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D.M. Lanyon[1,4], A. Cass[2], and D. Hansen[3]

[1]CSIRO Land & Water, PMB 2, Glen Osmond, SA 5064, Australia

[2]Alfred Cass and Associates, 2330 Mark West Springs Road, Santa Rosa, CA 95404, USA

[3]Southcorp, PO Box 50, McLaren Vale, SA 5171, Australia

[4]Corresponding author: Dr. Dean Lanyon, facsimile +61 8 8303 8520, email dean.lanyon@csiro.au

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Executive Summary

The importance of soil properties and soil management for wine grape production is acknowledged by most producers but is generally relegated as secondary to climate and canopy management. Perhaps because of this, many controversies and disputes exist about the role of soil in wine production. To help dispel misconceptions and settle controversies, we undertook an extensive review of the viticultural soil literature.

This review is underpinned by discussion relating to the meaning of “vine performance” and proceeds to develop the theme of how soil properties and management affect vine performance. In this review, vine performance largely focuses on vine survival and growth, root function and fruit quality. We concentrated on literature published in English in research and industry journals.

Alteration of many soil properties is often a slow process and several years may elapse before the effects of different soil management systems are manifested. Generally, in 60 % of the literature we reviewed, experiments and monitoring of soil management was not continued for more than one year. With this deficiency, we could only link soil properties to vine performance in general terms. With this in mind, we discuss the opportunities and limitations of soil related research that will provide a better framework for linking soil properties to parameters of vine performance.

The literature does reflect the widespread belief that proper soil selection, land preparation and amelioration are the keys to successful viticultural production and the first step towards obtaining superior fruit quality. The techniques for this are well known although not all aspects of this technology are underpinned by research in a viticultural setting. The literature acknowledges that when these techniques are correctly applied, differences between soils with respect to vine survival and growth largely disappear. However, finer detail regarding land preparation techniques and amelioration for assuring the best fruit quality in a given climatic and commercial setting are yet to be published in the public domain.

From the information we obtained in the literature we tried to formulate a set of benchmark soil property values to judge vineyard soil quality for best vine performance. We conclude that there is no one ideal soil for wine grape production per se but rather an ideal set of soil properties for a given climate, with possible further refinement based on consideration of target wine style and variety. The inclusion of irrigation causes a broadening of the characteristics of the ideal soil but may also give rise to a range of sustainability issues such as sodicity and salinity.

The review presents evidence to show that issues relating to soil water supply are generally regarded as very important in determining vine survival and growth, root function and fruit quality. Results of research in this topic, particularly in Australia, have had positive benefits for fruit quality and impelled the industry into sophisticated soil and vine water status monitoring. However, despite the progress made in this area, a prominent deficiency emerged from the literature. Differences in water supply capacities between soils are hardly acknowledged in the published work done on the role of water supply to vines. Researchers generally regarded all soils as equivalent in their capacity to supply water to vines. No serious attempts have been made to study and define the differential water supply properties of any important viticultural soils.

Generally the influence of soil properties on vine root function and health is poorly documented in the viticultural literature although there have been several excellent recent advances. In particular the effect of soil hardness and anoxia (waterlogging) are important issues that need considerable work before a complete understanding of the effects on vine performance, in commercial settings, are achieved. Several reports in the literature acknowledge that both areas are of importance in vine survival and growth and fruit quality. In fact, soil selection criteria and modern land preparation techniques (deep tillage and amendment application) for viticulture are centred on avoiding excess hardness and poor

internal water drainage in newly-developed vineyards. These topics are well documented in the literature although more research in both areas is required. However, the detail of the impact of root restrictions and waterlogging of vine roots in established vineyards on vine growth and fruit quality are not really known. In particular, the interactions of soil physical and chemical properties, particularly those effects that arise from high sodium (sodic soils) or high magnesium (magnesic soils) and nutrient uptake particularly and vine performance generally, are poorly understood.

The effect of salinity on vine performance is extensively dealt with in the literature. Measures to control salt accumulation are addressed and the use of various measures to combat high soil salinity are reported quite widely, especially in the Australian literature. Vine nutrition also enjoys wide coverage in the viticultural literature and generally technology and understanding of fertilizer application for optimum vine growth is well advanced. However, even though this topic is quite advanced, there are areas that seem to be poorly understood. The general relationship between soil vine nutritional composition and vine performance is obscure as judged from recent publications that address recommendations for optimum soil values of the nutrient macro- and micro-elements.

Techniques for soil surface management in established vineyards are prominently reported in the literature. Viticulturalists have done much research and reported extensively on the use of herbicides, cover crops and soil tillage to manage vineyard soils after establishment. However, it is clear from the literature that a variety of objectives are pursued in this work not just that of surface soil management. This multi-targeted activity has tended to obscure the central issue of the need to develop management techniques in vineyards that preserve optimum soil surface structure to ensure that soil physical processes such as infiltration, gas exchange, drainage and soil hardness proceed at optimum rates. All of the viticultural literature that we reviewed indicated that this aim could only be achieved if routine tillage of soil in established vineyards is reduced to an absolute minimum and cover crops managed to preserve a high level of biological activity in surface soil. The fact that universal commercial adoption of these techniques in viticulture lags behind the published literature is probably attributable to a lack of clear evidence that these conservative practices really promote vine performance and particularly fruit quality.

We discovered some general deficiencies in the viticultural literature in relation to soil issues. Although some effects of soil properties are well understood with respect to root growth, there is little information relating these effects to grape quality. The main difficulty we found in establishing a connection between soil properties and fruit quality was because of the lack of accompanying soils data, or adequate soil description, with data on vine performance. This is made more difficult by the absence of a suitable vine specific soil classification system (soil key). The advent of such a system in Australia may stimulate more research work in this area.

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1 Introduction

The association between wine quality and environmental factors has enjoyed research attention, intense discussion and heated debate for many decades. The three most basic environmental factors addressed in this debate are the influence of climate, soil, and canopy management on wine quality. Soil factors have generally emerged as secondary to the effects of the other two in determining the productivity of the grapevine and the quality of grapes, and ultimately, wine. However, in this debate, only few disagree that soil properties and management do play some role in wine production.

In many areas, soil does play a very significant role. Seguin (1986) attributed the quality of wine produced in the premium wine growing areas of Bordeaux and Médoc to soil factors. The basis of his argument is that regions that consistently produce high quality wines have soils that are well structured, highly permeable, well aerated and which attenuate the harmful effects of extreme climatic conditions such as long drought or heavy rainfall.

On the other hand, some have denied that soil does play a role on wine flavour. For example, Charters (2000) asserts that soil has little effect on wine flavour. So, a degree of contention does exist in this debate. Does soil play a role in some climatic settings and not in others? Is it possible that wine flavour is too far removed from the influence of soil but that it has a distinct role further back in the production stream?

Viticulturalists have often associated grape quality and wine quality with the type of soil from which the grapes are produced (eg Gregory 1963; Peynaud and Ribéreau-Gayon 1971; Rankine et al. 1971; Champagnol 1984; Carbonneau and Casteran 1986, 1987). The effects of soil type on wine quality were attributed to differences in mineral, thermal and physical properties of the soil. However, not all accept these views and its relationship to wine quality remains controversial (Gladstone 1992).

Most recent literature suggests that the effect of soil type on grape quality is associated with the interaction between vine vigour and soil water retention properties (eg. Saayman and Kleynhans 1978; Seguin 1983, 1986). Other authors and proponents take the view that "soil mineral character" influences grape quality. Champagnol (1984) acknowledges that moisture relations are important, but also asserts that soil mineral characteristics may influence the subtler qualities of grapes and the resultant wine. The difficulty in defining the influence of "mineral character" lies in the development of objective relationships between soil mineral properties, water relations and quantifiable grape quality indices

It is this variation of opinion about the value of soil knowledge in grape growing and the apparent potential benefits in increasing our perception of viticultural soils that lead us to review the literature on this topic. The purpose of this review is to explore the relationship between soil properties and vine performance and reveal what opportunities might exist to improve the selection and management of soils for wine grape production. In doing so, we hope to develop a set of critical parameters to form a framework for quantitative, soil-based criteria for judging the health and sustainability of vineyard soils in Australia and for designing soil specific development and management tools for new and existing vineyards.

2 Vine Performance

If we are to establish relationships between soil properties and vine performance, we need to define what we mean by "performance". Vine performance targets may be specific, such as lower water use, smaller berry size and reduced vigour, or more generic, such as improved grape quality or better vine balance, which are more difficult to quantify. Targets are determined by economic factors that may change depending on market forces and environmental factors that may or may not change. For example, many recent developments in viticulture are aimed at production of better quality fruit together with improved efficiency of production (Van Huyssteen, 1989) rather than high yields. This trend points to a useful definition of vine performance for the purpose of this review: '*the measure of vine response against targets that encompass economic and sustainable values*'.

To use this definition effectively poses the challenge of establishing a set of targets for vine performance from which manageable and unmanageable factors can be assessed. Although targets for canopy management are well established (Smart and Robinson 1991), targets for grape quality are harder to define. However, there are some obvious factors that can be discussed.

Yield is perceived, and commonly used, as an indicator of grape quality. However, target yields for quality grapes range from 25 tonnes per hectare in the Riverland down to 7 tonnes per hectare in the Adelaide Hills (Kennedy and James 1999). Consequently, the relationship between yield and grape quality is problematic, being location specific. De Garis (1999) has shown that yield is poorly correlated with other grape quality indicators such as Baume and colour.

Recently much activity and effort has been directed at correlating grape compositional characteristics with wine quality (eg. Johnstone et al. 1996; Francis et al. 1998; Dambergs et al. 1999). Johnstone et al. (1996) tested the usefulness of vine parameters together with the chemical measures of juice and berry composition as predictors of potential wine quality. They found that the most valuable predictors were berry weight (-ve), Baume (+ve), juice malate level (-ve), total anthocyanins and phenolics in berries or juice (+ve) and total glycosyl-glucose (G-G) (+ve).

We were not able to derive a set of target values, or ranges, for each of these grape attributes for the array of wine qualities from 'volume' through to 'elite' wine (Donald and Georgiadis 1999) from publications. The absence of these grape compositional targets makes the linkage between soil properties and wine quality subjective and limits our capacity to judge the appropriateness of site selection and various management practices with wine quality in mind. An example of notional targets for quality dry white or red table wines is shown in Table 1. Obtaining such notional targets will provide a quantitative awareness of the impact that soil properties have on vine performance and provide the viticultural industry with an opportunity for progress.

Table 1: Notional targets of grape composition for quality dry white or red table wine (Bishop and Thomas, 2002)

Parameter	Notional target
^{o}Baume	12 – 14.5
pH	3.3 - 3.5
Titratable acidity	>6.5 g/L tartaric acid

Despite the existence of these berry quality indicators, it has been difficult to extract clearly definitive relationships between soil properties and behaviour and berry quality from the viticultural soil literature. Burdened with this limitation, from the literature available, we could generally only judge the impact of soil properties on vine performance subjectively rather than objectively in relation to grape quality.

3 Soil Properties and Vine Performance

The part of the grapevine that is immediately affected by soil properties is the root system. Roots absorb and conduct most of the vine's water and nutrient requirements to the aerial parts of the plant. Various plant hormones, synthesised in the roots, are needed for adequate development of the shoot system (Richards, 1983). Consequently the size and health of the vine root system essentially governs the size (vigour) and performance of the canopy (Smart 1995, Southey 1992).

Vine vigour has an important impact on berry quality and optimum berry quality is seldom achieved if vines are excessively vigorous. On the other hand, vines with a restricted root system and canopy do not necessarily produce high quality fruit (Van Huyssteen and Weber 1980c). Consequently, for high quality berry production, it is necessary to target optimum, as opposed to maximum or minimum, root growth and development. The extent and distribution of roots in relation to considerations of optimum productivity, quality and sustainability are very important but not particularly well defined. The key issue, however, is the relationship between root functionality, soil structure and vine performance in relation to targeted yield and quality specifications. Hence, what follows is a reflection on how soil properties influence vine performance in relation to root and shoot growth, yield, and grape quality.

3.1 Physical properties

Soil physical properties essentially govern the potential volume of soil that can be explored by roots. This volume is primarily controlled by soil structure. Soil structure relates to the arrangement of primary particles and the associated pores between them (Oades 1993) and affects, both directly and indirectly, many physical, chemical and biological aspects of the soil. These include soil strength, water and nutrient movement, soil aeration, soil hydraulic properties, soil workability, preparation of seedbeds, and soil erodibility (Aylmore and Sills 1982; Oades 1984; Dexter 1988; Chan 1989a,b; Kay 1990b; Dexter 1991; Rengasamy and Olsson 1991; Oades 1993). The functional aspects of soil structure, namely water supply (Hamblin 1985) and aeration (Gupta and Larson 1982) are the two most important soil characteristics determining suitability of soil for viticulture (Northcote 1988). These are properties that we need to ascertain their degree of influence on vine performance, with specific attention to root and shoot growth, yield and grape quality.

3.1.1 Water storage and availability

The effect of water storage and availability on vine performance is a topic that receives a great deal of attention in the viticultural industry and in the viticultural literature. One obvious soil constraint to vine performance in the various climates of Australia is the lack of stored soil water. Although lack of water is mainly associated with climate, storage of water in soil and root access to the stored water is dependant on soil physical properties. The inter-row area can be a source of stored water but that water is often not utilised by the vine because of poor root penetration into the midrow. A variety of factors may be responsible for this, including compact wheel tracks. Other limitations to water storage may arise from textural characteristics such as high content of coarse sand or by impenetrable layers as for example in shallow duplex soils. Irrigation provides a way of adapting to these situations.

Rowe (1993) and Wang et al. (2001) demonstrated that, even in situations where water and nutrient availability are non-limiting, the size of the root system has a direct affect on shoot growth and, hence, associated vine balance. Passioura and Stirzaker (1993) have described this as a feed-forward response whereby roots sense restricted or difficult conditions in the soil and send signals to the shoot that slows growth even before the water supply is depleted. In principle, the same mechanism is used to slow shoot growth when using partial root-zone drying as described by Dry and Loveys (1998).

The distribution of water in soil has a strong influence on root distribution. There is also a relationship between water and air distribution in soil. For example, Freeman and Smart (1976) found when irrigation was applied at a rate of 100 % of evaporation, root growth was stimulated compared with irrigation at 300 % of evaporation. Van Zyl (1988) found that if irrigation was applied to grapevines when 25 and 50 % of the total plant available water had been used, there were 190 and 300 actively growing tips per m^2. When the soil was irrigated when 75% of the total plant available water had been used, a peak of approximately 40 tips/m^2 at flowering occurred and new root growth was consistently less than this for the remainder of the season. These data show that root development was adversely affected when soil water content remained close to saturation for lengthy periods of time.

Irrigation systems and soil water regimes also have a significant impact on grapevine root distribution. Roots have been observed to concentrate in the wetted plume under drippers but are more dispersed under various sprinkler systems (Van Zyl, 1984; Safran *et al.*, 1975; Stevens and Douglas, 1994). Root distribution under drippers has been reported to have an 'onion skin' distribution in finer textured soils (Silberbush et al., 1979; Safran et al., 1975). Stevens and Douglas (1994) and van Zyl (1988) compared the rooting patterns under drip and full cover micro-jet irrigation. They found that under drip irrigation, roots were concentrated under the vine row, whereas under micro-jet irrigation roots were evenly spread across the planting area. However, the root density under drip irrigation was higher than under micro-jet irrigation. Under drip irrigation the vines will become more dependant on irrigation due to a smaller rooting volume. Similarly, roots were found in high concentration in the inter-row relative to the vine row under furrow irrigation in a gradational calcareous loam for both Muscat Gordo Blanco and Shiraz vines (Stevens and Nicholas 1994). van Zyl (1988) also reported that root distribution under furrow and full surface irrigation were fairly uniform between rows and that soil water depletion closely matched the distribution of roots with depth.

In these observations, root density directly under the dripper was less than at the margins of the dripper plume because of periodic oxygen shortages in the excessively wet and slowly draining soil directly under the drippers. Root growth outside of the irrigated soil volume was found to occur principally in spring and autumn when rains moistened the non-irrigated parts of the vineyard sufficiently to allow root growth (Van Zyl, 1988). Following this observation, Van Zyl (1988) speculated that root distribution patterns were probably increasingly shaped by the irrigation system as the natural rainfall decreased.

Concepts related to measurement and management of soil water storage and supply in vineyards are well known (e.g. McCarthy et al. 1988). Water availability affects yield, fruit and grape quality both directly and indirectly. The major effects are indirect and act via vegetative growth due to the direct effects of leaf water potential, turgor, translocation of organic and inorganic substances, and canopy photosynthesis.

The rate of vegetative growth during each physiological stage of development affects the sink source relationships and consequently fundamental processes, such as bud fertility, fruit set, berry and cluster size, skin to flesh ratio, and accumulation and breakdown of sugars, acids and various colour, aroma and flavour compounds (Bravdo and Hepner 1986). The indirect effects dominate in the oversupply of water where as the direct effects dominate in the undersupply of water.

Large amounts of available water within the root zone invariably lead to large, dense canopies that may become photosynthetically inefficient (Smart 1974). This can lead to low fruitfulness (May 1965; Jackson and Coombe 1988) and poor microclimatic effects that increases the vine's susceptibility to diseases such as powdery mildew (Smart and Robinson 1991). Excessive vegetative growth after veraison has also been shown to adversely affect fruit colouration and quality (as expressed in terms of sugars, flavour and aroma compounds) due to sink competition between the ripening fruit and the shoot (Bravdo et al. 1985a,b) and results in maturity delays (Wildman et al. 1976).

Mild water stress on the other hand, caused by a reduced amount of available water within the root zone, may enhance sugar accumulation by suppressing shoot growth or reducing canopy density (Stevens et al. 1995), thereby permitting higher photosynthetic rates by interior leaves. Mild water deficits are also known to have positive effects on reducing berry size (Smart 1974) and on berry skin anthocyanin and tannin content in red grape varieties (Hardie and Considine 1976; Matthews and Anderson 1988; Koundouras et al. 1999).

However, water stress should not be regarded as a panacea for good quality fruit. Fregoni (1977), Seguin (1986) and Gladstone (1992) suggest that for the highest quality grapes in all climates, there needs to be a steady, moderate availability of moisture. However, measurable limits to what was meant by 'moderate availability' were not defined by any of these researchers. There is ample documentation of the negative effects that water stress can have on vine performance in terms of yield and grape quality. For example, water stress during flowering can lead to the abscission and desiccation of flowers (Hardie and Considine 1976), while water stress in the weeks following flowering can have a negative impact on yield by restricting cell division and enlargement in the young berries (McCarthy 1997; Matthews et al 1987; Van Zyl 1984). Water stress during canopy development can also result in insufficient leaf area after veraison, reducing the rate of sugar synthesis and causing sun burn damage to fruit (Weeks et al. 1984). Extreme moisture shortages can result in premature leaf senescence and incomplete fruit ripening (Hardie and Considine 1976; Van Huyssteen and Weber 1980c). Hence, the availability of water to the vine, which is essentially controlled by soil properties and irrigation, plays an important role in determining the ability to achieve a target vine performance.

The amount of water that is potentially available for grape production is determined by the amount of rainfall, the water holding characteristics of the soil and the root distribution of the vine. For winter-dominant rainfall, vine growth depends on stored soil water, and when this is inadequate, irrigation is necessary. The amount of water required by the vine for the production of a given amount of fruit of a given quality, is not easy to derive. Experiences in South Africa suggest that 500 mm of water is required from bud burst to maturity for economically successful viticulture (Van Zyl and Van Huyssteen 1983).

Part of the difficulty in attaining a more comprehensive view on the effects of water storage on vine performance is that nobody has addressed the water supply differences in relation to root extent and activity, including the use of irrigation, that exists within the spectrum of Australian viticultural soils, across varying climate zones. With attention focused on improvements in water use efficiency due to dwindeling water resource quality and quantity, this information will be invaluable in accessing potential vineyard sites and the benefits of soil management practices in existing vineyards as outlined by Fitzpatrick *et al*. (1993). Clearly, we need to make considerable effort into the collection and interpretation of water storage, root distribution and climate effects on vine performance for the range of soils used in Australian viticulture. Bramley (2001, 2003), who used precision viticulture technologies to associate vine response to soil properties linked to available water, has made a step in this direction. Defining the available water for vine growth, however, will need a better understanding of root distribution patterns, soil infiltration and storage properties and the balance between what is used by the vine (transpiration) and water lost to other forms of use (evaporation and transpiration from cover crops).

In situations where irrigation water quality is good and its quantity is not limiting, the volume of irrigation water could be reduced if the grapevine root volume was increased. However McCarthy et al. (1983) warned that increasing the root volume in this case may lead to poor berry quality. It is important to recognise that canopy management, irrigation management, and soil management affect grape quality and are interrelated. Given an increased rooting volume through improved soil management, it may be advisable to alter canopy and/or irrigation management to maintain grape quality.

3.1.2 Aeration and waterlogging

Waterlogging affects root and shoot growth and root survival (Kobayashi et al. 1963; Iwasaki et al. 1966). The susceptibility of soil to waterlogging is a function of rainfall, irrigation frequency, ability of the soil profile to drain and the distance to the water table (Fitzpatrick et al. 1993). Unimpeded soil drainage is often associated with of the highest quality wine (Seguin 1986; Champagnol 1984).

Grapevines are most sensitive to waterlogging during early spring and periods of active root growth (Myburgh and Moolman 1991a, b). Soils are regarded as effectively waterlogged when 93 % or more of the total soil porosity is occupied by water, depriving plant roots of access to oxygen. A critical air-filled porosity of 10 to 15 % of the total porosity is regarded as the minimum air porosity to allow root respiration and exchange of soil oxygen and carbon dioxide with atmospheric sources to proceed (Dexter 1988).

Early waterlogging can have a serious impact on initial shoot growth because new root growth can be delayed by up to 10 weeks after bud break (Freeman and Smart 1976). This was demonstrated in a glasshouse experiment by Dowley et al. (2002h) where shoot and leaf growth was severely reduced when the root zone was waterlogged beyond bud break. Stevens et al. (1999) found that severity of root and shoot growth reduction increased as the period of waterlogging increased during the growing season. These observations are in general agreement with field observations by Dowley et al. (2002a to g).

Myburgh (1994) observed that the majority of fine grapevine roots in a seasonally waterlogged sub-soil were dead when they were observed in late spring. Similar findings were also reported by Northcote (1973) and Smart and Coombe (1983). Clearly, root growth and function are restricted by anaerobic conditions bought on by waterlogging. Vines grown in furrow and flood irrigation systems are frequently waterlogged (May 1994).

According to Jackson (1985) the accumulation of ethylene under conditions of prolonged soil waterlogging is the cause of detrimental plant growth. Perret and Koblet (1981) stated that ethylene concentrations as low as 1 mg/kg can adversely influence vine root performance and postulated that ethylene inhibits the uptake of iron. Iron deficiency results in the typical chlorotic symptoms that accompany poor soil aeration and waterlogged conditions.

Although the understanding of waterlogging effects on root and shoot growth are improving, what is less clear is the extent to which the root system can compensate for partial root zone anaerobsis, and whether any compensatory response to partial and repeated seasonal waterlogging is translated into vine performance, especially with respect to grape quality.

3.1.3 Hardness and density

Many field and laboratory studies have been conducted to show the effects of soil hardness and density on plant root growth and distribution. Soils harden either because soil moisture content decreses and/or because soil becomes more dense as a result of compaction or aggregate slaking (eg. Philips and Kirkham 1962; Taylor and Gardner 1963; Taylor et al. 1966; Taylor and Bruce 1968; Cockroft 1968; Cockroft et al. 1969; Taylor and Ratliff 1969; Bennie 1991; Voorhees 1992).

Few studies have been conducted on the effect of soil strength on vine root growth. Among these, Myburgh et al. (1996a) found, in an extensive survey of soil conditions in vineyards in all the major grape producing areas across south-eastern and Western Australia, that poor vine performance (either yield or quality) could often be traced to restricted root development. The restricted root development was found to be caused by hard, dense soil layers such as those found in cemented pans, compacted clay subsoils, compacted sands and compacted wheel traffic lanes. The degree of soil hardness (strength) can be measured using a penetrometer.

Soil strength can be measured using a standard soil penetrometer. Both Myburgh et al. (1996a) and Van Huyssteen (1983) conclude that the critical penetration resistance of 2 MPa measured at field capacity water content adequately described the effective root zone of own-rooted vines. Penetrometer readings, however, should not be equated to the absolute resistance encountered by roots (Barley and Greacen 1967) but should be used as an indicator of soil strength within the soil matrix. Structural cracks common in swelling clay soils (Dexter 1988) and continuous macropores found in un-tilled soils (Ehlers et al. 1983) allow root growth to continue growing, but with reduced functional capacity with respect to water and nutrient uptake (Passioura 1988, 1991; Tardieu et al. 1992). These root systems are referred to as “sparse” and are a notable feature of hard soils.

The contribution of sparse root systems to the production of quality grapes, however, may be significant. For instance, Saayman and Kleynhans (1978) attributed good grape quality to the release of stored water from subsoil clay in a duplex soil. Van Huyssteen (1988a) concluded that occasional deep roots growing in pre-existing, continuous large pores did not add much to vine vigour, but probably did make a significant contribution to water supply of the vine during periods of prolonged water stress. The growth and distribution of these planar and structurally defined roots in the sub-soil is determined by the natural structural properties of the soil. Their distribution may also explain why soil type is sometimes believed to be a determinant of wine quality because the efficiency of these roots will determine the water status of vines during critical phenological stages (Van Huyssteen, 1989).

The consequence of high soil density and hardness on vine performance is due to the direct effect they have on the distribution and functional capacity of the root system to extract water and nutrients. The relative role of well-distributed versus sparse root systems in determining grape quality and the interaction with climate is less clear.

The physical factors of water supply, aeration and soil hardness affect vine performance simultaneously. Availability of water to vines can be limited by both a simple lack of water (wilting) or a lack of oxygen for root respiration (waterlogging) or by soil that is too hard for vine roots to explore and therefore make use of the volume of soil water (critical penetration resistance). The concept that accounts for these constraints to water availability has been called the "non-limiting water range" (NLWR). Letey (1985) defined a non-limiting water range in which the upper end (high soil water content) is controlled by macroporosity and its relation to aeration. The lower end of the range (low soil water content) is determined by the water content at which either soil strength or available water limits plant growth. Consequently there is a soil physical "window of opportunity" for maximum root growth and development known as the non-limiting available water range. Cass et al. (1994) showed that the non-limiting water range affected not only productivity but also sustainability of rice production. da Silva and Kay (1996) showed similar results for corn yields. However, similar studies have not been done for grape production.

Hall et al. (1977) also devised a classification of soils based on aeration capacity and total available water storage. Cass et al. (2002a) modified Hall's classification and adapted it for classifying viticultural soil. Cass et al. (2002a) postulated that optimal soil conditions for the best fruit quality was achieved when the total available water was approximately 150 mm and the ait-filled porosity at field capacity was more than 0.15 m^3 m^{-3}, in the effective root zone. It should be noted that Letey (1985) used the concept of "non-limiting water range" to account for lack of aeration and soil hardness on water availability. This concept has recently been expanded by Groenevelt et al. (2001) to include the water retention characteristics and hydraulic conductivity, combined with graded weighting factors for each soil property, to calculate an "integral water capacity". The integration of soil physical properties as an assessment of available water was inferred by Northcote (1988) as the most important characteristic of a soil for growing grapevines in Australia. Yet information to justify this statement or to develop a set of desired ranges or standards for water availability is not available.

3.2 Salinity

Many Australian soils are naturally saline and/or sodic (Northcote and Skene, 1972) Large parts of Australia grape growing areas of are sodic and prone to waterlogging and salt accumulation (Fitzpatrick et al. 1993). In addition, salinity and sodicity in many vineyards have increased since establishment because poor irrigation water is, of necessity, used for irrigation, and also because unsuitable irrigation practices and excessive water applications are common.

Rengasamy and Olsson (1993) defined conditions for irrigation-induced salinity and sodicity and provided evidence that shows that these conditions exist in most irrigation areas of Australia. Dowley (1995) has recently presented quantitative evidence for increases in salinity and sodicity at three locations in the McLaren Vale area. Of these two factors, soil salinity has the most immediate impact on vine performance, particularly if saline irrigation water is used for irrigation.

The response of vines to salinity was reviewed by Walker (1994) and the interaction of both salinity and sodicity by Cass et al. (1995). Information provided by these reviews shows that there is no doubt that an increase in salinity affects vine performance drastically. An increase in salinity has both an osmotic and a toxic effect causing reduction in yield, shoot growth, bunch number, berry weight and an increase in Cl^-, Na^+ and acid ion concentration in fruit (Prior et al. 1992a,b,c; Walker et al. 1996). Quintana Gana and Gomez Pinol (1989) found that soil sodium content was inversely related to and wine pH and content of undesirable phenolic compounds in several white grape varieties. Sugar concentration in the fruit is relatively unaffected, but tends to be decreased if an effect occurs (Prior et al. 1992c; Walker 1994).

The response of grapevines to salinity has been shown to vary depending on the grape cultivar (Groot Obbink and Alexander 1973) and rootstock used (Downton 1985; Southey and Jooste 1991). Because of this it is difficult to determine a universal relationship to describe the effect of salinity on vine growth, yield and grape composition. The assessment of salinity on vine growth and yield is confounded by the tendency to relate it to the quality of the irrigation water rather than the salinity of the soil (eg. Prior et al. 1992a). Mass and Hoffman (1977) summarised the growth rate of vines from data presented by Nauriyal and Gupta (1967), Taha et al. (1972), and Groot Obbink and Alexander (1973) into a generalised equation shown graphically in Figure 1.

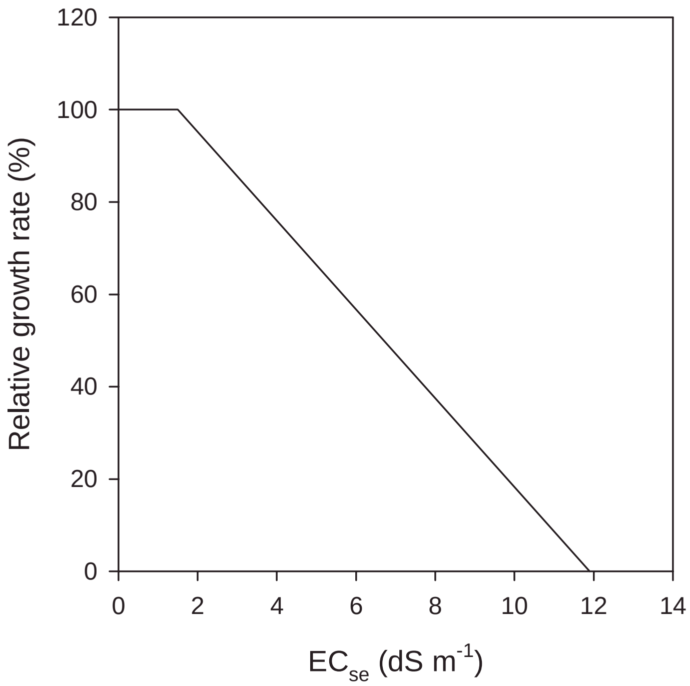

Figure 1: The relative response of vine growth to soil salinity (EC_{se}) where EC_{se} is the electrical conductivity of the saturated extract after Mass and Hoffman (1977)

Cass et al. (1995) adapted this and other sources to produce a salinity hazard assessment for vines (Table 2).

Table 2: Criteria for soil salinity and potential yield reductions for vines (after Cass et al. 1995)

Salinity hazard	EC_{se} dS/m	Effects on grapevine growth	1:5 Soil/water extract (dS/m)				
			Loamy sand	Loam	Sandy clay loam	Light clay	Heavy clay
Non-saline	< 2	Negligible effect on vines	<0.15	<0.17	<0.25	<0.30	<0.40
Slightly saline	2 – 4	Own-rooted vines begin to be affected	0.16-0.30	0.18-0.35	0.26-0.45	0.31-0.60	0.41-0.80
Saline	4 – 8	Own rooted vines severely affected but some rootstocks are unaffected	0.31-0.60	0.36-0.75	0.46-0.90	0.61-1.15	0.81-1.60
Very saline	8 – 16	Grapevines cannot be grown successfully	0.61-1.20	0.76-1.45	0.91-1.75	1.16-2.30	1.60-3.20
Highly saline	> 16	All grapevines will die	>1.20	>1.45	>1.75	>2.30	>3.20

EC_{se} is saturated paste electrical conductivity

3.3 Sodicity

The effect of sodicity on vine performance is usually associated with the deleterious effects of sodium on soil structure and the consequent indirect effects of poor soil structure on vine performance. Sumner and Naidu (1998) published an extensive review of the effects of sodicity on soil properties and management but it does not do justice to the direct effects of sodicity on crop response generally and certainly not on vine performance.

Sodic soils, generally defined in Australia as soil with an exchangeable sodium percentage (ESP) greater than 6, are regarded as structurally unstable. However, high soil salinity and variations in clay mineralogy may mitigate the effects of sodicity on structural stability (Cass et al. 1995 and Cass and Sumner 1982a,b,c). The effect of salinity on soil structural stability is reflected in the criteria for assessing the effects of sodic irrigation water on soil properties published by Richards (1954) and revised by Ayers (1977) as reproduced in Table 3. This table shows that if salinity is increased, soil can tolerate higher levels of sodicity without deterioration. However, the effect of soil salinity in relation to sodicity is generally ignored in assessing soil sodicity hazards and there is a tendency to regard all soils as sodic and structurally unstable if ESP is above 6 and very sodic (very unstable) if ESP is above 15.

All soils do not respond in the same way to increasing sodicity and decreasing salinity. Several studies have shown wide variation in the extent to which different soils deteriorate as exchangeable sodium is increased and/or soil solution concentration is decreased (McNeal and Coleman 1966; Naghsineh-Pour et al., 1970; Frenkel et al., 1978; Pupisky and Shainberg 1979; Cass and Sumner, 1982b and others). Physically degraded soils that are irrigated with poor quality water tend to accumulate more salts and sodicity tends to increase, leading to a downward spiral of physical fertility (Rengasamy and Olsson 1993). Unless stabilised, these soils will have poor drainage, low infiltration rates, reduced available water, high (steep) strength characteristics and will generally provide a hostile environment for root growth. Soils with large blocky structure, prismatic or columnar structure and marked swelling/shrinking properties are often sodic or have probably formed under conditions of high sodicity (Myburgh et al., 1996a). Typically, many Duplex soils (Solodic and Solothic soils), cracking clays (Grey and Black Clays), some Red-brown Earths and some Red, Gravely and Lateritic soils are sodic (Stace et al., 1968). Consequently, soil management that reduces sodium build up within the root zone is beneficial to soil structure and root growth.

Table 3: Criteria for assessing the sodicity hazard, and hence the likely development of soil sodicity, as a result of irrigating with various water qualities where EC_{iw} is electrical conductivity of the irrigation water (dS m^{-1}) and SAR_{iw} is sodium adsorption ratio of the irrigation water (Ayers 1977)

SAR_{iw}	EC_{iw}	Soil sodicity hazard
0 – 3	>0.7	None
	0.7 – 0.2	Slight to moderate
	<0.2	Severe
3 – 6	>1.2	None
	1.2 – 0.3	Slight to moderate
	<0.3	Severe
6 – 12	>1.9	None
	1.9 – 0.5	Slight to moderate
	<0.5	Severe
12 – 20	>2.9	None
	2.9 – 1.3	Slight to moderate
	<1.3	Severe

Although the consequence of sodicity for soil structure is well recognised, there is limited information that directly associates soil sodicity with vine performance, especially fruit quality. From data provided by Khanduja et al. (1980) and Samra (1985, 1986) we are able to deduce a relative response of shoot growth to an increase in ESP for low soil EC. Figure 2 shows data that suggests vine shoot growth declined as ESP increased. Whether these responses were due to the impact of ESP on soil structure and, hence, root growth and function or whether the responses were due to a change in nutrition balance remains unclear. More work on the consequences of soil sodicity, especially sub-soil sodicity, with respect to vine performance is needed. The impact of sodicity needs to be measured in dollar terms either through indirect measures, such as reduced root function, shoot growth and vine death leading to poor vine performance, or direct means, such nutritional impacts on vine performance, so that the consequent management practices can be economically appraised.

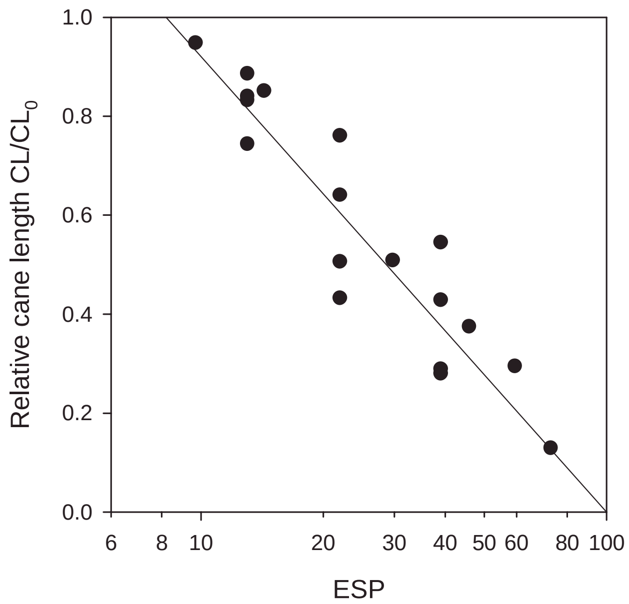

Figure 2: The response of vine vigour to exchangeable sodium percentage (ESP). Vine vigour is plotted as relative cane length, the ratio of measured cane length, CL, to the theoretical cane length at an ESP = 0, CL_0. Data was obtained from Khanduja et al. (1980) and Samra (1985, 1986)

3.4 Nutrition

Soil nutritional status affects all parts of the grape vine, from root growth and distribution through to shoot growth and grape composition. However, there is little objective evidence that relates soil nutritional status to vine performance (Gladstone 1992). This is reflected by the absence of soil-based nutrient recommendations in Peverill *et al* (1999) compared to a more comprehensive, but albeit short, list of petiole-based nutrient recommendations in Reuter and Robinson (1997), although the latter ignore variation between grape varieties and lack specific grape quality targets.

The difficulty in relating soil nutritional composition and concentration to vine performance is partly attributable to the complexity of the root-soil system. Many factors affect the so-called availability of soil nutrients to plants. A particular nutrient may be considered ‘abundant’ in the soil (as measured by a particular method), but deficient in the vine (as measured by petiole or other tissue analysis). A typical example of this is the restricted uptake of potassium from soils with high exchangeable magnesium contents, even though extractable soil potassium may be quite high.

Soil nutrition can be modified by the application of surface fertilisers, either organic or manufactured. However, the effectiveness of the applied fertilisers is influenced by their timing and placement, the rooting pattern of the vine, irrigation and rainfall, not to mention the inherent soil physical, chemical and biological properties of the soil. For this reason, soil analysis does not provide data about the availability of nutrient but rather an index of the availability that can be calibrated with crop response. Soil tests for micronutrients are not well calibrated for grapevines (Robinson - personal communication). Hence, it is not surprising that there so little information on the linkages between soil nutritional chemistry and vine performance. Further, being a perennial plant with storage organs that have temporally variable nutrient contents, soil test interpretations in relation to a final predicted yield, as in annual cropping, is associated with high levels of uncertainty.

Knowledge of soil chemistry provides a basis for interpreting routine tissue analysis and for tracking the dynamics of applied fertilizers and its possible effect on grape composition. To this end, some general effects of macro and micro nutrition on vine performance, including nutrient availability, are worthy of discussion here.

In general, the availability of each nutrient element is dependant on soil pH. Although Seguin (1986) argues that soil pH does not have much influence on the quality of wines, since quality wines are produced on acidic, neutral and alkaline soils, there are limits to the acidity and alkalinity of the soil tolerable by vines.

Vines do not perform well when soil pH is lower than about 5 due to stunted shoot and root growth (Conradie 1983a). At these low pH values the increased concentration of exchangeable aluminium is mostly responsible for the distorted root growth. Reeve and Sumner (1970) state that for unrestricted root development on the part of most crops, exchangeable aluminium should be less than 0.2 meq/100g (2 mmol+/kg). However, vines in California generally do not show symptoms of aluminium toxicity up to 11 mmol+/kg of extractable aluminium (D. Roberts, pers. comm., 2004).

In soils with pH above 8.0 availability of nitrogen, calcium, magnesium, iron, manganese, copper and zinc are reduced (Saayman 1981; Davidson 1991). These high soil pH values are also associated with boron toxicity which Saayman (1981) suggested occurs at boron concentrations in the saturation extract of 0.7 mg kg^{-1}, although there are conflicting opinions regarding the boron concentration at which toxicity occurs for different method methods of extraction.

In some soils with high pH (>8.3), associated elevated concentration of very fine carbonates may cause severe lime-induced chlorosis (iron deficiency). The most common cause of lime-induced chlorosis in these soils with high concentrations of bicarbonate ions and associated high pH is either a reduction in concentration of ferric iron or slower uptake of ferric iron by vines (Gelat, 1996). With these effects in mind it is generally accepted that soil pH_{CaCl2} should be between 5.5 to 8 for optimum vine survival and growth.

Studies of the effect of nutrition on vine performance, in particular vine growth and grape quality, have generally been confined to macro nutrients, in particular nitrogen (eg . Conraidie 1986; Robinson 1992; Treeby *et al*, 1995; Goldspink and Howes 2001; Retallack 2002). Information available for most micro nutrients is related more to the symptoms of deficiency and toxicity rather than the consequential effect on vine performance (eg Retallack 2002).

Soil environmental conditions, such as access to water, can also affect the availability of nutrients to the vine. For instance, phosphorous uptake can be severely limited when soil moisture approaches the wilting point (Eck and Fanning 1961; McMullen 1995). It is difficult to dismiss the assertion that the factors of fruit quality might not be affected by the presence or absence of selected nutrient elements for a given water supply. Indeed, this may be at the heart of the yield/quality debate.

Although tissue analysis provides the most promise for an objective guide to the nutrient status and fertiliser needs of grapevines (Robinson 1992) it should not be considered in isolation without considering the nutrient level of soil within the root zone and the effect the soil will have on the availability of applied nutrients. However, in the absence of tissue analysis, some indication of soil nutritional status as well as soil chemistry indices related to soil quality is required. This is especially so for site selection,. With this in mind, combining the soil nutritional and soil quality recommendations of Cass *et al*. 2002a, McMullen 1995, Robinson et al 1997, Goldspink and Howes 2001, Robinson 1992 with the recommended petiole nutrient scales of Reuter and Robinson (1997) a crude set of recommendations for sustainable soil quality and nutrition can be calculated (Tables 4 and 5), although not all nutrients can be specified due to the lack of information. What is clearly needed however, is a better understanding between soil chemistry, soil quality and vine performance with respect to specific targets such as grape aroma and flavour.

Table 4: Suggested benchmark criteria for soil nutrient and chemical status for wine grape production[A].

Nutrients[B]	Concentration range in soil (mg/kg)				
	Deficient	Marginal	Adequate	High	Toxic
NO_3-N	< 1	1 – 2	2 - 10	> 10	
K	< 50	50 – 100	100 – 250	> 250	
P	< 25	25 – 35	35 – 80	> 70	
Cu	< 0.1	0.1 – 0.2	0.2 – 0.4	> 0.4	> 2
Zn	< 0.5	0.5 - 1	1 – 2	2 – 20	> 20
Mn		< 2	2 – 4		
Fe			> 4.5		
Al					>100
B	< 0.1		0.2 – 1.0		> 3.0
S	< 10				

[A] combination of recommendations suggested by Robinson (1992), McMullen (1995), Robinson et al (1997), Goldspink and Howes (2001) and Daniel Roberts and Alfred Cass (personal communication 2003) using the assumption that petiole nutrient status is linearly related to soil nutrient status.
[B] K, P – Colwell bicarbonate extractable, Cu, Zn, Mn, Fe - DPTA extractable, Al – ammonium chloride extract, B - hot water extract

Table 5: Suggested criteria for soil chemical status for sustainable vine health for wine grape production[A].

pH	Cl_{se}[B]	Exchangeable cation concentration					
$CaCl_2$		Ca	Mg	Na	K	Ca:Mg	K:Mg
-	mg/kg	-------------------- % of total -------------------				Molar ratios	
5.5-8	<10	60-80	15-30	<6	5-10	2-10	0.1-0.4

[A] complied from McMullen (1995), Goldspink and Howes (2001), Daniel Roberts and Alfred Cass (personal communication 2003)
[B] 'se' is saturated extract

3.5 Temperature

Temperature fluctuations in soil affect the growth of roots, but the extent of the response differs depending on plant species (Kaspar and Bland 1992). Joost (1983) reported that vine root growth increased as soil temperature increased from 11 to 32 ^{o}C. A sharp decline in root elongation was found above 32 ^{o}C. Similar findings were reported by Khmeleyskii (1971) and Woodham and Alexander (1966). Daily maximum soil temperatures have been reported in vineyards and orchards to regularly exceed 35 ^{o}C during summer in the top 100 to 150 mm of the soil profile which is considered lethal for many plant species (Myburgh and Moolman 1993; Van Der Westhuitzen 1980; Cockroft and Hughan 1964). Soil temperature not only affects the rate of elongation of roots but also affects both passive and active water absorption by increasing permeability of the cell membrane and metabolic activity (Glinski and Lipiec 1990). This, in turn, affects shoot growth causing a reduction when the roots are cooled (Passioura and Stirzaker 1993). However, the consequence of high soil surface temperatures on vine performance will depend on the depth distribution of roots and the reliance of vine growth on water and nutrients stored in any particular depth interval.

Soil temperature can have an effect on grape quality through its thermodynamic connection with the climate around the vine (Gladstone 1992). The air temperature regime around the vine has been linked to grape quality through the effects on pH, colour, flavour and aroma components (Kleiwer and Torres 1972; Jackson and Lombard 1993; De Garis 1999). Surface stone concentration and colour influence the flux of heat from the atmosphere into and out of soil and soil temperature has a role in determining berry quality.

It is clear that soil temperature affects the size and function of the root system as well as the microclimate around the vine, and hence will have an impact on vine performance. What is less clear, however, is the magnitude and severity of soil temperature effects on vine performance and the consequence of soil surface management on grape quality. The interaction between climate and soil surface management, the principle means of manipulating soil temperature, reflectance and thermal connection with the vine microclimate, should be investigated in greater detail with respect to vine performance.

3.6 Ideal properties for wine grape production

There is no one ideal soil for wine grape production *per se* but rather an ideal set of soil properties for a given climate, with possible further refinement based on consideration of target wine style and variety. The inclusion of irrigation causes a broadening of the characteristics of the ideal soil but may also give rise to a range of sustainability issues such as sodicity and salinity. The aim of this section of the review is to develop this theme as a lead into the management of non-ideal soils.

Within the viticultural industry a range of soil types are used for grape production, with wide variation in soil properties and stability. Many of these soils have structural properties that are favourable to vine growth, some to the extent that vines become too vigorous, with the resulting shading impairing fruit quality. Others have favourable attributes moderated by depth or climate so that excess vigour is not a problem. The legendary Australian Coonawarra Terra Rossa soil is such an example. Terra Rossa and to a slightly lesser extent Rendzina soils, both found at Coonawarra, have elevated structural stablity and resilience (Myburgh et al., 1996a) attributable to a special combination of properties: high concentrations of calcium (Stace 1956), high free iron oxide content (Norrish and Rogers, 1956; McIntyre, 1956), high organic matter content (McIntyre 1956; Norrish and Rogers 1956), and an elevated manifestation of "subplastic" mechanical behaviour (McIntyre 1976). Sub-plastic behaviour is due to the presence of very stable clay micro-aggregates that behave collectively as much larger particles, conferring the favourable properties of sand size particles on the soil but retaining all the favourable properties of clays. The depth of these soils to underlying rock in relation to the local climate is also an important factor determining their suitability for premium wine production.

Although Cass et al. (2002a) and Cass and Meschmedt (1998) have suggested a range of benchmark values for soil physical properties in relation to vineyard establishment and yield for irrigated vines (Table 6), benchmarks aligned to grape quality currently do not exist and divergent views are held on what these values should be (Cass and Maschmedt 1998). Furthermore, an ideal set of soil criteria will need to be aligned with different climatic conditions and access to irrigation. Hence there is no one set of criteria that is suitable for all climates. However, the ability of the soil to drain would have to be the one universal soil quality applicable to all climates. A criterion for the depth of the root zone and the nutritional status of the soil is needed for vineyard selection or selection of the most appropriate soil management method for a given vine performance target.

Table 6: Suggested benchmark values for soil physical quality for moderately vigorous vines on wide spacing (3 x 2 m) (after Cass and Maschmedt 1998; Cass et al. 2002a)

Criterion	Benchmark
Infiltration rate	> 500 mm/day
Total available water in root zone mm	>200 (excessive) 150-200 (high) 100-150 (optimal) 50-100 (sub-optimal) <50 (insufficient)
Air-filled pore space	> 15% of soil volume
Penetration resistance	< 1 MPa at field capacity < 3 MPa at wilting point
Waterlogging	< 1 day of saturation/irrigation cycle or rainfall event

4 Soil Profile Modification in Vineyards

Productivity and management problems exist in many vineyards established on marginal soils. These problems relate largely to selection of inappropriate soils for new vineyards, lack of sufficiently rigorous design criteria for vineyards, poor soil preparation at establishment and inappropriate soil management during the life of the vineyard. Hence, it may be necessary to modify the soil condition to reduce any negative impact on vine performance. Van Huyssteen (1989) argued that when soils are properly managed to conserve soil water and to improve soil temperatures and when the necessary chemical adjustments are done, many of the natural differences in vigour between soil types in the same climate area largely disappear.

Issues related to soil preparation and soil management after vineyard establishment have enjoyed particular attention in South Africa where the following have made major contributions to understanding the effects of different approaches to soil preparation and management on physical fertility and grapevine performance: Van Huyssteen and Weber (1980a, b, c), Saayman and Van Huyssteen (1980, 1981, 1983), Saayman (1982), Van Zyl (1988), Van Huyssteen (1988a, b), Myburgh and Moolman (1991a,b, 1993), Myburgh (1994) and Myburgh et al. (1996b). While the aim of soil manipulation may be to alleviate a particular soil constraint to vine performance, it tends to change a number of soil properties. Hence, alleviating one soil constraint may create another. This inter-relationship between soil properties makes the task of soil management selection more complicated, especially if the aim is to change a specific factor of vine performance. Table 7 summarises the advantages of various soil, profile modification methods on soil properties that affect vine performance. However, linking these changes in soil properties to changes in vine performance, at least in a predictive manner, is not straightforward and needs to consider other factors such as climate.

Table 7: Generalisation of the effects of soil profile management practices on soil properties that affect vine performance. Symbols: - negative effect, + positive effect, | no effect.

Management practice	Water storage and availability	Improved aeration and drainage	Penetrability and porosity	Control of Salinity and sodicity	Increased chemical fertility	Improved Structural stability	Higher Soil temperature
Incorporating annual cover crop	-	--	--	-	++	---	+
Incorporating compost at establishment	+	+++	+++	+	+	+	+
Gypsum addition	++	-	+++	+++	+	+++	|
Lime addition	+	|	|	-	+++	|	|
Deep ripping before establishment	++	+++	+++	+++	+	|	+
Deep ripping after establishment	+	+	+	+	+	|	+
Mounding without mulching	---	+++	+++	-	+	+	+++
Mounding with surface mulching	+++	+++	+++	+++	+++	++	---

Until recently very little work had been undertaken on the effect of soil management on soil physical fertility and grapevine performance in Australia. However, research by Cockroft and Wallbrink (1966a,b), Cockroft (1966) and Cockroft and Tisdall (1978) on improvement of soil physical fertility in deciduous orchards has been a catalyst for improving soil physical fertility and grapevine performance in Australia. The first of these results were reported by Adem and Tisdall (1983), Cass et al. (1993) and Myburgh et al. (1996a). This section outlines the response of the soil to different soil management practices studied both within Australia and overseas and where likely benefits to Australian viticulture are likely to be achieved through improved knowledge and application.

4.1 Amendments

Organic matter, gypsum and lime are routinely applied and incorporated to ameliorate soil in vineyard development and improve vine performance in established vineyards. Criteria for use of these amendments have been extrapolated from general agricultural research and refined over time by experience. However, few reports on use of these amendments to improve vine performance exist, other than shallow incorporation of a cover crop, and most of these originate in South Africa.

4.1.1 Organic matter incorporation

There are many reports of beneficial effects of compost incorporation in agriculture (e.g. Wolf and Snyder, 2003). However, few reports contain cost-benefit information, particularly for the viticultural industries. Not all reports show benefit from compost. Saayman and Van Huyssteen (1980) and Saayman (1982) found that incorporation of compost and straw at commercial rates between 19 and 38 t ha^{-1} had no effect on grapevine performance. In 9 out of 9 years grape yields were less from compost incorporation with deep delving of soil (roll over ploughing) treatments compared with no organic matter and deep delving. Saayman and Van Huyssteen (1980) suggested that the negative response to organic matter incorporation may have been due to the placement of thin isolated bands of organic matter in the soil (insufficient mixing). Van Huyssteen and Weber (1980c) also found no increase in yield and pruning mass when prunings where incorporated in the inter-row compared to cultivation.

Dowley et al. (2002a,b) reported that root length density was improved in surface soil (0 to 400 mm) by incorporating 6 % commercial compost by weight into a seasonally waterlogged duplex soil and a cracking clay soil. The favourable root response was attributed to maintaining more favourable soil properties over a three year period. However, vine performance measurements were not reported.

4.1.2 Gypsum

Gypsum ($CaSO_4.2H_2O$) is the most widely used calcium compound for ameliorating soil structure. There are numerous research reports and reviews of its effectiveness in reducing sodicity by cation exchange reactions and increasing the soil solution electrolyte concentration to improve soil structural stability (e.g. Shanmuganathan and Oades, 1983; Blackwell et al. 1988; Grierson, 1978).

One of the most important soil types found in the viticulture regions of South Australia is the Red-brown Earth (Stace et al. 1968). Gypsum applied to these soils improved aggregate stability by replacing exchangeable sodium and magnesium by calcium (Grierson, 1978). At sites where the exchangeable sodium percentage was greater than 10, the addition of gypsum significantly reduced crust shear strength and decreased the amount of runoff by improving water infiltration. These benefits were seen at gypsum application rates of 5 t ha^{-1} and 12 t ha^{-1}. A rate of 2.5 t ha^{-1} had no significant effect on water infiltration rate. However, lower applications of gypsum have also been shown to be beneficial. Aljibury and Christensen (1972) showed that 1.25 t ha^{-1} of gypsum applied to a sandy loam soil in Fresno County, California, gave significantly improved water infiltration rates compared with no gypsum.

Generally, in the viticultural industry in Australia, there is widespread acceptance of the value of gypsum in correcting soil structural problems but there is a general lack of data on vine response to gypsum, however applied. Cass et al. (2003) reports currently accepted conservative recommendations for gypsum use in Australia and California and provides indicators for gypsum use. Generally they recommend that restraint should be exercised in deciding on the total amount to apply. Gypsum use is more complex than most growers realise and harm, although not common, can be done if incorrectly or too liberally used. Given the prevalence of sodic soils in the Australian viticultural industry, more research attention to refining criteria and procedures of gypsum use is warranted, especially in relation to expected vine response or the consequent vine response if gypsum is not used.

4.1.3 Lime

Use of lime in vineyards has enjoyed considerable research and comment from leading industry researchers. Important and useful information is available from Dry and Smart (1985), Robinson (1989), Van Zyl and Van Huyssteen (1983), Davidson (1990), McNab (1990), Smart, Kirchhof et al (1991), Cirami (1993), Robinson (1993) and McNab (1994). As a result, , there is a good appreciation of the value of lime in the Australian industry although the finer distinctions between Calcitic and Dolomitic Lime and the effect of lime as opposed to the effect of gypsum on soil pH may not be as clear to commercial viticulturalists.

According to Macrae (1991), lime application and incorporation prior to planting allows low pH levels, and the associated toxicity of aluminium and manganese, to be easily corrected. Saayman and Van Huyssteen (1981) compare various techniques to incorporate lime during soil preparation, namely, delve or winged plough and surface applied lime and lime blown into soil to depth or combinations of these treatments. They found that the best incorporation was achieved with the delve plough with a combination of surface and blown-in lime. Mixing was improved if the soil was ripped a second time. They also noted that the incorporated lime improved soil structural stability, as did Lanyon (2001) and Hansen and Cass (2002) at 1 % addition by mass. However, appropriate machinery to deliver lime to subsoil depths is not generally commercially available.

In established vineyards, because of the need to thoroughly till lime into the soil in close proximity to the vine root system, the use of lime is made difficult by the established trellis system. Jayawardane and Blackwell (1985) developed a soil slotting implement for the incorporation of gypsum into sodic soils and Kirchhof et al. (1991) used it to test incorporation of lime in a vineyard at Port Macquarie in New South Wales, slotting to 40 cm depth and incorporating lime at a rate of 2 t ha^{-1}. Results showed an increase in soil pH from 4.3 to 5.0 at 40 cm depth. Roots which had been restricted to about 15 cm depth increased in length tenfold. However, no yield or vine growth measurements were taken.

A substantial amount of literature exists on the use of lime in vineyards for South African and Australian conditions. Generally, in most viticultural industries, the benefits and use of lime are understood. However, there is a need for ongoing grower education regarding the differing needs for and properties of gypsum as opposed to lime.

4.2 Tillage

Vines, like most crop plants, need a healthy, active root system. Generally, the canopy size is a reflection of the size of the root system (Van Huysteen. 1988a). This is true for both young (Van der Westhuizen 1980) and mature vines (Saayman and Van Huyssteen 1980). Adverse soil physical properties and high concentrations of chemical toxins are the main factors that restrict vine root growth. According to Myburgh et al. (1996a) physical root restrictions explain why vine performance is often not optimum in many Australian vineyards. Van Huyssteen (1989) showed that soils with severe root restricting properties have a detrimental effect on wine quality because of the effect these have on the water status of vines during critical phenological stages. If these difficult soils are to be used successfully for wine grape production, the adverse physical properties need to be modified (van Huysssteen 1988a). Methods of soil physical profile modification include deep ripping, profile mixing, mounding (ridging), slotting, and root pruning.

4.2.1 New vineyards

Deep ripping is the most common form of deep tillage in Australian viticulture. Generally, when establishing a vineyard, the soil is deep ripped along the vine row allowing for both better root penetration into the subsoils and improved drainage of excess water from surface layers. The practice was established by South African researchers in the 1980's whos showed that deep tillage is beneficial and probably essential for successful establishment of grapevines where root growth is likely to be restricted (van Huyssteen 1988a). However, soil preparation has little positive effect on vine performance if the soil is non-restricting (Saayman and Van Huyssteen 1980).

In a ten year study in a dryland vineyard, Saayman and van Huyssteen (1980) and Saayman (1982) found a significant relationship between the depth of deep tillage in a soil known to have an impeding soil layer, and yield and shoot growth. In irrigated vineyards, deep delve ploughing improved vine performance up to a depth 750 mm in a soil known to impede root growth at 200 mm (Saayman and Van Huyssteen 1980; Saayman 1982). Deeper modification had no further significant effect. Freeman (1990) showed that vine performance was affected by soil depth even under frequent drip irrigation, although less so than for non-irrigated vines.

Myburgh *et al*. (1996b) also studied the effect of loosened soil depth on yield and shoot growth of young Pinot Noir for both irrigated and non-irrigated situations. For a soil with a surface layer of coarse sandy loam and sandy clay loam subsoil, they concluded that for optimal vegetative growth and physiological response the depth of the loosened soil should be 800-1000 mm for non-irrigated vineyards and 400 mm for irrigated vineyards. The water consumption at optimal vegetative growth and physiological response was approximately 400 mm for the irrigated vineyard compared to 500 mm suggested by Van Zyl and Van Huyssteen (1983). Myburgh *et al.* (1996b) also found that an increase in the loosened soil depth led to establishment of full-bearing vines quicker, but created excessive vigour. They established a clear increase in vegetative growth with an increase in root depth for irrigated vines.

The type of deep tillage has an effect on the performance of the vine. Saayman and Van Huyssteen (1980) compared a subsoiler (single wingless shank) to a deep delve plough (partial inversion of soil profile). They found that roots were more concentrated in the ripper line than compared to the deep delve plough but root numbers were similar when comparing the entire soil profile. Although little difference was found in the number of roots found in shallow and deep delved soil, the deep delved soil had significantly greater shoot and trunk growth.

Deep tillage implements vary widely. The most common tool used in Australia until recent times was the wingless shank (subsoiler) which creates minimum lateral soil disturbance but has the least draft and is, therefore, the least effective tillage tool for this purpose. Winged tines (Cass et al., 2003) fracture the soil at an angle from the wingtips to the surface and create a larger zone of disruption but have greater draft, requiring more daft power. In South Africa, delve (rollover or mouldboard) ploughs frequently feature in research reports and these tools do more mixing than shanks but with considerably increased draft. In California, rollover (mouldboard) ploughs and slip ploughs are commonly used, which invert the soil profile or slide subsoil to the surface, and consequently produce the most mixing. However, they have the largest draft requirements. In recent times, both in Australia and California, the winged tine has become the tool of preference for developing premium vineyards (Cass et al., 2003).

Cass et al. (2003) described the design details of a winged ripper with a 20^{o} rake angle, based on criteria from Spoor (1976) and Spoor and Godwin (1978), that had been widely used in Australia and California, first in a research setting and later extensively tested in commercial vineyards. They defined the conditions that indicated a need for winged tine ripping, and indicated the role of amendments in enhancing the positive benefits of winged tine ripping.

Van Huyssteen (1983, 1988a) reported on the success of delving in reducing soil strength and enhancing grapevine performance (root density, shoot mass and fruit yield) in a sandy clay loam soil in South Africa. Comparing different methods of soil preparation, Van Huyssteen (1983) found that the most favourable loosening was obtained by double delving to a depth of 700 mm. Single direction delving showed significantly greater soil strengths at all depths than double delving. A tine with a wing attached to the base yielded only slightly less favourable soil strength than double delving. Saayman (1982) showed that the advantage of deep delve ploughing, evident by more vigorous growth and higher crop loads, lasted up to six years compared to shallow delve ploughing and deep single tine ripping. Beyond this time frame, there was no significant difference between soil preparation methods.

Myburgh et al. (1996a) noted that mixing of subsurface layers was not common practice in viticulture in Australia and implements were not available for this purpose. The mixing of restricting layer with unrestricting layers has been postulated as a possible advantage over single tine ripping without mixing. However, Dowley et al. (2002a) mixed a restrictive (bleached) A_2 horizon with the A_1 horizon in an established vineyard and found the benefits of mixing questionable, possibly because the mixed soil profile slaked rapidly producing a poor physical condition (dense, hard, low macroporosity) which would restrict root growth. This outcome and the prevalence of subsoil sodicity in Australia, suggests that layer mixing should be avoided until more reliable evidence of the benefits are available.

Myburgh et al. (1996a) reported on deep tillage practices in south eastern Australia and showed the varying degrees of success that deep ripping with a single wingless shank had on reducing soil strength and allowing grapevine root development in vineyards. Cross ripping and ripping in the midrow were also not commonly practiced, resulting in roots being confined to a narrow band under the vine row. Cross ripping has proven to be an effective practice to soil preparation in South Africa and might warrent more attention in Australia to improve soils that are restrictive to vine performance. However, Cass et al. (2003) caution against cross ripping because of the destructive effect on soil structure caused by the high cumulative energy input of cross ripping. Instead, they advocate a single rip on the vine row using a winged tine.

The benefits of soil profile preparation can be short-lived due to instability of the soil profile, compaction by traffic or poor soil preparation techniques. Hence, further deep tillage is sometimes necessary in established vineyards when vine performance declines.

4.2.2 Established vineyards

Deep tillage in established vineyards has not enjoyed the same level of attention and development as deep tillage prior to vineyard establishment. Furthermore, of the few studies that have looked into different forms of deep tillage in an established vineyard the results are inconsistent. In a 7 year study, regular, annual deep tillage to 600 mm reduced growth and yield of an ungrafted Colombard vineyard on a deep red, calcareous Hutton soil in South Africa under flood irrigation and permanent sward, but had no effect on grape soluble solids and total titratable acidity (Saayman and Van Huyssteen, 1983). This was attributed to severe root pruning during the soil loosening process.

Van Huyssteen (1988b) suggested that inter-row ripping should be done only in vineyards where root growth, and thus canopy growth, is restricted by soil compaction. It should be done in alternative rows, after harvest in order to coincide with the second period of active root growth and only between the tractor tracks. Furthermore, it is not recommended that deep tillage be done more regularly than every five years to avoid excessive root pruning and to alleviate subsequent soil hardening, but data to support this assertion are difficult to find.

In some instances, where excess vine vigour is a problem, deep tillage has been used to prune roots to limit the availability of water to the vines and reduce canopy size. Proffitt et al. (2000) and Proffitt (2000) tried this technique in a black cracking clay soil in the Coonawarra, which resulted in better grape composition than the unripped control. However, experience with root pruning in viticulture is limited (Dry *et al*. 1995a) and the success of this technique has been shown to be variable (eg. Dry et al. 1998; Ferree et al. 2000). The most likely reason for the variable response was that, root distribution data was not used to guide the operation and pruning was probably ineffective.

Cass (2003) described the design details of a winged ripper used in a closely spaced (2 m) established vineyard. After ripping in spring, the vines ripped on one side of the vine row only to a depth of 300 to 400 mm had consistently more positive leaf water potential than the vines in the un-ripped control. This suggests that the ripped vines were under less stress than the control vines. However, there still remains a dearth of information pertaining to the criteria when established vines need to be deep tilled and the likely vine response given certain soil conditions. This warrants more attention in the Australian viticulture industry given that the industry has recently expanded onto less favourable soils.

4.2.3 Mounding

Mounding refers to the relocation of topsoil from the midrow onto the vine row to form a ridge This technique has been used to overcome root zone waterlogging and restricted root distributions caused by shallow surface soils and dense impervious subsoils. Mounding is used as an alternative to deep tillage when soil conditions prevent successful amelioration of the impeding layer, such as unrippable rock at shallow depths, very poor structural stability or high water tables.

Mounding has been widely adopted in many areas of the deciduous fruit industry in Australia (Tisdall and Huett 1987) especially on duplex soils (Cockroft and Tisdall 1978; Tisdall et al. 1984; Cass et al. 1997a, 1999). In Australian viticulture Macrae (1991) advocates the use of mounds for soils of limited topsoil depth over restrictive subsoils. Generally in Australia, these soils have limited lateral root growth into the mid-row and are prone to waterlogging.

Myburgh and Moolman (1991a, b and 1993) used mounding to increase aeration in the topsoil caused by a high watertable. Mounding increased the depth to the water table, which resulted in higher oxygen and lower carbon dioxide concentrations in the soil air. However, evaporative loss of water from the mounds increased as the size of the mound increased, due to the greater exposed surface area of the mound (Myburgh and Moolman 1991a) and consequent higher soil temperatures (Burrows 1963; Myburgh and Moolman 1993). Myburgh and Moolman (1993) also concluded that since soil temperature is generally low in waterlogged soils, particularly at the beginning of the growing season, an increase in soil temperature due to mounding could provide a more favourable environment to early root development. Myburgh and Moolman (1991a) also noted that surface crusting increased the likelihood of surface runoff from the mounds during rainfall or irrigation.

Myburgh (1994), studied the effect of various mounding conditions with and without ripping and irrigation over 4 years in a soil with a compact subsoil. Under both irrigated and non-irrigated conditions, mounding improved yield and vegetative growth compared to flat and ripped treatments with no significant loss of berry quality as measured by total soluble solids, total titratable acidity, and pH. However, under dryland conditions, mounds with a surface to volume ratio less than 0.6 and 1.0 decreased yields for double and single row mounds, due to late seasonal desiccation and high soil temperatures in the mounds. Increased desiccation of raised beds compared to a flat surface was also reported by Hansen and Cass (2002).

The use of mounds can improve soil physical properties relative to the initial soil conditions. Eastham et al. (1996) found that the bulk density of raised soil beds remained low (1.25 Mg m^{-3}) one year after forming compared to a flat surface (1.5 Mg m^{-3}). The better physical conditions allowed more rapid root development and significantly higher root lengths in raised beds. Improved growth of young vines in raised beds was related to greater extraction of water and possibly nutrients by the denser vine root system in raised beds.

The experimental findings reported by Eastham et al. (1996) were obtained after only one season of growth, whereas, similar experiments conducted by Cass et al. (1997a) showed that the bulk density of raised beds slowly increased over three seasons. Generally, the stability and sustainability of soil structure in raised soil beds was found to depend on water and soil management (Cass et al. 1997a, 1999). They found that the growth of ryegrass on raised soil beds during the winter period, retarded the decline of soil structure by stabilising aggregates against structural collapse and improved macroporosity and bulk density compared to mounds covered with straw mulch or left bare.

Little information on the advantages of mounding over deep ripping is available. In ungrafted (own rooted) vineyards where root depth and lateral extent is restricted, limiting available water, mounding may be a solution to poor vine performance. However, there are disadvantages in using mounds in viticulture compared to other cropping systems. Vine rows are generally spaced three meters apart or less, which limits the width of the mound if trafficking by tractor wheels is to be avoided. Further, mounds cause difficulties and discomfort to workers during hand pruning which raise occupational, health and safety issues. Generally, reported commercial experience of using mounds in Australian viticulture is limited.

5 Soil Surface Management

A variety of soil surface management strategies are in use in vineyards for achieving particular outcomes such as frost protection, moisture conservation, vigour suppression, microclimate manipulation, erosion control, aesthetic appeal, etc. In most vineyards, midrow avenue surface management differs from surface management under the vine row. Commonly the area under the vine is kept weed-free by herbicide application but in some vineyards weeds may be controlled with various types of shallow blade implement or vegetation may be left to grow there, either permanently or sprayed with herbicide periodically to reduce competition with vines (*in situ* mulch). Various plant residues or other materials, including polymer sheeting, may be imported onto the vine row to form a permanent surface cover (mulch).

The midrow area can be kept bare for most of the growing season by using herbicides or by clean cultivation, or the surface may be covered with some type of vegetation, living or dead (mulch) for part or all of the year. The cover crop may be periodically (usually annually) incorporated into the soil and re-sown annually or it may be retained permanently (five years or more) but mowed or sprayed with herbicide (*in situ* mulch) to control competition with vines or it may be left intact. One of the most obvious factors for judging merits of surface management is to distinguish between vine-row and inter-row surface soil management, but we found no published research that reports on the interactive effects of different combinations of mid- and vine-row management options.

The use of combinations of different cover crops, cultivation, herbicide strategies and various mulches has been the subject of many viticultural studies (eg Buckerfield and Webster 2002). These studies have examined the effects of these management strategies on moisture use and conservation, vine performance, temperature and soil structure on various soil types with and without irrigation. Most of the available research reports on soil surface management concentrate on water balance with little attention given to vine response. In addition, much of this published material does not report basic soil and site information such as profile descriptions, soil physical and chemical data, root distribution patterns, climate and irrigation. This obscures the effects of surface soil management on vine performance and points to a need that should be addressed by researchers in this field.

5.1 Options and strategies of surface management

A major objective of surface management is manipulation of soil water for conservation purposes (to increase available water supply for the vine) or to consume water (to control excess vigour). In areas where water supply is limited, the aim of soil surface management is often water conservation through elimination of weeds, increased water infiltration, reduction of surface evaporation and promotion of a root system that can exploit soil water reserves from the shallow surface layers down to depths of 1 m or more (Van Huyssteen 1983).

The detrimental effects of weeds on vine growth have been described by Shaulis and Steel (1969). Young vines are particularly susceptible to weed competition (Due et. al, 1999). However, weeds might have beneficial effects on vine performance if vines are excessively vigorous because of an excess of water but they are a serious problem when water needs to be conserved during summer growth. Shallow cultivation between rows and around individual vines within rows is one method of removing the competition (Winkler 1963), but the use of herbicides now predominates. Together or individually, shallow cultivation and periodic herbicide application constitutes the foundations of under-vine surface soil management strategies in many vineyards.

A wide variety of cover crop species are used in midrow surface soil management strategies for a variety of purposes not necessarily related to their effect on soil properties. However, the comparative differences between various cover crop species, such as oats, barley, cereals, legumes, peas, beans, vetches, clovers and medics, with respect to ameliorating subsoil constraints, and subsequent vine response, has not been studied in sufficient detail for us to draw general inferences.

5.2 Comparison of three basic strategies

Surface management provides a means to manipulate soil properties that can affect vine responses. To understand the effects of surface management on soil properties and the response of vines to these properties, we focus on the effects of three basic elements of surface soil management: (1) keeping soil permanently bare during the growing season either by tillage or by herbicide use (bare surface management), (2) sowing cover crops in the midrow during part of the growing season and removing them by tillage for the rest of the season (annual cover crop management), (3) permanently covering the soil surface with either a perennial cover crop that may be controlled by herbicide or mowing or use of a non-living mulch (permanent soil cover management). Table 8 summarises the advantages of various combinations of these basic surface management techniques on soil properties that affect vine performance.

Table 8: Generalised effects of soil surface management practices on soil properties that affect vine performance. Symbols: - negative effect, + positive effect | no effect.

Management practice	Water storage and availability	Improved aeration and drainage	Penetrability and porosity	Control of Salinity and sodicity	Increased chemical fertility	Improved Structural stability	Higher Soil temperature
Bare midrow surface	--	--	--	-	--	---	+
Bare under vine-row	-	-	--	-	-	-	+
Mulched vine-row or mid-row	++	++	+	++	+	++	-
Mid-row annual cover crop	-	--	---	-	-	---	|
Mid-row mown perennial crop	+	++	+	+	++	++	|
Continuous mid-row crop	---	+++	++	+	++	++	|

Shallow cultivation of soil in the midrow avenue of vineyards is a long established and fundamental strategy for controlling weeds and, it is thought, conserving water and frost protection. A bare soil surface can also be created by frequent, regular applications of herbicides. Use of herbicides has become the preferred option for controlling weeds under the vine row, although some growers control weeds here by shallow cultivation with special machinery designed to avoid vine trunks. Effective application of these surface management techniques requires frequent herbicide application or tillage (up to 10 times per year).

Although these techniques are effective for weed control, they have adverse effects on surface soil structure and soil biological activity.

Annual cropping of the inter-row is widespread in many viticultural industries. This practice keeps soil covered with a crop during winter and spring alternating with bare surface management in summer and autumn. Soil is usually cultivated in autumn, although winter or early spring is an alternative option, and an annual cover crop is sown and incorporated into the soil in spring. Consequently at least two tillage operations are done each year. Several viticultural and pest management benefits are claimed from this practice: improving soil organic matter and fertility, mostly nitrogen economy. However, there is substantial evidence to refute these claims (eg. Troeh and Thompson 1993; Penfold 2003). McCarthy (1991) concluded that because of the negative effects of regular tillage in the inter-row area of vineyards, there is little if any net benefit to soil from annual crop growth. The basic problem in this system of surface management is regular, annual tillage of the soil. This practice has been shown in all research conducted on cereal and annual cropping systems to be deleterious to soil structure (e.g. Cornish and Prately 1987).

Keeping the soil surface covered with a continuous cover is a surface management strategy variously referred to as “permanent sod”, “sod culture”, or permanent mulch. The meaning of “permanent” in the context of a growing cover crop generally seems to imply a permanently living (i.e. perennial) cover crop. However, in this review permanent means the cover is permanent present but may not be living i.e. the soil surface is continuously covered but not tilled. These management systems are also variously referred to as “no-till”, “minimum till” or “mulched” systems. Crop residues for covering the surface are generally derived from one of two practices: (1) growing fibrous rooted, monocotyledonous crops (grasses) in the midrow (less commonly under the vines) and controlling competition with the vines, if necessary, by periodic herbicide spraying (*in situ* mulch) or by mowing or slashing, after seed set; (2) by spreading on the vine row and/or on midrow area imported crop residues from outside the vineyard or, less commonly, sawdust, compost, gravel or plastic sheet (surface mulch). Whatever its source, the surface barrier has three main functions that influence soil structural conditions and vine performance: (1) reduction of raindrop and irrigation impact on the surface, leading to preservations of surface macro-porosity; (2) promotion of greater infiltration of water through the preserved surface macro-porosity; and (3) reduction of evaporative loss of water from the soil due to the insulating effect of the surface barrier.

We reviewed the relevant literature to make comparisons of the advantages and disadvantages of these three basic approaches to soil surface management in vineyards. We discuss the results of our review in terms of soil water conservation, changes in soil physical and biological properties and the effect these basic elements have on vine performance.

5.2.1 Soil water conservation

Regular cultivation often reduces soil moisture and accelerates evaporation from the surface (Van Huyssteen and Weber, 1980b). Generally, surface evaporative loss of water from the soil represents a considerable proportion of the total loss of water from soil, especially where the soil surface is frequently wetted by rain, sprinkler or furrow irrigation (Smart and Coombe, 1983).

Freeman and McLachlan (1988) compared the water use of a flood irrigated vineyard using three different inter-row management techniques (1) cultivated, (2) “permanent” sod, and (3) plastic cover. They showed that the uncontrolled permanent sod (soil surface cover with living vegetation throughout the year) reduced vine performance through significant consumption of the soil water reserves. However, shallow cultivation of the inter-row area caused even greater loss because water lost via evaporation was even greater than water consumption by permanent sod. Their “permanent” sod treatment did not include killing the cover crop in summer and so it competed with the vines for soil water. If this were controlled with herbicides, conservation of soil water through the summer would presumably have been as effective as the plastic mulch.

Van Huyssteen et al. (1984) compared water use of cover crops with herbicide and bare soil treatments in a deep alluvium soil and concluded that shallow cultivation conserved very little water. Plant transpiration and evaporation from the surface was higher from a bare soil surfaces compared to a mulched surface but was similar to an annual cover crop. In contrast, Van Huyssteen and Weber (1980b) found that in dry-grown vineyards, water was conserved under a weed-free, dry, cultivated (bare) surface layer that behaved like a mulch. Stevenson (1975) also found that clean cultivated plots contained, on average, 11 percent more moisture than plots under a mown cover crop. This resulted in increased yields but had little effect on quality, as assessed by berry titratable acidity and sugar levels.

These apparent conflicting moisture conservation effects reported for bare surface treatments are a result of complex interactions between moisture status, climate and surface condition and their effects on the flux of water vapour in soils. In the first instance, water vapour flux can be enhanced or retarded by differences in unsaturated water content in such a way that the water vapour flux peaks at intermediate water contents but drops to a minimum at low or high water contents (Cass et al., 1984). Bare cultivated soil, that is dry for long periods, will have a lower rate of evaporative water loss than wetter surfaces (where rainfall or irrigation is more regular) (Bristow et al., 1986). So, the conservation of water by bare soil surface treatments depends on the wetting history of the soil .

Mulches of various types are very effective in moderating and stabilising soil temperatures, reducing water loss, reducing nutrient leaching and preventing compaction (Jones et al. 1977; Richards 1983; Van der Westhuizen 1980; Van Huyssteen and Weber 1980a, b). Most of these researchers advocated the use of surface mulches where rooting depth is limited. The mulch improved soil structure, allowing water and air to move more freely through the profile and reduced evaporation of water from the soil surface. Surface mulches can be imported (cereal straw, plastic sheet, etc.) or created by growing suitable perennial crops *in situ* and controlling them at appropriate times by mowing or herbicide application.

Moisture conservation also involves accession of water via infiltration. Most research has shown that soils that are regularly cultivated have drastically reduced infiltration rates (e.g. Van Huyssteen and Weber, 1980b; Saayman and Van Huyssteen, 1983; So et. al, 1995). Cultivation reduces the organic matter content, exposes soil to raindrop impact and predisposes the soil to slaking. Slaked surfaces form a crust on drying, which impedes water transmission (Bristow et al, 1995).

5.2.2 Physical and biological properties

Favourable physical properties are compromised by regular tillage in vineyards (Van Huyssteen and Weber, 1980a; Baeumer and Bakermans 1973; Unger and Phillips 1973; Van Huyssteen and Weber 1980a; Lal 1989). Most of these reports showed that initially the cultivated layer has good soil physical properties but these are soon moderated by surface slaking and below the cultivation layer a tillage pan developed with high bulk density and low total porosity. Oades (1993) showed that large aggregates and corresponding large pores are destroyed by cultivation, particularly if the soil is cultivated when wet or when dry. All processes that depend on large pores (air exchange, infiltration, drainage, root growth) are retarded. Dexter (1988) showed that even at low soil strength, roots preferentially grow in pores rather than through soil aggregates. On a duplex soil of limited topsoil depth (350 mm) Hansen and Cass (2002) found that covering the soil surface with straw mulch reduced surface crusting compared to a bare soil surface and increased surface soil moisture.

Long-term vineyard yield declines have been attributed to decreased organic matter and nitrogen supply (Pool et al. 1990), which are attributed to reduced biological activity. Soil tillage disturbs the habitat of microfauna and microflora and reduces the numbers of these beneficial organisms. Surface-feeding earthworms are particularly important for creating biopores that exit to the soil surface and aid in infiltration of water and aeration (Oades, 1993). Earthworm casts are often more stable than other soil aggregates. Fungal hyphae and bacteria also create and stabilise soil structure (Oades, 1993). Hyphae enmesh soil aggregates and create pores during growth. Hyphae, roots and bacteria excrete mucilages that stabilise soil aggregates. Micro-organisms stabilise soil aggregates through filamentous structures, biopolymers and polysaccharides. Tisdall (1978) found few earthworms in cultivated orchards and. Van Huyssteen and Weber (1980a) found low levels of fungi in the topsoil under clean cultivation. In contrast, where the soil surface is mulched or where organic matter is increased (as would be the case under all types of mulch), higher populations of earthworms and fungi were found.

5.2.3 Vine performance

Clean cultivation destroys surface roots (Cockroft and Wallbrink 1966a; Richards and Cockroft 1974; Van Huyssteen and Weber 1980c). In vineyards that are regularly cultivated, as much as 200 mm, or more, of the upper part of the profile is free of any root growth (Van Huyssteen and Weber 1980a,b,c) and low in clean cultivation treatments.

Because regular cultivation of vineyards affects the fundamental soil physical factors that affect vine growth, some impact on shoot growth and general vine performance can be expected. After six years of different tillage treatments in dry-grown Chenin Blanc on 101-14 rootstock, shoot mass under clean tillage was 33 and 13 % lower than for a straw mulch and full surface herbicide application, respectively (Van Huyssteen and Weber 1980c). They also reported that berry yields were reduced under clean cultivation. However juice composition (sugar, TA and pH) was not adversely affected by cultivation (van Huyssteen 1989). Morlat (1987) compared clean cultivation and permanent sward systems and found that the competition from the grass negatively affected development of the root system, water supply and mineral nutrition of vines. Pruning weights decreased as the level of competition increased from the permanent sward treatment. Must quality was also affected by the intensity of the competition.

Pool et al. (1990) compared the use of sod, mulch, herbicide and clean cultivation in established unirrigated vineyards with deep and shallow surface soils and found that cane pruning weight, yield and soluble solids content were similar for all treatments on vines growing on deep topsoils. However, on shallow topsoils vines grown under mulch management had significantly greater cane pruning weights than vines grown under sod management. Similarly, Lombard et al. (1988) reported that a cover crop of perennial (permanent) grass in the midrow area reduced vine size, canopy density and nitrogen status in non-irrigated vineyards.

Van Huyssteen and Weber (1980c) produced the highest quality wine from a straw mulch treatment in 2 out of the 3 years that quality was evaluated. This treatment also had the highest pruning mass and yield. In contrast, the permanent sward (continuous living cover) treatment produced the lowest yield because of competition with the cover crop for water and nutrients. It also produced the poorest quality wine due to incomplete fermentation caused by low N content in the musts. The low N content in the musts was attributable to the low uptake of water and N by the vines.

6 Discussion and Conclusions

This review largely covers the English scientific literature relating to viticultural soil research and management and consequently, reflects a bias towards research done in Australia, California, South Africa and New Zealand with some, but not exhaustive coverage of the European literature. It really only covers documented research findings. We need to be aware that there is another body of soil knowledge, held within the commercial sector, that has been neglected because it is generally poorly available in the public domain. General access, in the widest sense, to this information is restricted and may be “commercial in confidence”.

If one asks the question “what is the importance of soil properties in the production of crop X”, the answer is generally quite positive and definitive. However, in reviewing the viticultural soil research literature, we became aware that. Generally, soil research in viticulture lacks a rigorous soil science basis. There are certainly exceptions to this sweeping assertion, notably the research done in South Africa by van Huyssteen, van Zyl, Weber and Saayman in the 1970' and 80's. However, an examination of the list of references in this review reveals that (1) there are few papers with a viticultural theme where soil issues form the core of the research, (2) few, if any, professional soil science society meetings (as judged by the contents of proceedings of these meetings) have featured viticultural themes, (3) few professional soil scientists work in viticulture (except for in the South African industry and more recently, Australia) and (4) most prominent viticultural tertiary curricula in the English-speaking world, have either no or weak soil science components (deduced from a review of web site course offerings of various undergraduate viticultural teaching institutes). These four factors probably explain why the real contribution of soil properties to wine production is so obscure.

Alteration of many soil properties is often a slow process, and several years may elapse before the effects of different soil management systems become manifest. Generally, in 60 % of the literature we reviewed, experimentation and monitoring was not continued for more than one year. Some work stands out as superior in this respect: soil research conducted at the Viticultural and Oenological Research Institute, Stellenbosch, South Africa in the 1970's and 1980's. This work continues to stand as the most comprehensive and reliable study of the interaction between soil properties, root growth and vine performance.

6.1 Soil Properties and Vine Performance

In reviewing the literature on soil properties and vine performance, we took the broadest possible view of “vine performance” and regarded it as ranging across the entire considered spectrum of wine production from vine survival and growth all the way through to the price of bottled wine, and passing through vine survival and growth, vine balance, berry quality, wine flavour, wine quality and wine pricing. We tried to define each of these stages in terms of measurable factors that could be related to soil properties. This was achievable with respect to vine survival and growth but less so for berry quality. We were generally unsuccessful with respect to the other factors, but we were not able to dismiss them entirely, despite the fact that they were treated lightly, if at all, in the literature.

6.1.1 Vine survival and growth

The effect of available water supply on vine growth forms a major component of the published viticultural soil literature and has been extensively reviewed here both in the context of vine growth and vineyard surface management. Issues of both quantity of water applied as irrigation and the effect of irrigation water quality on vine survival and growth as well as berry quality are extensively covered in the literature. Australian research has made major contributions to knowledge in this area. Clearly, this fact reflects the serious interest that the Australian industry takes on improving water use efficiency, manipulating applied irrigation water as a means of controlling berry quality and the sustainability threats arising from use of saline irrigation water.

Although issues relating to irrigation water management enjoy a prominent place in the literature we have covered here, there is an obvious gap in research and knowledge relating to how different soils behave in supplying water to vines. Most of the existing literature on this topic is dominated by a common and tacit underlying assumption that all soils receive, store, and supply water to vines in a similar way. Some researchers may acknowledge differences between soils in these processes and some information is available in the literature concerning measured soil properties. However, without exception, detailed characterization of the hydrological properties of important viticultural soils is not available in a format that can be used by vineyard managers. What little information is available is not effectively used to develop soil-specific management packages. This deficiency is particularly evident in Australia, where a user-friendly viticultural soil classification has not been available to serve as a platform to carry this technology. The recent development of the Australian

Viticultural Soil Key (Maschmedt et al, 2002) may redress this imbalance. Even in viticultural industries like those of South Africa and California, where soil classification systems seem to be more widely used, and where more soil-specific hydrological information is available, the existing scientific viticultural soil literature reflects poor use of that data to develop soil-specific management packages for even the most important viticultural soils.

Aeration issues are acknowledged by the classical viticultural literature as a serious threat to vines but the detail of exactly how and when a lack of aeration impacts on vines, the effect on yield and fruit quality and the role of different soils in providing different aerobic environments has been generally ignored by most of the main viticultural research establishments. Among a few others, the work of Dowley, Cass and Fitzpatrick, reviewed here, has approached this topic in a rigorous, soil-based way. Unfortunately most of their findings have not yet been published in the mainstream soil or viticultural literature.

Root extension issues (such as soil hardness) have been addressed in soil preparation research, particularly by the South African research community, but generally ignored elsewhere. The detrimental effects of young vine mortality or poor growth is a key issue in vineyard establishment. Consequently the technology for deep ripping is well developed, thanks to the work done in South Africa, Silsoe College in the United Kingdom and more recently in Australia and California by soil scientists. It is probably true that soil preparation techniques for new vineyards are among the most advanced in agriculture. This does not mean, however, that further advances are not required. For example, the effect of implement design and depth of ripping on fruit quality does need to be pursued, as does the issue of soil-specific ripping and ripping in established vineyards.

Soil compaction effects, resulting from management practices in established vineyards has not enjoyed similar attention from researchers. There is a growing body of work that addresses the issue of soil compaction and hardness on crop growth in general and key items have been reviewed here. Many of these findings are applicable to viticulture, but the application of this knowledge often needs careful interpretation. For example, soil compaction is regarded as generally detrimental to crop productivity. However, in the viticultural industry, wheel traffic compaction in vineyards may or may not be a problem for wine production, depending on whether root restriction aids fruit quality or not. Given that many vineyards are subject to frequent and regular trafficking with heavy machinery and equipment, it is surprising that definitive studies, beyond what the South African research community has contributed, have not been published on the effects of wheel and tillage compaction on fruit quality.

Generally the literature tacitly addresses the effects of toxic elements in soil on vine survival and growth. In topics such as salinity and sodicity, which are major management and sustainability issues in many parts of the world, research has made extensive gains. The effect of salt on vine survival and growth and fruit quality as well as soil productivity has enjoyed extensive investigation. The effects of salinity on vine performance have been confined to shoot growth and yield responses with little attention to root growth. Sodicity is somewhat less well studied in viticulture, but even in this area major gains have been made with respect to soil properties but the link with vine performance is less clear. Well-developed standards and criteria exist and technologies for control of salinity and sodicity are widely applied in all viticultural industries.

Technology relating to other chemical threats to vine survival and growth range from being well developed to non-existent. For example, while the effects of boron on vine survival and growth are well known and measures to combat boron in vineyards are known, the comparable effects of high concentrations of magnesium are not. The deleterious effect of high concentrations of exchangeable magnesium, relative to calcium, on soil physical properties has enjoyed some attention from soil science research but not in a viticultural setting. Apparent inhibition by magnesium on the uptake of nutrients by vines, although widely acknowledged, has not enjoyed any attention from viticultural researchers. The mechanistic role of magnesium in these nutritional problems hardly features in the viticultural soil literature. The deleterious effects of high concentrations of heavy metals (particularly copper, cobalt, manganese and nickel) on vine survival and growth is hardly mentioned in the viticultural soil literature, let alone the possible effects on berry quality and wine flavour.

All evidence obtained from the literature can only loosely confirm the widely held view that the soil nutrition status cannot predict vine performance very well. Of the research work conducted on manipulating mineral nutrient composition of soil has yielded few, if any, basic principles to guide soil assessment or fertilizer application recommendations to change vine performance. This is not surprising considering the complexity of the soil-vine-atmosphere system. Knowledge of soil chemical composition has more value in assessing toxic and deficient conditions rather than for assessing chemical fertility. Many grape growers rely entirely on tissue analysis to guide vineyard fertilization rather than soil analysis. Although tissue analysis provides the most promise for an objective guide to the nutrient status and fertiliser needs of grapevines it should not be considered in isolation without considering the nutrient level of soil within the root zone and the effect the soil will have on the availability of applied nutrients.

6.1.2 Vine balance

Vine balance is a concept widely used in the viticultural industry. It is defined in terms of vine performance factors that relate to vegetative and reproductive growth. However, the factor of root mass, volume or cumulative length is not often included in this concept. Since roots are the plant organs in contact with the soil, the relationship between soil properties and vine balance should be assessed through root factors. Generally, issues related to vine root growth and extent are poorly dealt with in the viticultural industry. There are serious misconceptions prevalent in viticultural science about the density of vine roots. Dowley et al. (2002a-h) found much greater root densities in a variety of viticultural soils than the literature generally suggested. Because of the lack of knowledge of vine root systems, concepts about the relationship between soil properties and 'vine balance' must be regarded as suspect. If a more rigorous relationship between vine root growth and soil properties is developed, the relationship of vine balance to soil properties will become clearer.

Having said this, in reviewing the literature, we assumed when comparing the results of similar experimental trials, that the vines have been managed so that reproductive and vegetative growth remains in balance. However, commonly authors did not clearly demonstrate the steps taken to ensure that the vines were in balance with the treatment effects. Thus, assessment of vine performance can be misleading. For example, increases in available water can stimulate vigour, which, in turn, can cause a reduction in fruit quality if not pruned to accommodate the extra vigour (Smart and Robinson 1991). Hence, assessment of treatments should be conducted over a number of years. It is arguable that the minimum time required is three years before recommendations can be made. Of the literature reviewed less than 40 % reported measured vine response for more than one year. Even fewer explained the steps taken to ensure that the vines remained in balance.

6.1.3 Berry quality

Measurable, well defined berry quality factors are available and have been examined in this review in relation to soil properties. Despite the existence of these berry quality indicators, it has been difficult to obtain from the viticultural soil literature clearly definitive relationships between soil properties and behaviour and berry quality. Most of the literature we reviewed where the topic was included, permitted only a subjective judgment to be made about the impact of soil properties on fruit quality. However, there is enough evidence to show that, given the right approaches and techniques, a better and more quantitative relationship with soil properties is distinctly possible (see below).

6.1.4 Wine flavour, quality and price

Wine flavour is difficult to define in terms of parameters that can be related to soil properties. It is a sensory factor that is both subjective and qualitative and subject to changes in popularity over time. These issues preclude a rigorous connection with soil properties. Wine prices are driven by market factors that are generally (but not always) far removed from the soil properties on which the wine was produced. However, it cannot be categorically denied that at a broader scale, some sort of relationship may exist. For example, it has been said that perhaps the distinctive flavour component of many Australian wines is the common factor of higher soil salinity compared to most wines from the rest of the world. This may or may not be true, but certainly the body of scientific literature that we have reviewed does not really support this or other flavour issues that are often attributed to soil “mineral character”.

6.2 Soil Surface Management

The literature reviewed here shows clearly and unambiguously that soil surface management options that expose the soil surface to rainfall and rapid drying or which involve frequent disturbance by tilling are not conducive to optimum vine survival and growth. Although not as clearly shown, these management practices are not generally compatible with the best fruit quality, if only because of indirect effects such as poor water economy. An added feature of these management practices is that they are ‘high input’ practices in terms of machinery and fuel and are environmentally suspect.

Use of various techniques to keep the soil surface covered at all times and minimize soil disturbance produced the best soil properties (Table 8) and the most obvious features of sustainable production. The effects of these management options on berry quality are again not directly obvious, but they are certainly important contributors to quality in an indirect sense. Examples of these indirect effects can be found in the improved soil water conservation and better soil aeration that certainly contribute to fruit quality. In addition, these management options are clearly environmentally sound and usually enhance the sustainability of the vineyard. There seems little doubt that the industry could benefit considerably if bare surface and annual cropping management practices are abandoned in favour of the lower input and more sustainable surface cover options.

6.3 Linking soil conditions to vine performance

It is clear from the information presented that there are many interactions between soil properties that can affect vine performance. This was shown by Bramley (2002) where, in a site known to have soil salinity limitations, soil salinity only partially accounted for the reduction in vine yield suggesting other soil properties were having an impact. However, there is a scarcity of available data to effectively assess the impact of soil properties on vine performance as material presented in this review has shown. Nevertheless, knowledge of the effect soil conditions on root growth and function is substantial (eg. Cass et al., 2002a,b; Dowley et al. 2002h) and should be used more succinctly in relation to describing vine performance and climate interactions. The challenge for viticulture research is to account for variability in soil properties through space and time and link the data to vine performance in various climates.

Essentially, through the use of established vineyards that are in balance with the soil conditions, targeted sampling for both soil conditions and vine performance could be used to develop an empirically based model of vine performance. The influence of climate should not be overlooked with year to year variation in vine performance (Bramley 2001). For example the approach shown on Figure 3 to relate soil water storage to rainfall and irrigation might be useful in this regard. Hence, the evaluation of vine performance in relation to soil properties will improve as the number of years of data increase. A key question in relation to climate is whether the variability in climate has a greater impact on vine performance than the variability in soil properties. Bramley and Hamilton (2004) have made steps in answering this question in relation to yield but not quality. They demonstrated that the pattern of yield variation was correlated with variation in soil properties more so than the influence of seasonal differences. More information like this could then provide a basis for amelioration recommendations based on soil profile assessments and regional climate interactions.

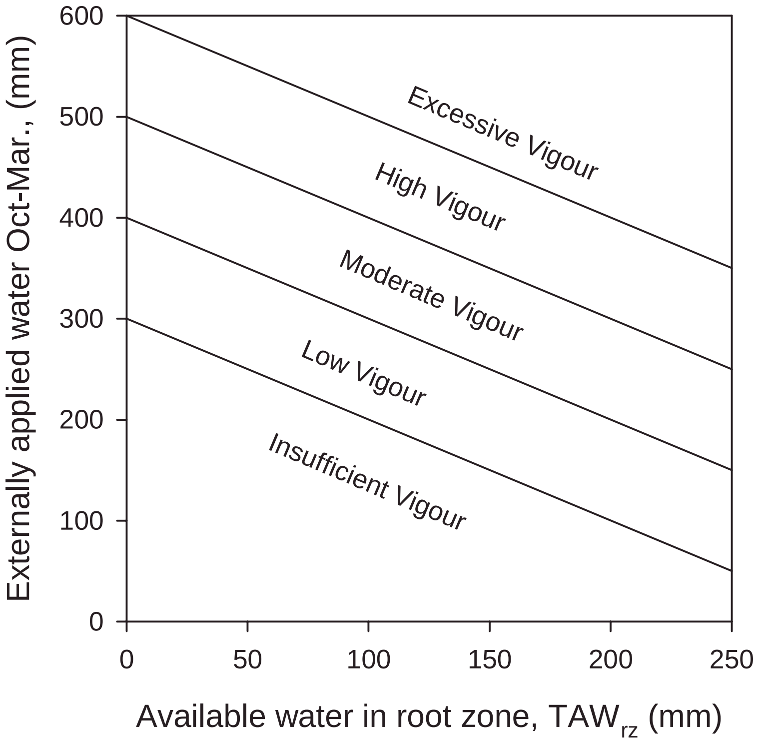

Figure 3: A proposed index for describing the interaction between applied water (either via rainfall or irrigation) and soil storage properties and its effect on vine vigour

To relate vine performance to soil properties it is important to establish a minimum set of measured parameters that will allow a database to develop. This can then be used to suggest optimal soil properties for soil selection with a grape quality in mind and provide the basis for the suggestion of appropriate soil management practices if they are needed.

6.4 Selection of appropriate management practices

The viticultural soil literature shows that water use efficiency is regarded as a central issue to improved resource management in viticulture. However, the main thrust of this research seems to miss an obvious point. The most obvious way of improving water use efficiency is by improving use of natural rainfall, stored in soil and reducing or eliminating reliance on irrigation. This approach does not necessarily demand complex irrigation techniques, but does require new approaches to soil management, particularly tillage and soil surface management. The primary mechanism by which such water use efficiency increase is obtained is to either increase the volume of the root zone or to elevate root efficiency in extracting water from the existing root zone. A major barrier to exploitation of natural rainfall accession to soil by vine roots is poor or degraded soil structure. Clearly, greater emphasis of research on soil structure improvement might yield considerable benefits to the industry.

It is apparent from the viticultural soil literature that there is little differentiation between the resources available in the inter-row and the vine row. We do not mean that differences in soil properties have not been identified (which is true), but rather that little work has been reported in Australia in using the resources of the inter-row. The inter-row area can account for two thirds of soil volume based on a 3-meter vine row spacing and, thus, represents a significant resource. Myburgh et al. (1996a) have identified limitations to root growth on many different soil types where vines performance was known to be poor. Yet there has been little evaluation of amelioration methods that overcome these constraints in established vineyards.

Van Huyssteen (1988b) suggested that the efficiency of sporadic deep roots should be studied since their contribution to water supply during periods of stress may be significant. This is supported by the views of Passioura (1988). Hence, soil management practices, either intended for the vine-row or the mid-row, that encourage sporadic root penetration into water reserves not usually available to the vine should receive greater attention that it has it the past.

Further work is required to assess which soils are prone to restricted root volumes and what the best management methods are which utilise the inter-row and vine row to improve vine performance. This information is needed to add value to the recently developed Australian Viticultural Soil Key (Maschmedt et al. 2002), which does not currently provide management options. Initially, this key should be correlated with vine performance parameters to see whether it can successfully separate differences in vine performance. Recommendations as to the soils suitability to produce a target quality in particular climates could then be made as well as possible soil management options, as demonstrated in Table 8.

6.5 Future research

At best the current literature only links soil properties to vine performance in general terms. Although some work has been done on the impact of soil management systems on soil physical and chemical conditions, there is a lack of information relating this work to vine performance. Generally, it is believed that the better the soil in terms of some benchmark indicators, the better the performance of the vine. However, we need to be careful that the underlying aims of crop production that were used in determining these benchmark values are the same aims in viticulture production. In fact we can show that the aims are often different. Grape production for wine needs a different set of soil benchmark values than other crops or at least adaptive management systems that allows the vineyard manager to control vine performance according to the soil characteristics that the vine grows in.

There is a lack of documented soil specific management packages for viticulture throughout the world. In Australia, development of a manual for the management of the soil resource that builds on the recently-developed Australian Viticultural Soil Key is necessary. This key provides a suitable platform to develop management tools for various soil conditions. However, past soil viticultural experiments have, largely, not devoted sufficient effort to describing soil properties. Consequently, at present, linking vine response results to the Viticultural Soil Key is not possible because of the poor description of the soil properties in past experiments.

Van Huyssteen (1988a) expressed the opinion that ‘further studies of the soil volume/plant available soil water interactions should lead to a more definite understanding of the required rooting volume’ and that ‘the optimum working depth that will not lead to a too vigorous top growth should be established for each climatic/soil type/rootstock association’. We agree with this directive.

Although the literature abounds with vine response to changes in management, it is difficult to assess the relative merits of each management decision in relation to vine performance as such because of the lack of definitive target values, for either economic or sustainability value. This is confounded by the short periods of time over which management systems research has been assessed in the past. Changes many in soil properties are inherently slow. Hence, trials aimed at evaluating different soil management systems require long periods of time such as those published by South African researchers (i.e. 3 to 5 years).

The focus of future research work in viticulture that has a soil component and that addresses vineyard sustainability should include the following features:

- Soil management practices, both surface and profile, should be aligned to variations in soil type and or profile characteristics and individual relevant soil properties;
- Better information about the expected vine response to soil degradation and remedial soil management practices;
- Long-term soil management experimental sites are needed that allow researchers to accommodate assessment of the inherently slow process of changes in soil properties and to link these to vine performance (yield and quality);
- Better, soil- and possibly, variety-specific guidelines for vine nutrition are needed;
- Closely related to 4, an improved basis for the use of both soil and petiole analysis for prescriptive addition of nutrients to the soil with respect to grape quality targets is needed;
- Application of precision agriculture tools for targeted management and as an aid for site selection and research into better management practices;
- Better matching of rootstocks to soil properties through the development of a comprehensive soil/vine performance database; and
- Drawing on all of the above, appropriate selection of new vineyard sites based on expected vine performance and required management practices.

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