The Soil Component of Terroir

Le rôle du sol dans le terroir viticole

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Abstract: Evidence for a specific effect of soil mineral composition on wine character is largely anecdotal. However, soil potassium supply to the vine must be properly balanced between deficiency and excess for good fruit quality. Nitrogen supply interacts with soil water to affect vine vigour, yield and fruit quality. With irrigation, water availability in the top 40-60 cm of soil can be managed through regulated deficit irrigation, thereby subduing the mineralization of soil organic N and decreasing vine N uptake, with favourable effects on fruit quality. In dry land vineyards, water availability depends on climate and soil physical properties, the latter being beneficially modified by calcium. The effect of soil variation on terroir should be evaluated on a scale of metres rather than kilometers. High density real-time measurements of relevant soil properties enables digital soil mapping at very high resolutions. Thus, vineyards can be divided into small blocks with the same mesoclimate allowing site-specific soil management and cultural operations (precision viticulture).

Key words: grapevines, precision viticulture, soil management, soil variability, terroir

Is there a soil component to terroir?

« Terroir » is everywhere in the sense that the word appears on many wine labels and frequently in promotional material for wineries and in wine magazine articles. However, there is much ambiguity about the role of soil as a component of terroir. A Google search for « viticulture and terroir », « wine and terroir » or « soil and wine » reveals many sites with a variety of opinions about terroir and soil. On these websites intended for public access, soil is often subsumed under the term « geology ». For example, Shadow Canyon of York Mountain, California (www.shadowcanyon.com) states that terroir invokes geology, which encompasses « soil depth, chemical composition, physical structure and drainage ». At the other extreme, the Africus Rex site of Toronto advocates « soil-less viticulture » in which wine grapes can be grown successfully in confined spaces without soil.

The geological focus on terroir, and its overshadowing of soil, may well result from geologists having shown more interest in soil and wine than soil scientists. Books have been written about the geological aspect of terroir, especially from the perspective of French wine regions (Pomerol, 1989; Wilson, 1998). The website Terroir Australia (www.terroir-australia.com) promotes the mapping of the geology of vineyards, such as in the Coonawarra region of South Australia. However, some authors (e.g. Elliott-Fisk and Noble, 1992) acknowledged that geology influenced the soil to create a diversity of environments (terroirs) in the Napa Valley, California. Apart from the marketing hyperbole extolling the uniqueness of the relationship between geology or soil and the character of individual wines, data on specific soil effects on wine character or « personality » are sparse, so the question arises - how well do we know the essentials of the soil effect in terroir?

Chemistry of the soil

The relationship between soil chemistry and terroir is especially confusing. Bramley and Hamilton (2006) argue that this could be due to the coarse resolution (small scale) at which most soil observations have been made, a topic I return to in the last section of this paper. Johnson and Robinson (2001) repeatedly refer to the soils of the wine regions they review, but usually in simple descriptive terms (such as gravelly, sandy or heavy clay), linked to the rock types on which the soils are inferred to have formed. There are a few references to the chemistry of the soil, such as for Moulin-à-Vent in Beaujolais, where the soil is said to be « rich in iron and manganese », which « probably » influences the wine character. Tablas Creek of Paso Robles, California (www.tablascreek.com) states that « calcareous soil lends minerals and structure to the grapes ». To make a link between calcium (Ca) and terroir is superficially tempting because so many of the great vineyards of the world occur on calcareous soils formed *in situ* on limestone or chalk, or on transported materials derived from these rocks. Saxton (2002a, b) stated that soil Ca created « a favourable medium for root exploration, uptake of minerals and growing a healthy vine » – one could hardly have a more non-specific statement than that. Saxton also argued that the greater root growth of vigorous vines maximized Ca uptake and this would result in a more pronounced expression of terroir. By contrast, Smart (2002) interpreting the work of Seguin (1986) and others in Bordeaux, concluded that the best Bordeaux crus occurred on acidic gravelly soils deficient in most nutrients, and that soil chemistry had no specific influence on wine quality. However, Mackenzie and Christy (2005) reported that for Riesling grapes produced in the northern Adelaide Hills, South Australia, the juice sugar content (Baumé) and titratable acidity (TA) were correlated with several plant-available trace elements (*sic*.) in the soil, notably Ca, strontium, barium, lead and silicon. The latter confirms the view that correlation analyses can sometimes produce nonsensical results and do not explain mechanisms, a point made by Moran (2001) in his article on « Terroir » when he wrote « nobody has yet been able to demonstrate the *processes* (my emphasis) by which elements of the soils are transferred to the flavours, colours and other qualities of wines » .

Reviewing Australian viticultural soils, Halliday (1993) considered there was no link between soil mineral composition and grape quality or wine character, with the exception of nitrogen (N) discussed below, and potassium (K). Potassium tends to be plentiful in soils derived from micaceous parent materials (e.g. schists, shales) and transported materials, as in the Murray-Murrumbidgee region of southeastern Australia. Potassium and Ca are competitive in uptake, which may explain why K uptake is substantial in many Australian soils that are naturally low in plant-available Ca. Irrigation, which is almost universal for vineyards in inland Australia, also enhances K uptake by vines (Sipiora *et al.*, 2005). Potassium is involved in sugar translocation to the ripening fruit and too much K in the berries increases the malic:tartaric acid ratio and raises juice pH (Goldspink and Frayne, 2000). Following malo-lactic conversion during fermentation, the wine pH can be raised leading to colour instability in red wines, which is detrimental to quality (Freeman and Kliewer, 1983). Consistent with other authors, van Leeuwen *et al.* (2006) found no significant correlation between petiole K concentration, measured at veraison, and berry total acidity.

In a seminal review drawing on the results of research in Bordeaux and other French regions, Seguin (1986), subsequently supported by van Leeuwen *et al.* (2004), concluded there was no correlation between quality of wine and the soil content of any nutritive element. Clearly, there is much yet to be done to unravel any relationships between soil nutrient supply and wine quality and character.

Physical properties of soil

Seguin (1986) and others (e.g. Pomerol, 1989; van Leeuwen *et al*., 2004) concluded that soil physical properties – structure (in particular macroporosity, which influences internal drainage and ease of root penetration) and the amount and rate of release of available water - together with microrelief which influences external drainage, were predominant in determining wine quality and character. Seguin argued that the main influence of Ca on wine quality was through its beneficial effect on soil structure, particularly in clay soils. The good soil structure with adequate macroporosity of the pebble-sands in the dryland vineyards of the Médoc, Sauternes and Graves regions enabled roots to penetrate to 5-7 m depth (Seguin, 1986). However, vines grown in soils on hard limestone, as in parts of the Côte d » Or, Saint-Émilion and the upper slopes of McLaren Vale, South Australia, or over a calcrete capping as in the Coonawarra, have a restricted rooting depth: similarly for vines grown on clay soils with poor internal drainage as in Pomerol, and on many duplex soils with compacted B horizons in Australia and South Africa. Poor subsoil drainage is corrected in parts of Saint-Émilion and Pomerol by under-drainage with « aggie » pipe. South African soil scientists are especially concerned about subsoil impediments to root growth (due to hard pans or compacted B horizons) and have developed a « finger mixed plough » that rips through a dense subsoil to 1.5 m depth, without any inversion of soil material, and allows the incorporation of lime and phosphate fertilizer if required.

As with internal soil drainage, good external drainage due to a slope or slight elevation favours wine quality. For example, in the northern Haut-Médoc (e.g. Saint-Estèphe) where the soils are deeper and contain more silt and clay than the gravelly soils of the southern Haut-Médoc (e.g. Margaux), topography is crucial. Most of the Premier Grand Cru Classé wines are produced on the tops of the gravelly mounds (*croupes*) and upper slopes that face towards the Gironde (Johnson and Robinson, 2001). Similarly, in the Napa Valley the best wines with distinctive character are produced on the « benches » , such as Rutherford, Oakville, St Helena and Stag » s Leap, which are colluvial fans formed at the valley footslopes where the soils are stony, often deep, but well drained (Lambert and Kashiwagi, 1978). Good soil water drainage and cold air drainage on slopes in cool climate regions (Gladstones, 1992) provide the potential for the production of top class wines, as evidenced by the Rheingau, Germany, Barolo and Barbaresco regions in Piedmont, and the newly emerged Central Otago region of New Zealand.

Whether on shallow soils on limestone in Saint-Émilion or deep gravel-sands in the Haut-Médoc, the rate of water supply to the vine between flowering and harvest is a very important soil factor affecting wine quality (Seguin, 1986; van Leeuwen *et al.*, 2004). The same factor probably applies for the Grand Cru and Premier Cru vineyards on Rendzinas and shallow Calcareous Brown Soils on limestone in the Côte d'Or, although the latter have not been as intensively studied as in Bordeaux. The regulation of water supply may be a key factor determining the undoubted quality of red wines produced on the Terra Rossa of Coonawarra in South Australia, or the deep gravelly loams of the Margaret River, Western Australia, but the interpretation of water relations in Australian vineyards, as in California, Chile and South Africa, is complicated by the use of irrigation. In many of the best quality vineyards in these regions, regulated deficit irrigation (RDI) or in some cases partial root zone drying (PRD) is practised to restrict the water supply to the vines (Keller, 2005), primarily between fruit set and veraison when excessively vigorous shoot growth can compromise the ripening of the fruit and development of maximum flavours and colour (especially for red grapes). Where vines rely heavily on irrigation, as in the hot inland regions along the Murray and Murrumbidgee Rivers and on many duplex soils in southeastern Australia, the rooting depth is almost entirely confined to the top 40-60 cm of soil (Pudney *et al*., 2001). Thus, deep exploration of the subsoil and parent material, where the concentration of weathering minerals is higher than in the upper soil profile, does not occur. Seguin (1986) argued that one benefit of a vine » s deep rooting on the gravel-sands of the Médoc was access to large *quantities* of cations and anions in soils that are poor in terms of nutrient concentrations. Consistent with the « geological factor » , several authors have suggested that minerals derived by vines from weathering parent material confer distinctive character to the wines (Wilson, 1998; Darlington, 1999), although the evidence to support this direct link is anecdotal.

Can soil management influence terroir?

There is a view amongst some winemakers in the New World that any problems due to soil imbalances can be solved in the winery. For example, a winemaker for a large wine company in South Australia once told a workshop on nutrient management « I don't care what kind of grapes you bring me, as long as they do not have too much nitrogen » . His attitude was that he could fix any problems of the grapes in the winery, except for high N, which induced too rapid a fermentation (« it boiled »). More commonly, however, grapes are deficient in yeast assimilable nitrogen (<200-300 mg/L of juice), which can lead to « stuck fermentations » , and the addition of diammonium phosphate to the fermentation must is a common practice to avoid this problem.

Apart from the question of N concentration in grapes, there are good reasons for optimizing the N supply to vines in the vineyard. The early growth of the vine, up to about flowering, relies mainly on the mobilization of N reserves in the woody tissues (Lohnertz, 1991). After flowering the rate of N uptake through the roots increases rapidly to a maximum around veraison. If the availability of N in the soil is too great, and given an adequate water supply to the vine during this post-flowering period, the vine can produce too much vegetative growth and be out of balance – too much photosynthate goes into producing shoots and leaves relative to fruit and there is too much fruit shading, which hinders ripening. This problem can be corrected to some extent by canopy management (Smart and Robinson, 1991), but is more appropriately dealt with by soil and water management in the vineyard. This is an example of managing the soil component of terroir to enhance fruit quality, and I use our recent research results to illustrate the point.

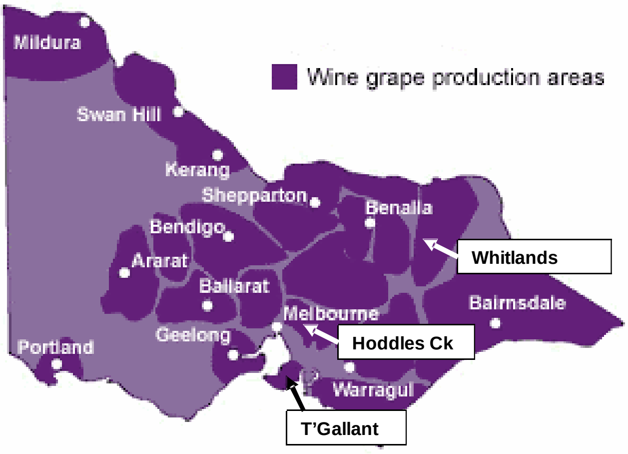


Figure 1 - Location of three cool climate experimental sites in Victoria, Australia

Table 1 - Latitude and climatic conditions for the three experimental sites in Victoria

Site	Latitude	Altitude (m)	Mean annual rainfall (mm)	Mean January temperature (°C)	Heat degree days (>10°C from budburst)
Whitlands, King Valley	36°21 » S	800	1410	18.5	1100
Hoddles Creek, Yarra Valley	37°45 » S	400	910	19.4	1490
T » Gallant, Mornington Peninsula	38°20 » S	250	740	19.9	1570

Preliminary studies were carried out at three sites, shown in figure 1, in cool climate vineyards on deep fertile soils in Victoria, Australia. The growing conditions at these sites are summarized in table 1. The soils are deep red loam soils or Krasnozems (Ferrosols in the Australian Soil Classification of Isbell (2002)) derived from basic volcanic rocks, and are typical of the soils supporting a number of cool climate vineyards in Victoria and Tasmania. Based on records of vine performance, high vigour sites were identified at the Whitlands, Hoddles Creek and T » Gallant vineyards. When the soils were sampled to 1 m depth to measure mineral N (NH_4^+ and NO_3^-), we found that mineral N was consistently greatest in the top 20 cm, and decreased with depth. Table 2 shows that the C and N contents of the A horizons were also high, and C/N ratios in the range where net N mineralization would be expected (White, 2003). This was confirmed by the mineralization potential (N_o), measured by a standard anaerobic incubation procedure in the laboratory (figure 2), which translated into a potential rate (under optimum conditions for mineralization) of 24 kg N per ha per day for the top 10 cm of soil at Whitlands, the most fertile site. These rates are at the top end of mineralization rates reported for soils under broad-acre agriculture (White, 2006).

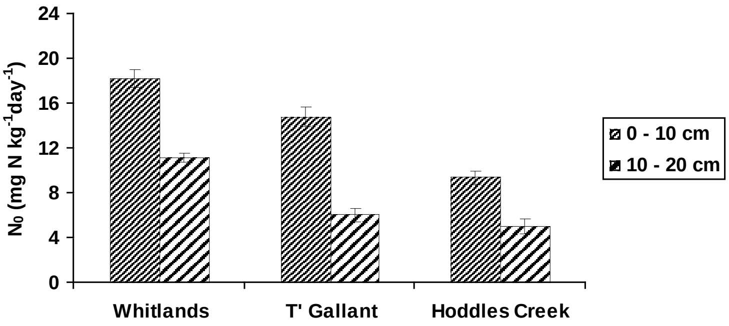


Figure 2 - Mineralization potential of the surface soil at the three experimental sites in Victoria

Table 2 - Some properties of the Krasnozems (0-20 cm depth) at the three experimental sites

Vineyard	Depth (cm)	pH (1:5 in 0.01M $CaCl_2$)	C content (% dry soil)	N content (% dry soil)	C/N ratio
Whitlands	0-10	5.20	9.44	0.64	14.8
	10-20	5.36	7.87	0.45	15.7
Hoddles Creek	0-10	5.09	9.12	0.62	14.7
	10-20	4.83	7.89	0.49	16.1
T » Gallant	0-10	6.27	7.59	0.55	13.8
	10-20	5.55	6.88	0.41	16.8

A field experiment was conducted at Whitlands from 2001 to 2004 on nine year old Sauvignon Blanc vines, on Schwartzman rootstocks, to examine options for managing the N supply in this soil. Given that mineral N availability was greatest in the top 20 cm, it was hypothesized that if the soil in this zone could be kept as dry as possible during the period of most rapid N uptake, between flowering and veraison, the uptake of N by the vine would be decreased. Two treatments were therefore imposed – one of full irrigation to maintain the soil at or near field capacity (FC) throughout the growing season, and the other to allow a large soil water deficit (SWD) to develop in the top 60 cm of soil. The main treatment plots were subdivided to impose four inter-row treatments – a control (the existing sward mix of naturalized grasses and white clover (*Trifolium repens*), a ryegrass (*Lolium perenne*) only sward, a clover only sward and a dead grass mulch. In addition, a ^{15}N labelling experiment was carried out on irrigated and non-irrigated vines between flowering and veraison in 2002-03 to determine the proportion of soil N that was taken up from different soil depths. Accordingly, 98%-enriched $(NH_4)_2SO_4$ was placed, with the nitrification inhibitor N-serve, at depths of 15, 45 and 75 cm around individual vines 10 days after flowering (Figure 3). Each vine received only 0.176 g N, so the « carrier » $(NH_4)_2SO_4$ made an insignificant contribution to the resident soil N and the ^{15}N was effectively labelling the pool of soil mineral N available to the vine.

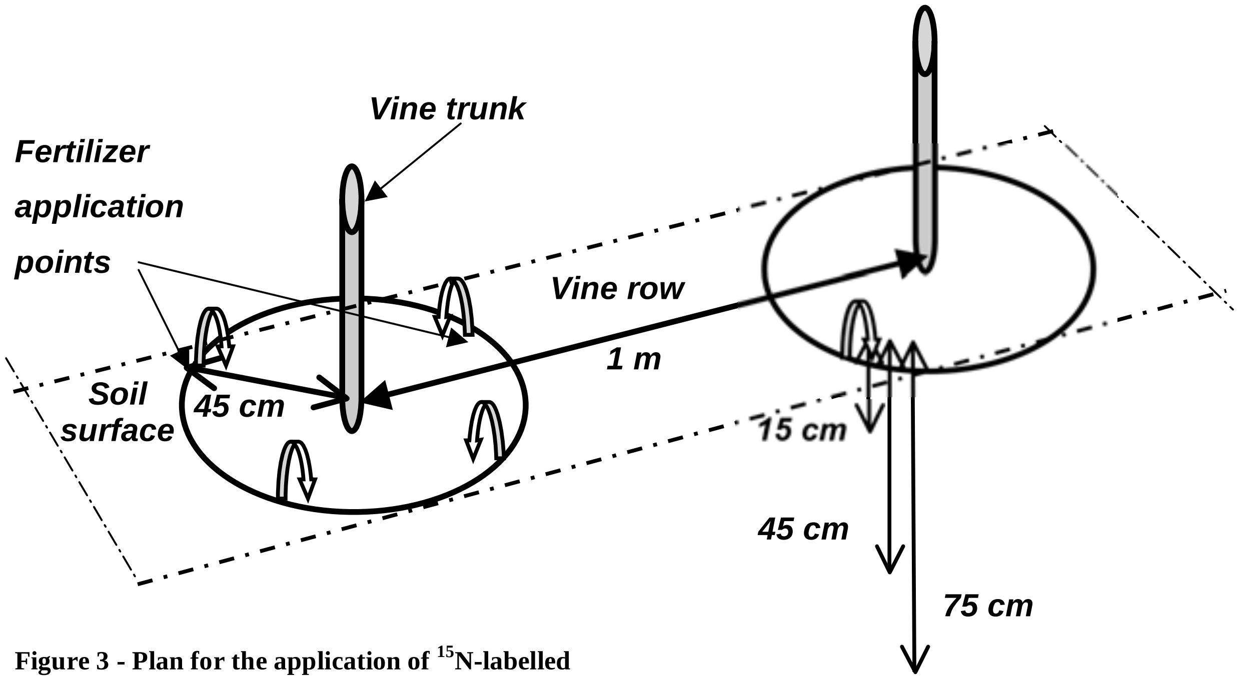


Figure 3 - Plan for the application of ^{15}N-labelled $(NH_4)_2SO_4$ fertilizer and N-serve (not to scale)

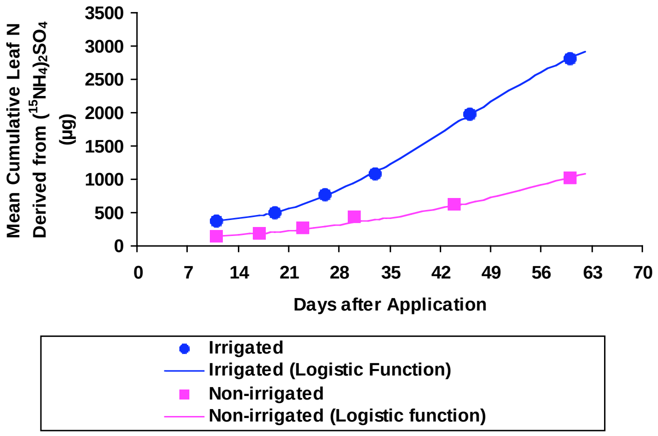


Figure 4 - Cumulative uptake of ^{15}N from Whitlands soil under irrigated and non-irrigated conditions

Leaves from the treated vines were sampled for analysis at regular intervals for 60 days after labelling, and the berries were analysed at harvest. The rate of ^{15}N uptake was initially slow as the vines recovered from a hail storm that occurred three weeks before N application, but the results in figure 4 show a large difference between ^{15}N uptake by the irrigated and the non-irrigated vines at the end of 60 days. Further, graphs of cumulative ^{15}N uptake from each depth showed that N uptake was greatest for both vine treatments from the 15 cm depth, but uptake by the irrigated vines was 4.5 times greater than the non-irrigated vines from this depth (figure 5). Berry ^{15}N concentrations supported these results.

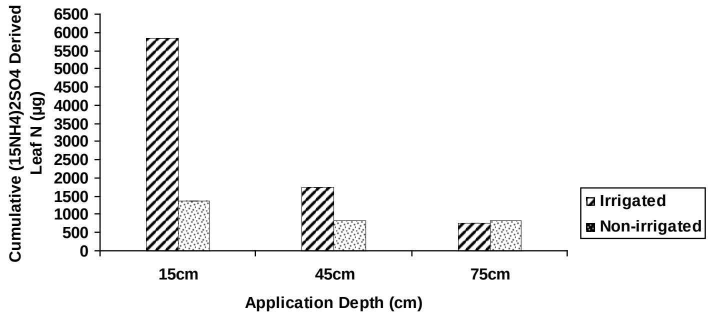


Figure 5 - Total ^{15}N uptake by irrigated and non-irrigated vines from three depths in Whitlands soil

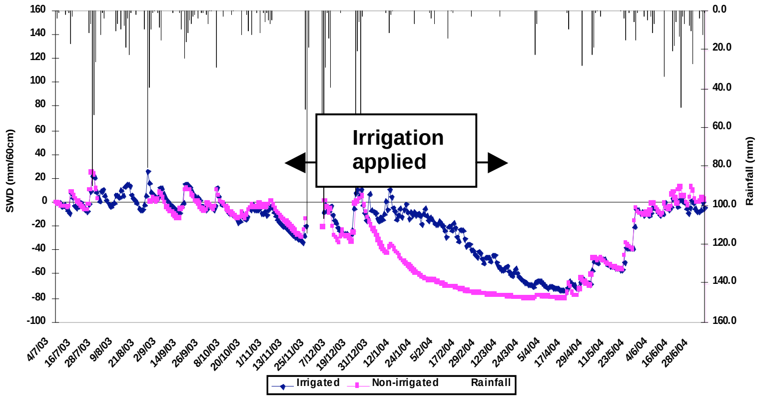


Figure 6 - Rainfall and soil water deficit for irrigated and non-irrigated vines at Whitlands in 2003-04

In the Whitlands experiment, soil water content was measured continuously within the 0-60 cm soil depth and the SWD relative to the FC (attained at a matric potential of -10 kPa at the surface) was calculated. The graphs in figure 6 show the SWD and rainfall plotted against time for the year 2003-04. There was little difference between the irrigated and non-irrigated treatments up to flowering (early January) because of substantial rainfall in early summer. After flowering, however, rainfall ceased and irrigation was used to maintain a substantial difference in SWD between the irrigated and non-irrigated vines. Irrigation was stopped after veraison and the SWD of both treatments converged, before being steadily eliminated as the soil wet up from autumn-winter rain.

The effect of decreased water and N availability on vine growth and fruit yield can be seen in the results for the 2003-04 crop (table 3). The effect of withholding irrigation in decreasing mean bunch weight was highly significant ($P \leq 0.001$), but because of a larger number of bunches per vine in the non-irrigated treatment the yield per vine and yield per ha were slightly larger than in the irrigated treatment. However, the yield/pruning weight ratio, a good indicator of whether the vines were « in balance » or not (Smart and Robinson, 1991) was significantly higher ($P \leq 0.01$) in the non-irrigated vines. Further, there were significant effects ($P \leq 0.05$) of the inter-row treatments, with the yield/pruning weight ratio of the dead mulch plots being 40 percent less than for the control plots, irrespective of irrigation treatment. With respect to fruit quality factors, in two years out of three, Baumé for the non-irrigated vines was significantly higher ($P \leq 0.05$) than for the irrigated vines, while juice pH was higher and TA lower, as shown in figure 7. These trends are consistent with those reported by Rodriguez-Lovelle *et al.* (2000a) for the effect of decreased soil water and N availability, induced by competition from inter-row grass, on the properties of Merlot Noir fruit in a Bordeaux vineyard.

Table 3 - Vine growth and fruit harvest properties at Whitlands for 2003-04

Main treatment	Inter-row treatment	Mean bunch weight (g)	Yield per vine (kg)	Yield (t/ha)	Yield/pruning weight ratio	°Baumé

Irrigated	Control	202	3.6	20.9	4.5	11.1
	Ryegrass	188	3.4	19.6	3.1	10.6
	Clover	202	3.4	19.8	2.9	10.8
	Mulch	196	3.8	21.8	2.7	10.1
	Mean	197	3.6	20.3	3.3	10.7
Non-irrigated	Control	172	4.7	27.4	6.4	10.7
	Ryegrass	174	3.7	21.2	4.7	11.5
	Clover	165	3.9	22.6	4.7	10.4
	Mulch	157	3.4	20.0	3.8	10.3
	Mean	167	3.9	22.8	4.9	10.8

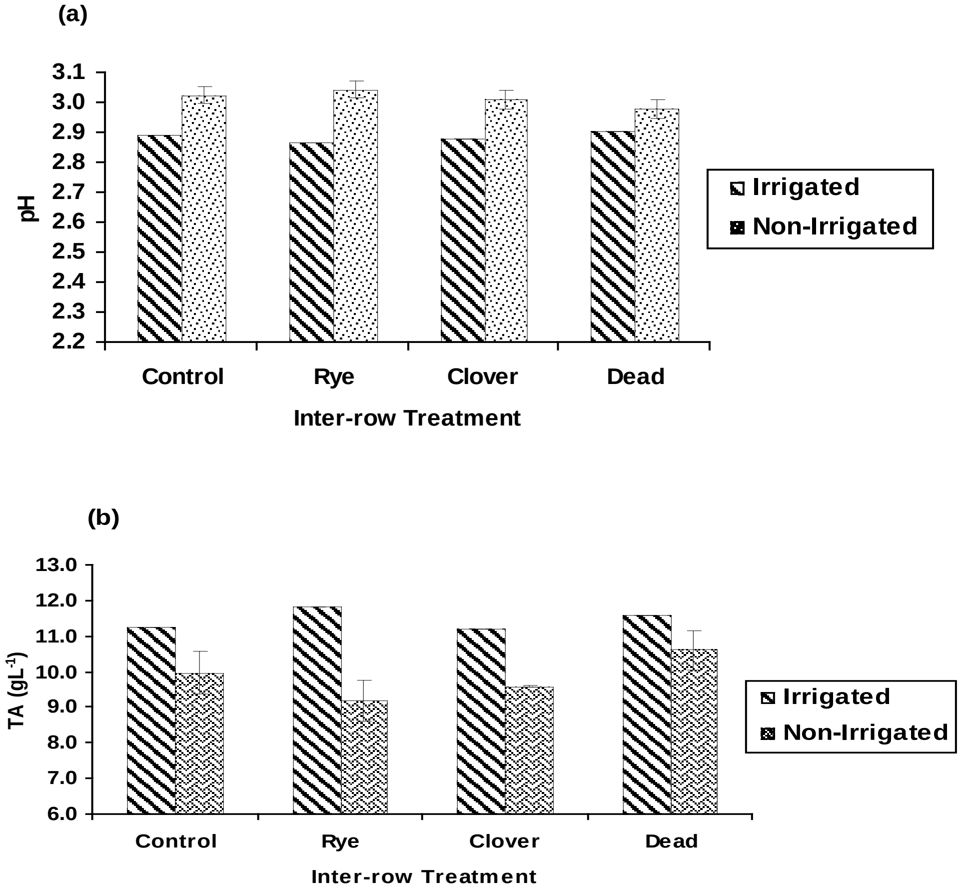
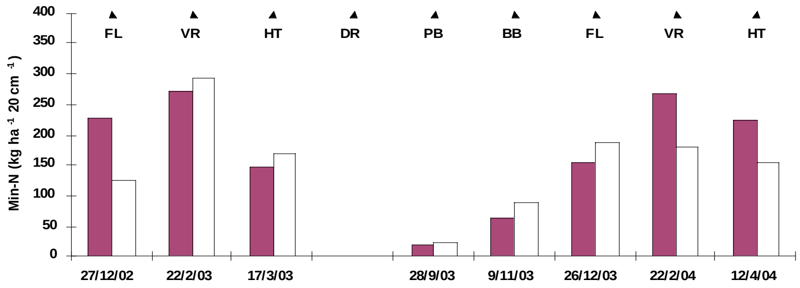


Figure 7 - Juice quality parameters for irrigated and non-irrigated vines according to inter-row treatments

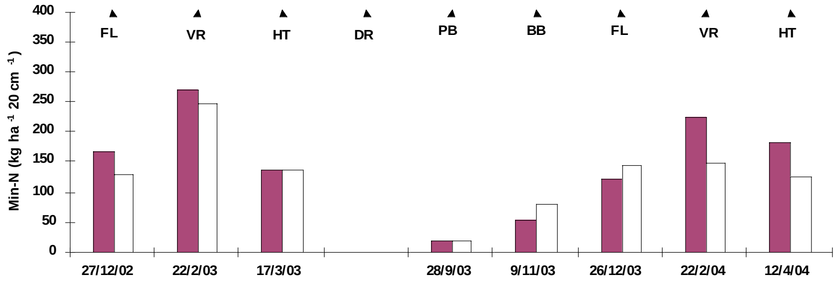
Regulated deficit irrigation (RDI) is promoted as a quality-enhancing practice for red grapes in many irrigated vineyards in Australia, Spain, Chile, South Africa and California. In Australia, one of the aims of RDI is to manage the water content of the top 40 cm of soil only, and pulse applications are now advocated to encourage more lateral flow under the drippers than occurs with a continuous application of water. This focus on the top 40 cm of soil may also reflect the fact that many vineyards in southeast Australia are on duplex soils in which the B horizon is not a particularly inviting medium for root growth. Our experiment at Whitlands demonstrates that, even in a deep soil of abundant natural N supply and in an environment where significant summer rainfall can occur, vine N uptake can be moderated through soil water management. We also speculate that one of the reasons for the success of RDI in irrigated vineyards on fertile soils is the moderation of N uptake, especially between fruit set and veraison, not only for red grapes but for white grapes too. This effect can occur directly through decreased N demand by the vine due to moderate water stress, and indirectly through a decrease in N mineralization rate in the top 20 cm of soil that is kept drier than under unrestricted irrigation. Evidence for the latter mechanism came from our inter-row treatments where N uptake under a dead grass mulch (which inhibited soil evaporation and so conserved soil moisture) was greater than the control, which was greater than the ryegrass only treatment. Rodriguez-Lovelle *et al.*

(2000b) also found that an inter-row grass crop decreased the availability of soil N to grapevines in four Bordeaux vineyards on sandy soils with ≤ 4 percent organic matter. Our results for the effects of inter-row treatment and withholding irrigation on soil N availability are shown in figure 8.

(a) Control



(b) Ryegrass



(c) Dead mulch

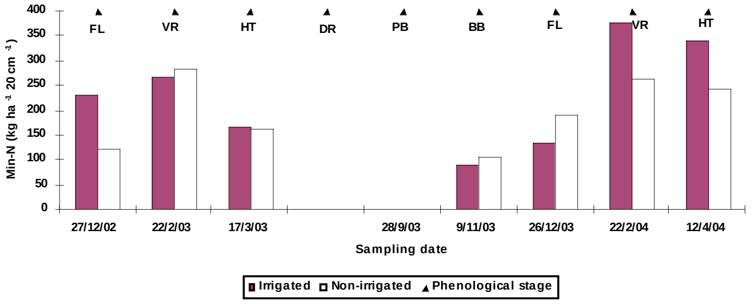


Figure 8 - Effect of irrigation and inter-row treatment on soil mineral N (0-20 cm).
DR: dormancy, PB: before budbreak, BB: budbreak, FL: flowering, VR: veraison, HT: harvest

On deep fertile soils in low rainfall areas, such as in many vineyard areas in inland southeastern Australia where excess vigour acts against the production of high quality grapes under irrigation, the potential of RDI for managing N uptake is even greater than in higher rainfall, cool climate regions. On the other hand, in soils that are deficient in N such as the gravelly soils of the Wairau Valley, Marlborough and the Gimlett Gravels of Hawkes Bay, New Zealand, the soil N supply must be supplemented by NH_4NO_3 or urea dissolved in the irrigated water. In dryland vineyards on sandy or gravelly soils, such as in the Haut-Médoc or the southern Rhone Valley near Orange and Châteauneuf-du-Pape, extra N has to be supplied through leguminous cover crops or from solid N fertilizer.

Terroir, soil classification and precision viticulture

For centuries, wine makers in the Old World have been aware of a relationship between soil variation, the performance of individual grape cultivars, and wine character. The best recorded examples go back to the early Middle Ages (from c. 8th century AD) in Burgundy and the Rheingau. Successive generations of monks in these regions identified, by trial and error, the specific character of wine made from small parcels of land (*goût de terroir*). Thus were laid the foundations for the later concept of terroir that is the basis of the French Appellation d » Origine Contrôlée system of wine classification. However, as the top Appellation wines of Burgundy and Bordeaux attest, recognition of distinctive terroirs in these regions requires experiential knowledge of soil properties crucial to cultivar performance on a scale of metres rather than kilometres. Thus, the concept of terroir embodies a *de facto* soil classification at a very large scale for the specific purpose of growing grape cultivars to produce distinctive wines. General-purpose classifications operating at a national level (small scale) are of no value for viticulture except to provide broad descriptions of soils: for example, the Great Soil Group classification and its derivatives (Thorp and Smith, 1949) provide soil class names such as Rendzinas, Terra Rossas, Calcareous Brown Soils and Krasnozems that have some currency in viticultural circles.

In Australia, a special-purpose classification has been developed that uses non-technical terms to describe soil properties that are important for the growth of vine roots (Maschmedt *et al*. 2002). However, the real potential for identifying the soil component of terroir lies in digital mapping of soil in a given mesoclimate (blocks up to 5 ha) using data obtained by proximal sensing of the soil by instruments linked to a global positioning system (GPS). When a differentially corrected GPS is used in conjunction with a real-time sensing instrument such as an EM38, data can be rapidly collected in, say, a 2 by 2 m grid pattern, which provides 2500 values of a soil property per hectare. Further, if a real-time kinematic GPS is used (accurate to ± 2 cm in the x, y and z directions), together with ground-truthed EM measurements of soil salinity, for example, a very accurate 3-dimensional map of soil salinity and elevation can be produced.

An EM38 measures by electromagnetic induction the electrical conductivity (EC) of the bulk soil, which in turn is related to the soil » s texture, water content and concentration of soluble salts. Depending on the distance between the transmitting and receiving coils and the instrument » s orientation, the effective depth of measurement ranges from 0.75 to 1.5 m (McNeill, 1980). Where the EM38 is used on a shallow soil and there is a marked change in EC at the soil-parent material boundary (e.g. the Terra Rossa over limestone in the Coonawarra) it is possible by careful ground-truthing to measure soil depth very accurately, as shown in figure 6 of Bramley (2003). A number of sensing instruments that operate close to the soil or more remotely are now available or being developed – for example, for sensing pH, soil water content, EC, penetrometer resistance, texture changes and visual properties such as colour (including mottling), cracking, and the deposition of clay films due to transport by water through the profile (see www.earthit.com). More comprehensive information can often be obtained with a multi-sensor, such a cone penetrometer to measure soil resistance (related to texture and bulk density), combined with an imaging penetrometer that registers soil colour. Electromagnetic techniques can also be applied remotely, as from aircraft, but the resolution is much lower than for proximal sensing and of less relevance to soil survey for viticulture. Gamma-ray spectroscopy can be used at close range or remotely and measures gamma radiation that is emitted from the top 30-45 cm of soil by naturally occurring radioactive elements, such as potassium-40 and its daughter products uranium-238 and thorium-232 (www.terroir-australia.com). Other methods make use of ground-penetrating radar (long wavelength) and laser-imaging in the ultraviolet, visible and near-infrared regions of the EM spectrum.

In all cases, the sensor instrument must be calibrated using measured values of the soil property, observed at specific locations in the area of study – for example, actual soil depth, or clay content and EC measured in a laboratory, or by using a model of soil chemical reactions, as in the case of estimating a soil » s lime requirement. Once this is done, a large amount of spatially referenced data can be collected, stored and used directly without the need for filtering through a soil classification. This knowledge of soil variation expressed through properties of relevance to viticulture can be used to guide a more detailed survey based on soil pits at a low resolution (e.g. on a 75 m grid, as required for purchasers of new water entitlements in the irrigation areas of Victoria (Brown Brothers, personal communication)). Also, high resolution digital soil maps can be used as the basis for precision viticulture (PV) in which vineyard layouts are planned using knowledge of soil variation – depth to rock, clay content, adequacy of drainage, salinity levels and so on. Similarly, irrigation infrastructure can be planned efficiently, and cultural operations such as pruning, shoot thinning and mulching organized on a zonal basis, where a zone is an area of uniform soil that may or may not coincide with a vineyard block. Since soil variation is often reflected in yield and fruit quality (Bramley, 2005), it is often to the winemaker » s advantage for these zones to be individually harvested. Thus, the application of modern technology leading to PV potentially closes the circle that began with the identification of particular terroirs in monastic vineyards on the slopes of the Côte d » Or centuries ago.

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