines **(Table 2**), whereas cane pruned vines without supplementary irrigation, as during the previous year, suffered from water stress, This resulted in a depressed assimilation rate, stomatal conductance and raised leaf temperature relative to the other treatments. The lower assimilation rate of unirrigated cane pruned vines was probably caused by water deficits. Our measurements also suggest that the effects of water deficits in unirrigated vines became increasingly severe after veraison as soil water was depleted (data not presented).

Table 3 Yield, bunch number, berry weight, juice sugar, pH and acid of spur and minimal pruned Chardonnay and of cane and minimal pruned Cabernet Sauvignon vines growing in commercial Vineyards at Nangiloc, Victoria during 1991/92 and 1992/93. (n=5).

Nangiloc			Chardonnay			Cabernet Sauvignon		
			Spur	Minimal	SE	Cane	Minimal	SE
1992	Yield	t ha^{-1}	26.1	37.9	2.8	20.2	20.9	1.9
	BunchNo		172	432	22	199	358	21
	Berry weight	g	1.24	0.90	0.04	1.03	0.83	0.03
	Juice	Sugar (°Brix)	24.0	20.9	0.4	24.5	23.6	0.3
		pH	3.50	3.42	0.01	3.45	3.41	0.01
		Acid (g L^{-1})	6.40	6.46	0.14	5.28	5.76	0.11
1993	Yield	t ha^{-1}	22.1	17.9	3.4	12.6	17.1	0.8
	BunchNo		205	227	39	222	386	13
	Berry weight	g	1.15	1.14	0.03	0.92	0.89	0.04
	Juice	Sugar (°Brix)	22.5	23.0	0.1	20.9	20.4	0.2
		pH	3.53	3.54	0.02	3.69	3.39	0.02
		Acid (g L^{-1})	6.16	6.13	0.11	4.90	6.45	0.16

creasingly severe after veraison as soil

3.2.2.2 Leaf and shoot size

As was observed in Sunraysia, in both seasons' minimal pruned vines had on average smaller leaves and shorter shoots than either cane pruned or hedged vines **(Table 2**). Leaves and shoot under traditional cane pruning without supplementary irrigation were smaller than those from hedged vines. Supplementary irrigation increased the average leaf size and shoot length of cane pruned vines.

3.3 Yield, must and wine quality

3.3.1 Irrigated inland district (Sunraysia)

3.3.1.1 Nangiloc

Chardonnay vines of this trial had been converted from spur to minimal pruning at the end of the preceding season. As a result of this conversion minimal pruned vines produced a significantly higher yield, had more than twice the number of bunches but smaller berries than vines that continued to be spur pruned (Table 3). The high crop in 1992 harvested from minimal, as compared to spur pruned pruned vines, lead to a delay in maturity, with must of a lower pH but higher titratable acid level. Conversely, in 1993 minimal pruned vines produced a much lower yield with similar bunch numbers and berry weights as spur pruned vines. The level of maturity, measured as sugar content, pH and titratable acid level of the must, were also similar for both pruning regimes. The spring of 1993 was considerably wetter and cooler than the long term average weather data recorded for the Sunraysia region. This resulted in some infection with downy mildew which, together with the very high yield in the preceding season, probably was the cause of the a considerable yield decline in 1993.

The commercial vineyard with Cabernet Sauvignon, unlike that with Chardonnay, had been under the present pruning regimes for a number of years. Therefore no short term effects on yield due to conversion of the pruning system were to be expected. Yields in 1992 were similar for the cane and minimal pruned vines. Minimal pruned vines had many more bunches but smaller berries than cane pruned vines. Fruit of minimal pruned vines ripened more slowly than that of cane pruned vines, resulting in a reduction of about one degree Brix. The delay was paralleled by a lower must pH and higher must acid content for fruit of minimal relative to cane pruned vines. In the second year, as for Chardonnay, the general yield level of Cabernet Sauvignon was lower than in 1992 but minimal pruned vines had considerably higher yields, more bunches, but smaller berries than cane pruned vines. Minimal pruning only slightly delayed maturity but resulted in a considerably lower must pH and a higher must acid content than cane pruning.

3.3.1.2 Koorlong

Compared with the 1991/92 seasons, vine development in the 1992/93 season was delayed by between 3-4 weeks due to un-seasonally wet and cool spring weather **(Table 4**). As a consequence of such unfavourable climatic conditions, all vines, but especially grafted vines, suffered from infection with downy mildew and consequently, yields in 1993 were considerably lower than in 1992.

Koorlong			Minimal		Cane		Minimal	Cane		
1992			Own	Ramsey	Own	Ramsey			Own	Ramsey
	Yield	t ha^{-1}	25.5	49.9	15.0	33.1	37.7A	24.0 B	20.2 B	41.5 A
	Bunch No		345 b	824 a	128 c	160 bc	585 A	144 B	236 B	492 A
	Berry weight	g	0.78	0.92	0.96	1.13	0.85 B	1.04 A	0.87 B	1.02 A
	Juice	Sugar (° Brix)	24.6	23.1	25.8	23.5	24.0 B	24.6 A	25.3 A	23.3 B
		pH	3.41	3.43	3.48	3.50	3.42 B	3.49 A	3.45	3.47
		(Acid g L^{-1})	5.43 b	6.41 a	5.06 c	6.61 a	5.92	5.83	5.25 B	6.51 A
1993	Yield	t ha^{-1}	19.7a	-.-	10.9 b	-.-	-.-	-.-	15.3	-.-
	Bunch No		383 a	-.-	134 b	-.-	-.-	-.-	259	-.-
	Berry weight	g	0.74	-.-	0.94	-.-	-.-	-.-	0.84	-.-
	Juice	Sugar (° Brix)	20.6 b	-.-	22.3 a	-.-	-.-	-.-	21.5	-.-
		pH	3.42	-.-	3.59	-.-	-.-	-.-	3.51	-.-
		(Acid g L^{-1})	6.16	-.-	5.46	-.-	-.-	-.-	5.81	-.-

Table 4 yield, bunch, number, berry weight, juice sugar, pH, and acid of minimal and cane pruned Cabernet Sauvignon either growing on own roots or grafted to Ramsey rootstock planted in a research vineyard at Koorlong, Victoria during 1991/92 and 1992/93. (n=6).

3.3.1.2.1 Rootstock effect

As was-just pointed out, during the spring of 1992/93, in the second year of the experiment, grafted vines were severely infected with downy mildew, resulting in pre-mature loss of leaves and bunches. A valid comparison of the performance of grafted and ungrafted vines was therefore possible only in the first season of the experiment (1991.92). In the first season, grafted vines had returned twice the yield of ungrafted vines with more bunches and larger berries. Fruit of grafted vines had yielded must of a higher acid content, a similar pH, but a lower sugar concentration than fruit of ungrafted vines (**Table 4**). It is interesting to note that despite the significantly higher acid content in the must of fruit of grafted

Table 5 Average wine pH, titratable acid and spectral evaluation of cane and minimal pruned Cabernet Sauvignon growing on own roots or grafted to Ramsey rootstock at Koorlong, Victoria during 1991/92 and 1992/93. (n=3).

Koorlong		Minimal		Cane		Minimal	Cane		
Wine		Own	Ramsey	Own	Ramsey			Own	Ramsey
1992	pH	3.50	3.66	3.57	3.84	3.58	3.71	3.54 B	3.75 A
	Acid (g L^{-1})	8.04	7.38	7.96	6.88	7.71 A	7.42 B	8.00 A	7.13 B
	Colour density (abs. units)	5.10	2.53	6.24	2.80	3.81	4.52	5.67 A	2.67 B
	Colour hue	0.63	0.75	0.66	0.80	0.69	0.73	0.65 B	0.78 A
	Total anthocyanins (mg L^{-1})	545	352	608	448	449	528	577 A	400 B
	Ionised anthocyanins (mg L^{-}	69	29	75	28	49	52	72 A	29 B
	Ionised anthocyanins (%)	21.6	17.3	19.0	14.0	19.5 A	16.5 B	20.3 A	15.7 B
	Total phenolics (abs. units)	51	34	53	35	43	44	52 A	35 B
	Tasting Score (max.20)	14.2	13.9	14.1	14.7	14.1	14.4	14.1	14.3
1993	pH	3.40 b		3.61 a				14.15	
	Acid (g L^{-1})	7.29		7.31				3.51	
	Colour density (abs. units)	2.66 b		3.79 a				7.3	
	Colour hue	0.59 b		0.66 a				3.23	
	Total anthocyanins (mg L^{-1})	378 b		508 a				0.63	
	Ionised anthocyanins (mg L^{-}	49		57				443	
	Ionised anthocyanins (%)	27.4 a		21.0 b				53	
	Total phenolics (abs. units)	35 b		42 a				24	
	Tasting Score (max.20)	13.6 b		14.5 a				14.0	

vines, their pH was similar to that in must of fruit of ungrafted vines. Normally a comparatively higher acid content is parallel by a comparatively lower pH. A similar result with vines grafted to Ramsey rootstocks has been observed elsewhere (RuhI1993) and was largely attributed to high potassium levels in the juice.

The wine data indicate that Ramsey had a major negative impact on wine quality parameters and style producing wines of high pH with low colour densities, high colour hue and low phenolics **(Table 5).** Lower total anthocyanins, and reduced ionisation of the anthocyanins, compared with own rooted vines, both contributed to the poor wine colour.

3.3.1.2.2 Pruning effect

During both growing seasons minimal relative to cane pruned vines always produced higher yields, more bunches, smaller berries, similar acid, but lower pH and sugar levels in the must (**Table 4**). Ripening of fruit of minimal pruned vines always lagged behind that of cane pruned vines ranging between 0.6 and 2 degree Brix depending on the fruit load. The delay in ripening due to pruning was more severe in the relatively cooler season of 1992/93 as compared to that of 1991/92. Data presented in **Figure 6** clearly show the delay in sugar accumulation, which was also reflected in a lower acid concentration and a lower pH throughout the period of berry maturation. The graph also shows the substantial differences in berry size resulting from the different pruning regimes.

Minimal pruning gave wines with a lower pH, higher titratable acidity and a lower colour hue **(Table 5**). The lower colour density with minimal pruning was caused by lower total anthocyanins, not the degree of ionisation. Minimal pruning had little impact on phenolics despite the high crop load.

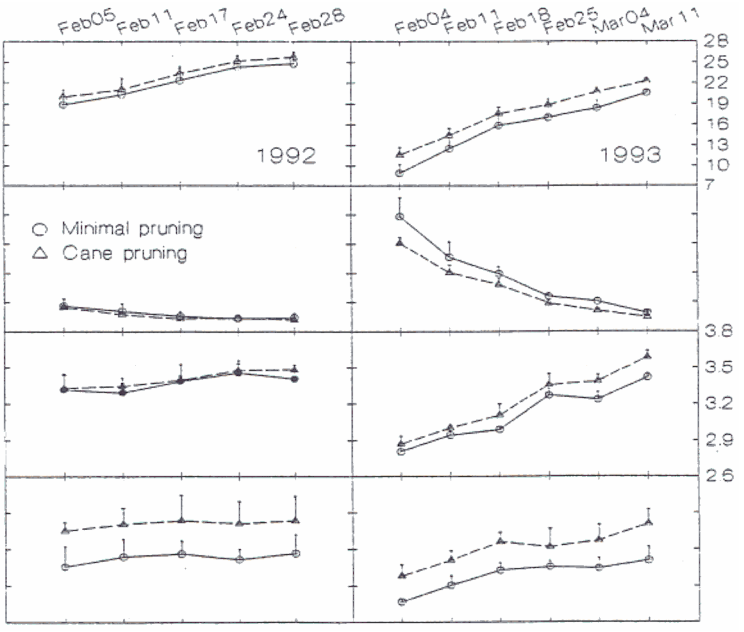


Figure 6: Development of berry weight, pH. Titratable acidity, and sugar content of minimal and cane pruned Cabernet Sauvignon vines measured at weekly intervals prior to maturity during 1991/92 and 1992/93 seasons (vertical bars =+ SE).

Table 6 Yield. bunch number, berry weight, juice sugar, pH and acid of cane pruned, machine hedged and minimal pruned Cabernet Sauvignon growing in commercial vineyards at Coonawarra, South Australia during 1991/92 and 1992/93. (n= I 0). The minus sign indicates that vines received no supplementary irrigation with all other treatments receiving supplementary irrigation.

Coonawarra			Cabernet Sauvignon				
			Cane(-)	Cane(+)	Hedge	Minimal	SE
1992	Yield	t ha^{-1}	3.1		4.8	15.7	2.0
	BunchNo		76		57	308	20
	Berry weight	g	0.84		1.01	0.76	0.06
	Juice	Sugar (°Brix)	20.0	-	22.1	21.8	0.4
		pH	3.42	-	3.51	3.55	0.05
		Acid (g L^{-1})	6.40	-	5.56	5.62	0.2
1993	Yield	t ha^{-1}	7.1	4.1	9.5	18.6	1.0
	BunchNo		102	40	96	294	13
	Berry weight	g	0.79	1.00	0.97	0.77	0.03
	Juice	Sugar (°Brix)	23.0	23.2	23.2	21.2	0.20
		pH	3.34	3.35	3.37	3.31	0.02
		Acid (g L^{-1})	6.08	7.04	6.51	6.91	0.15

Likewise, despite the large treatment effects on yield wine parameters and style of all the wines received similar tasting scores. The cane pruned Ramsey treatment, which was described as being more herbaceous was preferred by the tasters.

3.3.1.2.3 Interactions

In 1992 the increase in bunch number, as a result of grafting, was significantly higher under minimal than cane pruning **(Table 4**). Acid content of must from ungrafted minimal pruned vines was higher than that of ungrafted cane pruned vines. The opposite was found for must from berries of grafted minimal as compared to grafted cane pruned vines.

3.3.2 Cool climate district (Coonawarra)

3.3.2.1 Cabernet Sauvignon

In Coonawarra yields of all treatments were considerably higher in 1993 than in 1992 (**Table 6**). Hedged vines always had fewer bunches but larger berries than either minimal or unirrigated cane pruned vines. Of all treatments minimal pruning consistently achieved the highest yield. In the first season, sugar levels, pH and acidity were similar in must from fruit of minimal and hedged vines but ripening was severely delayed in unirrigated cane pruned vines, probably because of water stress. A large crop in the second season (1993), delayed ripening of minimal pruned vines by about 2 degrees Brix relative to the other treatments. Yield performance of cane pruned vines with supplementary irrigation, as compared to those without, was extremely low and probably had its cause in the recent conversion from hedge to cane pruning, in turn resulting in a much lower fruitfulness and fewer bunches.

Wines from the unirrigated cane pruned treatment, relative to the other treatments, always gave wine of deeper colour, with higher levels of total and ionised anthocyanin, more total phenolics and a higher percentage of ionised anthocyanins. The latter was probably associated with the lower pH and differences in organic acid composition. Tasters preferred wine made from fruit of unirrigated cane pruned vines. Hedged and minimal pruned vines, when compared with each other, gave wines of similar composition but with a tendency towards a higher level of ionised anthocyanins, percent ionised anthocyanains and phenolics for the 1atter. Therefore, in spite of a more than two-fold yield difference, wine of minimal pruned vines was of similar or higher quality to that of machine hedged vines and attracted a higher tasting score than the latter. It is interesting to note that in the second year of the

Table 7 Wine pH, titratable acid and spectral evaluation of cane pruned, machine hedged and minimal pruned Cabernet Sauvignon growing in commercial vineyards at Coonawarra, South Australia during 1991!92 and 1992/93. (n=3). The minus sign indicates that vines received no supplementary irrigation with all other treatments receiving supplementary irrigation.

Coonawarra		Cabernet Sauvignon				
Wine		Cane(-)	Cane(+)	Hedge	Minimal	SE
1992	pH	3.30		3.34	3.32	0.05
	Acid (g L^{-1})	8.42		8.31	8.65	0.20
	Colour density (abs. units)	8.1		5.5	6.0	0.8
	Colour hue	0.53		0.59	0.54	0.02
	Total anthocyanins (mg L^{-1})	788		685	673	31
	Ionised anthocyanins (mg L^{-1})	166		93	116	17
	Ionised anthocyanins (%)	31.6		23.3	27.0	1.3
	Total phenolics (abs. units)	62		54	57	5
	Tasting score (max. 20)	-.-		-.-	-.-	-.-
1993	pH	3.24	3.31	3.36	3.39	0.05
	Acid (g L^{-1})	8.47	9.03	8.75	8.44	0.15
	Colour density (abs. units)	9.0	5.8	5.5	6.5	0.4
	Colour hue	0.49	0.56	0.56	0.49	0.02
	Total anthocyanins (mg L^{-1})	827	643	631	720	22
	Ionised anthocyanins (mg L^{-1})	208	111	106	149	14
	Ionised anthocyanins (%)	34.8	26.9	27.5	30.8	1.6
	Total phenolics (abs. units)	63	51	50	53	2
	Tasting score (max. 20)	15.8	15.6	14.8	15.1	0.3

experiment most quality indicators of wine that came from the irrigated cane pruned treatment, with the exception of wine acid level, were similar to those of hedged and minimal pruned vines. Such a result would suggest that the observed differences to the unirrigated cane pruned vines were mostly due to contrasting irrigation regimes and not due to pruning method. However, despite the similarity in their spectral assessment, tasters still preferred wine that came from cane pruned vines, irrigated or not.

3.3.2.2 Shiraz

Shiraz yields of minimal and particularly of mechanically hedged vines in Coonawarra were quite variable from the 1991/92 to the 1992/93 season **(Table 8).** Curiously, in 1992 a relatively low yield for minimal pruned vines coincided with a high yield for hedged vines, whereas the opposite result was obtained in 1993. Conversely, yield of cane pruned vines was similar in both years but was always much lower relative to the other pruning treatments. As expected from the yield data, minimal pruned vines had more bunches with smaller berries. In both seasons ripening of fruit from minimal pruned vines was delayed by between 2-4 °Brix and gave must of a lower pH and higher acid content compared with fruit from hedged and cane pruned vines.

Table 8 Yield, bunch number, berry weight, juice sugar, pH and acid of cane pruned. machine hedged and minimal pruned Shiraz growing in commercial vineyards at Coonawarra, South Australia during 1991/92 and 1992/93. (n=10). The minus sign indicates that vines received no supplementary irrigation with all other treatments receiving supplementary irrigation.

Coonawarra			Shiraz			
			Cane(-)	Hedge	Minimal	SE
1992	Yield	t ha^{-1}	9.3	18.7	12.2	1.6
	BunchNo		64	102	194	12
	Berry weight	g	1.16	1.21	1.07	0.03
	Juice	Sugar (°Brix)	21.9	22.6	20.1	0.3
		pH	3.42	3.41	3.36	0.02
		Acid (g L^{-1})	6.27	6.42	6.26	0.12
1993	Yield	t ha^{-1}	9.6	6.5	23.6	1.0
	BunchNo		68	63	258	8
	Berry weight	g	1.34	1.25	1.25	0.03
	Juice	Sugar (°Brix)	23.7	24.1	20.2	0.3
		pH	3.29	3.33	3.22	0.02
		Acid (g L^{-1})	6.99	8.13	7.39	0.12

Spectral assessment showed that colour density was always highest in wine from cane and lowest in wine from minimal pruned vines (**Table 9**). All treatments produced wines with an acceptable hue although the cane pruned wines had the brightest, while wine from hedge pruned vines had the least bright hue. There was a close association between colour density, the amount of total anthocyanins, ionised anthocyanins and total phenolics which were, relative to the other treatments, lowest in wine from minimal and highest in wine from cane pruned vines. The differences between wine from minimal pruned vines as compared to wine from other treatments were more obvious in the second season probably as a result of the much larger crop on minimal pruned vines. In spite of the relatively low anthocyanin level in wine of minimal pruned vines their degree of ionisation was similar to that of cane and higher than that of hedged vines. Tasters clearly favoured wine of the cane pruned treatment and found wine of the minimal pruned treatment least favourable.

Table 9 Wine pH, titratable acid and spectral evaluation of cane pruned, machine hedged and minima! pruned Shiraz growing in commercial vineyards at Coonawarra, South Australia during 1991/92 and 1992/93. (n=3). The minus sign indicates that vines received no supplementary irrigation with all other treatments receiving supplementary irrigation.

Coonawarra		Shiraz			
Wine		Cane(-)	Hedge	Minimal	SE
1992	pH	3.42	3.50	3.43	0.03
	Acid (g L^{-1})	7.68	8.26	8.11	0.08
	Colour density (abs. units)	5.5	4.6	3.8	0.3
	Colour hue	0.55	0.59	0.54	0.01
	Total anthocyanins (mg L^{-1})	694	651	523	32
	Ionised anthocyanins (mg L^{-1})	105	79	75	5
	Ionised anthocyanins (%)	23.1	19.8	23.6	0.7
	Total phenolics (abs. units)	57	52	43	3
	Tasting score (max 20)	16.2	14.8	14.5	0.2
1993	pH	3.38	3.55	3.47	0.03
	Acid (g L^{-1})	8.04	8.01	7.68	0.32
	Colour density (abs. units)	5.0	4.4	2.4	0.3
	Colour hue	0.53	0.60	0.56	0.01
	Total anthocyanins (mg L^{-1})	624	623	392	14
	Ionised anthocyanins (mg L^{-1})	102	79	45	6
	Ionised anthocyanins (%)	27.1	23.0	25.2	0.6
	Total phenolics (abs. units)	47	45	31	1
	Tasting score (max 20)	15.8	14.7	13.5	0.3

3.4 Carbohydrate economy (Irrigated inland district; Sunraysia)

In the present study vines grown under minimal pruning were found to have accelerated leaf area development and in most cases attained a larger leaf area than traditionally cane or spur pruned vines. Other work has shown similar results (Clingeleffer 1984; McCarthy and Cirami 1990; Downton and Grant 1991). It has been argued that enhanced leaf canopy development is a result of improved carbohydrate storage with minimal, compared to traditional cane or spur pruning of grapevines, which removes up to 95% of the annual wood production and a proportional amount of carbohydrates, mainly in the form of starch and sugars (Winkler 1958; Winkler et al.(1974).). Conversely, with minimal pruning, because old wood is retained during winter, vines have the capacity to store a relatively larger amount of carbohydrates at the end of a growth period. This presumably would provide them with an advantage over traditionally pruned vines by the beginning of the following season resulting in enhanced growth and accelerated leaf area development.

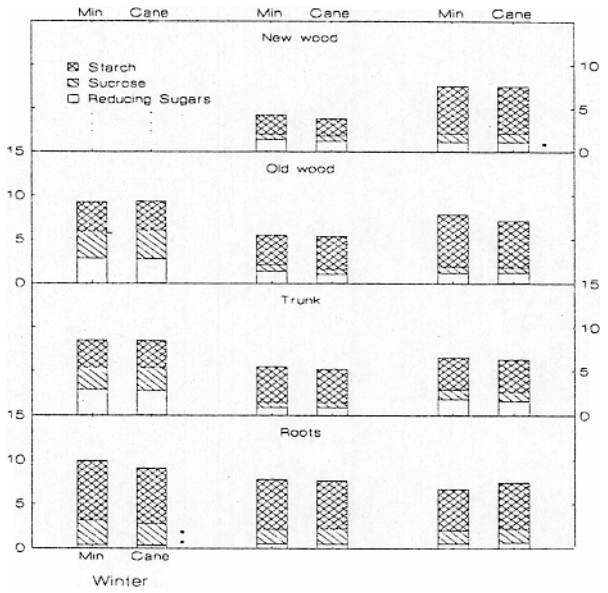


Figure 7 Seasonal development of the concentration of starch, sucrose and reducing sugars in samples from roots, trunks, old wood and new shoots of minimal and cane pruned Cabernet Sauvignon vines at Koorlong. Victoria. Presented are the averages of two seasons 1991/92 and 1992/93. Capital letters indicate treatment differences in the concentration of total carbohydrate for each plant part. Stars indicate treatment differences for carbohydrate fractions within each plant part ($p<0.05$).

Therefore the objective of this aspect of the project was to investigate the seasonal change of the carbohydrate content and composition of minimal and cane pruned vines in the field. The work also examined how grafting on Ramsey rootstock, as compared to growing vines on their own roots, influenced wood carbohydrate content. Investigation was carried out in the Koorlong research vineyard in the Sunraysia district near Mildura.

3.4.1 Carbohydrate content and composition: Seasonal trends

The carbohydrate content of roots, trunk, old wood (cordons, canes) and new wood (shoots) showed little variation between plant parts but there was considerable variation between sampling dates (Figure 7, Figure 8). Generally, regardless of pruning method or grafting, as compared to no grafting, the total carbohydrate content followed a distinct seasonal pattern (Figure 7, Figure 8). In spring, carbohydrate levels were relatively high, compared with those found in mid season. Towards the end of the growth period vines again had attained levels similar to those observed in spring. In winter a larger fraction of the total carbohydrate in roots was stored in the form of sucrose, as compared to spring and autumn, when the proportion of sucrose was considerably lower. Most of the carbohydrate in the roots was stored as starch and to a lesser extent as sucrose. Only a very small concentration of reducing sugars was found in roots. Independent of sampling date the overall level of carbohydrate in roots was always similar with regard to pruning method and grafting as compared to no grafting.

In trunks, compared with roots, more of the total carbohydrate was present in a soluble trunks, except in winter, when its proportion was lower than later in the season. Small but statistically significant differences in the total carbohydrate content were found when comparing grafted and un-grafted vines in winter and spring.

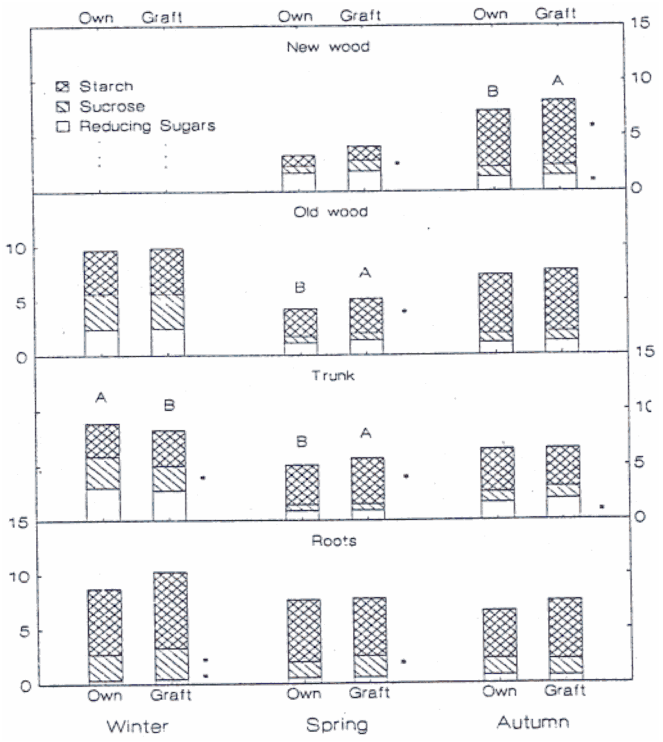


Figure 8 Seasonal development of the concentration of starch, sucrose and reducing sugars in samples from roots, trunks, old wood and new shoots of grafted (Ramsey) and un grafted Cabernet Sauvignon vines at Koorlong, Victoria. Presented are the averages of two seasons 1991/92 and 1992/93. Capital letters indicate treatment differences in the concentration of total carbohydrate for each plant part. Stars indicate treatment differences for carbohydrate fractions within each plant part ($p<0.05$).

Overall concentration was lower in grafted vines in winter but higher in spring. Conversely, pruning method throughout the growth period neither appeared to affect the total level of wood carbohydrate nor that of its components (Figure 7, Figure 8).

In old wood, as was observed for trunks, relatively more carbohydrate was present in a readily soluble form than in roots. Irrespective of treatments, a higher carbohydrate level was found in winter than in either spring or autumn. Grafted vines had higher carbohydrate levels in late spring but otherwise contained similar concentrations as ungrafted vines. In spite of seasonal fluctuations old wood of minimal and cane pruned vines always contained similar carbohydrate levels.

In newly grown wood the carbohydrate levels, in particular that of starch, underwent a marked increase between late spring and autumn regardless of treatment.

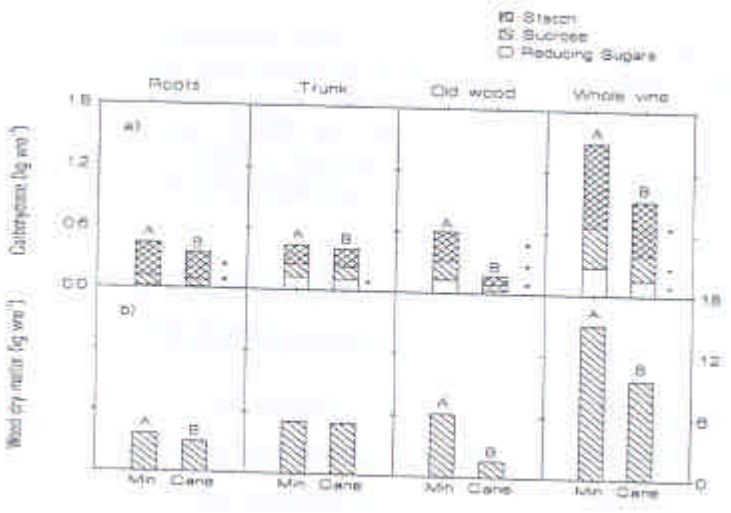


Figure 9 Seasonal development of the concentration of starch, sucrose and reducing sugars in samples from roots, trunks, old wood and new shoots of grafted (Ramsey) and ungrafted Cabernet Sauvignon vines at Koorlong, Victoria. Presented are the averages of two seasons 1991/92 and 1992/93. Capital letters indicate treatment differences in the concentration of total carbohydrate for each plant part. Stars indicate treatment differences for carbohydrate fractions within each plant part ($p<0.05$).

The concentration of the various carbohydrate fractions contained in new wood was higher for grafted than ungrafted vines but was similar in new wood from vines of either pruning method.

3.4.2 Wood dry matter and carbohydrate storage

At one sampling date in mid winter whole vines were removed and the fresh and dry mass of roots, trunk, and old wood (cordon and canes) were assessed. Minimal pruned vines had a considerably larger wood mass than cane pruned vines (Figure 9a). The observed differences were mainly due to a much larger proportion of old wood, *i.e.* permanent cordons and one year old shoots, in minimal as compared to cane pruned vines.

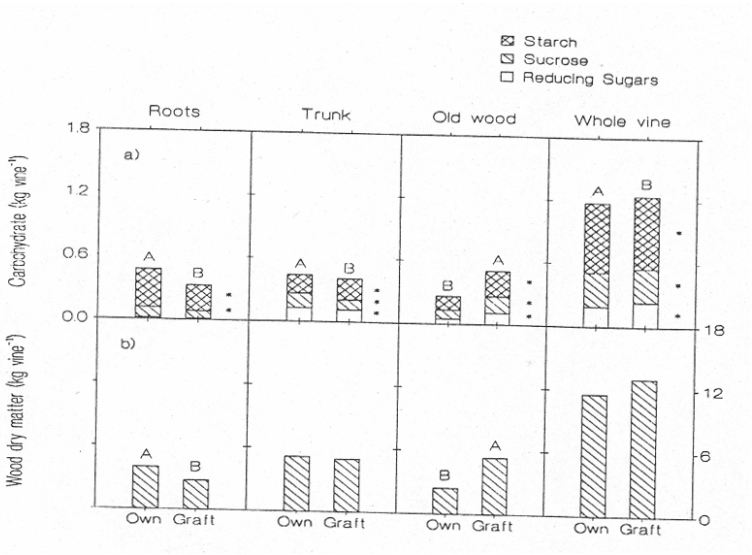


Figure 10 Seasonal development of the concentration of starch, sucrose and reducing sugars in samples from roots, trunks, old wood and new shoots of grafted (Ramsey) and ungrafted Cabernet Sauvignon vines at Koorlong, Victoria. Presented are the averages of two seasons 1991/92 and 1992/93. Capital letters indicate treatment differences in the concentration of total carbohydrate for each plant part. Stars indicate treatment differences for carbohydrate fractions within each plant part ($p<0.05$).

A higher root mass was recorded for minimal than for cane pruned vines but trunks from vines of either pruning system were of similar mass.

Irrespective of the time of season, as was shown earlier, vines of both pruning systems always had a similar concentration of carbohydrate in their woody tissues (Figure 7). In contrast, as was just pointed out, more wood mass was retained over the years as a result of minimal compared with cane pruning. Consequently, the mass of carbohydrate stored in the vine in mid winter was higher for minimal than for cane pruned vines (Figure 9a).

The comparison of ungrafted and grafted vines showed a trend toward a larger wood mass and hence increased carbohydrate storage for the latter (Figure 10ab). Conversely, roots of grafted had a smaller wood and carbohydrate mass than roots of ungrafted vines. Trunks of grafted and ungrafted vines were of similar mass but because of a lower carbohydrate concentration in the latter represented a smaller mass of carbohydrate. Mass of old wood and hence mass of stored carbohydrate were almost twice as high in grafted as compared with ungrafted vines. Old wood therefore was the main contributor towards a higher vine carbohydrate mass in grafted over ungrafted vines.

3.4.3 Pruning weight

The average mass of wood removed from the vines in mid winter of 1991 was much larger as a result of cane as compared to minimal pruning (**Table 10**). Similarly, a considerably larger mass of wood was pruned from grafted compared with ungrafted vines (**Table 10**). These observations largely complement the findings on vine wood mass production in mid winter suggesting that the observed differences between pruning methods were largely the result of wood removal by winter pruning. Differences in wood mass of grafted as compared to ungrafted vines were mainly due to inherent vigour differences between vines grafted to Ramsey rootstocks and those growing on their own roots.

Table 10 Average pruning weights of Cabernet Sauvignon growing at Koorlong, Victoria (1991). Different letters indicate statistical significance between main treatments ($p<0.05$).

between main treatments ($p<0.05$).

		Pruning weight kg vine^{-1}
1991	Cane	2.49 a
	Minimal	0.39 b
1991	Ungrafted	0.83 b
	Grafted	2.01 a

4. Discussion

The introduction of mechanical harvesting techniques in Australia in the mid seventies was closely followed by the adoption of new machine and minimal pruning techniques.

Practical experience in the last twenty-five years has shown that most wine grape varieties can be successfully grown using machine hedging and minimal pruning techniques. Apart from obvious cost savings because of reduced manual labour inputs there are, however, many aspects in relation to vine growth and physiology that need to be considered in order to apply the systems successfully.

This project compared mechanical, minimal and traditional pruning techniques with regard to their influence on vine development, leaf physiology, yield performance, wine quality and carbohydrate economy.

4.1 Leaf canopy development

Light pruning normally leads to a retention of a higher node number during winter than conventional pruning. As a consequence, lightly pruned vines form more but shorter shoots in the spring and fill their leaf canopies more quickly than those under traditional pruning.

The response of vines to light pruning was first investigated and described by (Winkler et al.(1974).). In his work he established a number of principles regarding the morphological and physiological response of vines to varying degrees of pruning. The principles he established are still very applicable today.

For example, he emphasised that light pruning increases vine capacity because of an increase in leaf area and, more importantly a lengthening of the time span during which this leaf area is active.

Results of the present study showed that this principle, almost without exception, applied to the leaf area development of lightly *i.e.* minimal pruned and mechanically hedged vines. Their leaf area development was always significantly accelerated over traditionally, more severely pruned vines. Regardless of location or vine variety (Figures 1, 2). Furthermore, the principle equally applied to grafted (Ramsey) and ungrafted vines. As a consequence of minimal pruning and mechanical hedging and compared with traditional cane and spur pruning, vines always filled their leaf canopy sooner and on average leaves were functional for a longer time span, they had a longer leaf area duration (Clingeleffer 1984; Downton and Grant 1991). Early season canopy fill as a result of light pruning is mostly due to the relatively larger number of buds retained during winter. In the case of minimal pruning up to five times the number of buds of cane pruned vines are retained. After bud burst the relative much larger shoot population rapidly forms a leaf canopy. Conversely, spur and cane pruned vines have to develop their leaf area from a much smaller shoot number. Because leaves on a shoot of either pruning system appear at similar rates the total leaf number and hence canopy leaf area of conventionally pruned vines is much smaller than that of lightly pruned vines. We observed that traditionally pruned vines are compensating for the smaller leaf number by developing larger leaves. Also in many instances, usually by the end of berry set traditional pruned vines are able to attain leaf areas similar to those under light pruning. Fig 1. This was particularly so when traditionally pruned vines were also trained to a wide trellis providing the framework to expand the canopy.

4.2 Leaf physiology

It might be expected that the fewer leaves of a traditionally cane or spur pruned vine compensate by photosynthesising more efficiently than the smaller but more numerous leaves of minimal or machine pruned vines. We regularly measured and compared leaf performance of a large population of leaves of pruning systems ranging from minimal over machine to cane pruning.

In the irrigated inland districts leaf physiological performance, namely assimilation rate, stomatal conductance and water relations of sun leaves, showed similar levels of performance independent of pruning level. This suggests that under the present conditions the capacity of individual leaves for carbon assimilation was not affected by the pruning level. Comparing minimal and spur pruned Riesling vines Downton (1991) observed similar assimilation rates but delayed leaf area development of the latter. He estimated that minimal pruned vines fixed around 12% more carbon in the period between bud burst and harvest.

In Coonawarra, leaf physiological performance between pruning levels was similar, provided the irrigation management between the treatments was identical. Traditional systems of growing grape vines in Coonawarra, as pointed out earlier, do not apply supplementary irrigation. In both years this depressed assimilation rate and leaf conductance and ultimately, particularly in the 1992, reduced sugar levels and yield. Consideration of supplementary irrigation, even in areas that normally receive sufficient rainfall, is therefore important. This result further illustrates that adequate water supply is even more crucial on systems with reduced pruning levels because of their comparatively larger vine leaf areas and transpiration rates.

4.3 Crop capacity and wine quality

(Winkler et al.(1974).) demonstrated that lightly pruned vines, because of their greater capacity, were able to support larger crops than severely pruned vines. This agrees with our observations particularly in the hot irrigated inland district of Mildura where water and other environmental constraints such as light and temperature are less limiting than in cooler areas closer to the coast.

4.3.1 Irrigated inland district (Sunraysia)

At two commercial vineyards at Nangiloc minimal pruned vines of the varieties Chardonnay and Cabernet Sauvignon on average produced higher crops of similar juice quality as spur pruned Chardonnay and cane pruned Cabernet Sauvignon **(Table 3**). Except with very large yields, as were obtained in 1992 for minimal pruned Chardonnay, sugar level and juice quality were comparable to that of spur pruned Chardonnay.

Very high yields with adequate sugar levels were achieved by minimal pruning in the Koorlong experiment, planted to Cabernet Sauvignon **(Table 4).** Data showed an almost two fold increase in crop yield attributable to the choice of pruning method. Other work has shown similar yield increases including other wine grape varieties (McCarthy and Cirami 1990). Obviously severe pruning reduced vine capacity and therefore vines were unable to grow to their full potential in a given environment. Minimal pruning also increased the number of bunches per vine and reduced berry size resulting in less tightly packed berries than with cane pruning. These are desirable attributes with regard to fruit quality because small, loose bunches are less likely affected by bunch rot (Emmet et al. 1995).

In spite of substantial yield differences between the pruning treatments, in 1992 minimal pruned vines produced wines of similar quality as cane pruned vines. However, in the following season probably because of delayed ripening and lower juice sugar, wine quality obtained from minimal pruned vines was lower than that of cane pruned vines. The decline in quality was clearly seasonal, suggesting that minimal pruned vines because of their larger crops were less able to compensate for adverse seasonal conditions.

In 1992 grafted vines produced more than twice the crop of un-grafted vines but the difference in yield was clearly reflected in an inferior juice and wine quality due to grafting **(Table 5).** Grafting resulted in wines of inferior colour and high pH. The wine analysis data suggested that grafted vines had a high proportion of shaded fruit probably as a result of the very vigorous canopy growth. Surprisingly the wine analysis data was not confirmed by the tasting panel who gave wine of grafted vines a similar score to wines produced from un-grafted vines.

A detrimental effect of high vigour in combination with wet weather conditions was observed in the following season (1992/93) when grafted vines were repeatedly and severely infected with downy mildew which led to almost total- fruit loss. Conversely, the less vigorous un-grafted vines suffered far less damage from disease probably because the preventative chemical spray applications better penetrated and covered the leaf canopy. Also after rainfall events the open leaf canopy of un-grafted vines dried up more quickly than the comparatively vigorous and dense canopy of grafted vines, thereby preventing conditions, conducive to infection. Consequently grafted vines, because of high vigour, were more susceptible to infection. Grafted vines in a good season produced a very high yield, but their fruit and wine was of inferior quality compared with un-grafted vines.

4.3.2 Cool climate district (Coonawarra)

The problem of over-cropping is potentially of concern with light pruning in cooler climatic areas such as Coonawarra in South Australia. The capacity of a vine to ripen a crop is largely determined by two factors: the leaf area of the vine and the climatic constraints of a given environment. If a crop is larger than what may be supported by a given leaf area and climate, it will not mature and the result is an over-crop (Winkler et al.(1974).). Associated with over-cropping is a decline in fruit quality characterized by poor colour and low sugar often leading to reduced wine quality.

4.3.2.1 Cabernet Sauvignon

In the trial with Cabernet Sauvignon minimal pruned vines did produce a substantially bigger crop than vines of the other treatments and a delay in ripening was associated with the bigger crops. However, fruit quality was similar to that of hedge pruned vines, which had produced less than one third of the crop of minimal pruned vines. Similarly, in spite of a more than two-fold yield difference, wine of minimal pruned vines was of similar or higher quality to that of machine hedged vines and achieved a higher tasting score than the latter. Wine of the irrigated and un-irrigated cane pruned treatment always rated higher than either wine from minimal or hedged vines. However, in seasons of low rainfall, cane pruned vines without irrigation were very susceptible to water stress and produced very low yields. It would appear that for the two seasons minimal pruned vines did produce comparatively high yield with very acceptable quality, equal or superior to hedge pruned vines but not as good as traditional cane pruning.

4.3.2.2 Shiraz

Strong seasonal yield, fruit and wine quality fluctuations were observed for minimal and hedge pruned treatments in a commercial Shiraz vineyard in Coonawarra. Most of the variation in quality was related to the size of the crop. In the first year of the trial minimal and hedge pruned vines produced acceptable fruit and wine quality and much higher yields than traditionally cane pruned vines. In the second season hedge pruned vine yield were down relative the previous season and to minimal pruned vines which had exceptionally high yields. The high yield did compromise juice and wine quality of minimal pruned vines characterised by low sugar in the juice and poor colour and phenolics in the wine. In years of high cropping potential Shiraz vines did not have the capacity to ripen the crop within the constraints of the given environment. Data of (Clingeleffer 1993) showed that minimal pruned Shiraz may produce a crop of over 30 tons per ha in the Coonawarra region but at the expense of a delay in maturity and reduced fruit quality. An alternative to avoid over-cropping is crop thinning or skirting which reduces the crop to a level that may be supported by the photosynthetic capacity of the vine.

4.4 Carbohydrate storage

In a comparison of minimal and traditionally pruned vines there were no differences in either sugars or starch concentration of the woody tissues of roots, trunks, old wood or new wood attributable to the level of pruning. This is in contrast to (Ruhl and Clingeleffer 1993) who found slightly higher sugar levels in trunks and roots but lower starch levels in roots of minimal as compared to cane pruned Cabernet Franc. On the other hand, they also reported similar overall carbohydrate concentrations in all plant parts regardless of pruning levels. Substantially higher levels of total vine carbohydrates were found in minimal over cane pruned vines because of large differences in vine dry matter, most of which was attributable to an accumulation of old wood because of minimal pruning. This was similar to (Ruhl and Clingeleffer 1993) whose minimal pruned vines, converted from spur pruning, were also larger than their spur pruned variants and hence total vine carbohydrate was also higher. This demonstrates that vine size is a probably more important factor in determining vine carbohydrate storage than carbohydrate concentration in the tissue.

5. Conclusions

Research has demonstrated that leaf canopies of minimal pruned vines developed more quickly and filled their leaf canopies sooner than either machine hedged, cane or spur pruned vines. As a result minimal pruned leaf canopies were functioning for a longer time span, they had a longer leaf area duration and probably a higher assimilation capacity.

Minimal pruned vines retained a higher number of buds over winter than traditionally cane and spur pruned vines. As a consequence they developed a much larger number of shoots than traditionally pruned vines. On average shoots of minimal pruned vines were shorter, with fewer, more compact internodes, resulting in fewer and smaller leaves compared with shoots of traditionally cane or spur pruned vines.

The potential for carbon assimilation of single sun-exposed leaves of minimal pruned vines was similar to that of traditionally pruned vines.

In the irrigated inland district of Sunraysia minimal pruning resulted in higher yield levels but similar fruit and wine quality as was achieved with traditional cane and spur pruning. In the more limiting cool climate areas vine capacity was not always sufficient to ripen fruit from vines under minimal pruning, particularly in years with a high crop yield, reducing fruit and wine quality.

Differences in vine performance between mechanical hedging, minimal pruning and traditional pruning are mostly attributable to vine capacity, namely leaf area development and duration. No significant differences were observed in the assimilation capacity of single sun-exposed leaves.

The carbohydrate concentration of different plant parts was similar between minimal and cane pruned vines but because of a higher wood mass, mainly due to retained shoots from the previous season, minimal pruned vines had a higher capacity to store carbohydrate.

Results emphasise that less severe mechanical and minimal pruning systems increase vine capacity and yield potential. However, in some situations this increased capacity may have to be adjusted to suit the predominant climatic and soil conditions.

6. Publications arising from the study

Sommer, K.J. and. Clingeleffer, P.R. (1993). Comparison of leaf area development, leaf physiology, berry maturation, juice quality and fruit yield of minimal and cane pruned Cabernet Sauvignon grapevines. Pruning Mechanisation and Crop Control. Fredonia State University, Fredonia, New York, USA.pp.14-19.

Sommer, K.J., Clingeleffer. P.R., and Ollat, N. (1993) Effects of minima! pruning on grapevine canopy development, physiology and cropping level in both cool and warm climates. Viticultural and Enological Sciences 48,135-139.

Ollat, N., Sommer, K.J., Pool, R.M. and Clingeleffer, P.R. (1993) Quelques resultats sur la taille minimale en Australie et en France. Comptes Rendus No.6, Group Europeen d'etude des systemes de conduite de la vigne (G.E.S.C.O., Reims, France, April 14-16, 1993).

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.

Ollat, N., Sommer, K.J., Pool, R.M. and Clingeleffer, P.R. (1994) La taille minimale, pratique viticole Australienne. Progres Agricole et Viticole 111, 329-334.

Clingeleffer, P.R. and Sommer, K.J. (1995). Vine development and vigour control. Proceedings of. a Seminar on Canopy Management. Australian Society of Viticulture and Oenology. Adelaide.pp.7-17.

Sommer.. K.J. (1995). Mechanisierung des Rebschnitts in Australien. In: Mechaniserung der Stockpflegearbeiten. A. Rohling, W.Achilles eds. KTBL. Darmstadt.pp.23-50.

Sommer, K.J. and Clingeleffer, P.R. (1996). Vine canopy development and carbohydrate partitioning as influenced by pruning. Proceedings Ninth Australian Wine Industry Technical Conference. Adelaide pp. 123 -,127.

7. Bibliography

Clingeleffer, P.R. (1983). Minimal pruning -its role in canopy management and implications for its use for the wine industry. Proceedings Fifth Australian Wine Industry Technical Conference. Perth.pp.133-140, 145.

Clingeleffer, P.R. (1984) Production and growth of minimal pruned Sultana vines. Vitis 23,42-54.

Clingeleffer, P.R. (1989) Minimal pruning of cordon trained vines (MPCT). Rivista di Ingegneria Agraria 112-120.

Clingeleffer, P.R. and Possingham, J.V. (1986). The role of minimal pruning of cordon trained vines (MPCT) In canopy management and its adoption in Australian viticulture.pp.615-631.

Clingeleffer, P.R. and Possingham, J. V. (1987) The role of minimal pruning of cordon trained vines (MPCT) in canopy management and its adoption in Australian viticulture. Australian Grapegrower and Winemaker 280, 7-11.

Downton, W.J.S. and Grant, W.J.R. (1991) Photosynthetic physiology of spur pruned and minimal pruned grape vines. Australian Journal of Plant Physiology 19, 309-316.

Kerridge, G.H. (1983). Small-scale winemaking in varietal assessment. *Fermentation Technology;* Proceedings of a seminar. Australian Society of Viticulture and Oenology. Glen Osmond, South Australia.pp. 71- 77.

Kidd, C.H. (1986). Canopy management. Sixth Australian Wine Industry Technical Conference. Australian Wine Research Institute. Glen Osmond, South Australia.pp.212-213.

May, P. and Clingeleffer, P.R. (1977) Mechanical pruning of grape vines. Australian Wine, Brewing Spirit Review 96, 36-38.

McCarthy, M.G. and Cirami, R. (1990) Minimal pruning effects on the performance of selections of *Vitis vinifera* cultivars. Vitis 29, 85-96.

Northcote, K.H. (1958) A pedological study of the soils occurring at Coomealla New South

Wales. CSIRO Bulletin No 264

Northcote, K.H. (1988) Soils and Australian Viticulture. In: 'Viticulture'. Eds. B.G. Coombe

and P.R. D (Australian Industrial Publishers: Adelaide) Vol. 1. pp. 61-90.

Rohl, E.H. (1993). Rootstock evaluation for low juice pH. Proceedings Eighth Australian Wine

Industry Technical Conference. Adelaide.pp.64-67.

Somers, T.C. and Evans, M.E. (1977) Spectral evaluation of young red wines: Anthocyanin equilibria total phenolics, free and molecular S02, "chemical age". Journal of Science in 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 Pia Physiology 21,197-206.

Winkler, A.J. (1958) The relationship of leaf area and climate to vine performance and grape quality.
American Journal of Enology and Viticulture 9,10-23.

Winkler, A.J., Cook, J.A., Kliewer, W.M., et al.(1974) 'General Viticulture'. (University of California Press: Berkley.)