A risk assessment of irrigation needs and pesticide fate under vineyards

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Abstract
The Marlborough District Council (MDC) and the Marlborough Grape Growers Association are concerned about minimising the environmental risks associated with intensive pesticide use and/or the inefficient use of irrigation water. HortResearch has been commissioned to carry out a measurement and modelling exercise to determine the irrigation demand for Marlborough vineyards, and to assess the fate of surface-applied chemicals that might be used under the export wine grape spay schedule. This paper describes field experiments to measure the vineyard water balance, and presents modelling results from a risk assessment of pesticide fate.

Key Words
Irrigation, Pesticide fate, risk assessment, vineyard, modelling

Background

Marlborough is New Zealand's largest grape growing area. Vineyards are expanding rapidly across the region. This expansion is placing increased pressure on developers, who are seeking more water for irrigation of their high-value crops, as well as resource and policy analysts who are seeking a wiser stewardship of this precious resource. Effective management of water is critical because all of the main population centres are totally or partially dependent on groundwater for their domestic supply. A recent survey in Marlborough noted that '… the region is approaching a crossroads in water management, with a growing deficit between natural supply and the demand of water' (Davidson, 2001). The challenge for the irrigators and the regulators, as well as the wider community of domestic users, is to manage the use of water more efficiently.

Vineyards also adopt an intensive pesticide spray programme, with a range of fungicides used to control mildews during the growing season and *Botrytis cinerea* at harvest, insecticides used for leaf roller, mealy bug and mite control, and herbicides used for general weed control under the vines. The intensive use of pesticides could pose an environmental risk of leaching to groundwater, especially if chemicals are inappropriately applied to the land. The risk of contamination will depend on the timing and rate of application, as well as the specific physio-chemical properties of each chemical. But soil and climatic conditions can also play an important role in determining the environmental fate. The Marlborough District Council (MDC) and the Marlborough Grape Growers Association are concerned about minimising the environmental risks associated with intensive pesticide use and/or the inefficient use of irrigation water.

HortResearch has been commissioned to carry out a measurement and modelling exercise to determine the irrigation demand for Marlborough vineyards, and to assess the fate of surface-applied chemicals that might be used under the export wine grape spay schedule. The computer model that we used for this task (SPASMO – Soil Plant Atmosphere System Model), links the mechanisms of soil water flow through the root zone, with the complex pesticide transformations that result from both natural processes, and those consequent upon the application of a pesticide to the soil surface (Sharma et al., 2003). The calculations are based on local soil and climate data, they use published chemical-transport properties, and they assume 'normal' spray diaries for the export wine grapes. This paper describes field experiments to measure the vineyard water balance, and presents modelling results from a risk assessment of pesticide fate.

The vineyard water balance

Vine water consumption depends on three factors: the atmospheric demand for water that is defined by the local microclimate; the vine leaf area that is determined by the number of shoots and the leaf area per shoot; and the response of the leaves to their aerial and soil environment. Changes in trellis design and/or vine spacing will alter the vineyard microclimate, especially with regard to the light environment. Narrow spaced vines will tend to intercept more light and, as a consequence, they will also tend to produce higher crop yields. However, to our knowledge, there have been no reports of the impacts of vine spacing on the water demands of grape vines. To answer this question we have used a detailed computer model to simulate the canopy light environment, in 3 dimensions, and to calculate vine water use (Green et al, 2003a).

Figure 1. The left hand panel shows point-quadrat measurements of leaf area being taken at the Squire Estate. The right hand panel shows an array of light sensors used to measure light interception and to deduce a 'crop factor'.

The vineyard is approximated using an array of truncated ellipsoids, with each vine having a uniform density of green leaves that are randomly distributed within the canopy volume. We calculate the absorption of both direct and diffuse solar radiation, plus multiple scattering of visible, near infrared and thermal long-wave radiation. For this study on grapevines, many of the model inputs (e.g. half-hourly weather data, canopy dimensions, vine leaf areas) and model parameters (e.g. leaf response functions) were derived from field experiments at the Squire Estate and the Brancott vineyards in Marlborough. Figure 1 shows how the vine leaf area was monitored.

Vine water use was monitored directly using heat-pulse measurements of sap flow in the vine stem. Two sets of probes, each consisting of a line heater of 1.8 mm diameter and two temperature probes also of 1.8 mm diameter, were installed into parallel holes drilled radially into the stem at heights of about 0.5 m above the ground. Theoretical calibrations factors were used to account for the probe-induced effects of wounding (Green et al, 2003b). Volume flow rates, E_H [L/hr], were calculated by integrating the radial profile of sap velocity over the sapwood cross-section. A Campbell CR10 data logger (Campbell Scientific Ltd., Logan, Utah, USA) was used to control the heat-pulse equipment and to record the measurements once every 30 minutes.

The SPASMO model was used to calculate water and chemical movement through a 1-dimensional soil profile of 5 m depth, divided into 0.10 m intervals. The calculations run on a daily time step using a continuous sequence of daily weather data (1972-2003) obtained from the NIWA climate database using the on-line search engine 'METBROKER' (http://www.agmodel.org). A standard crop-factor approach is used to relate vine water use to the prevailing weather (Allen et al., 1999). Water transport through the soil is modelled using a water capacity approach (Hutson and Wagenet, 1993) that considers the soil to have both mobile and immobile pathways for water and solute transport. The mobile domain is used to represent the soil's macropores and the immobile domain represents the soil matrix. The soil's physical and hydraulic properties required for the modelling were got from soil cores taken in mid-winter from the vineyard site.

A conservative approach is used to calculate irrigation need. The model applies irrigation whenever more than 50% of the readily available water was consumed from the root-zone soil (Green et al., 2002). After rainfall or irrigation any dissolved solute is allowed to percolate rapidly through the soil in the mobile domain only. Subsequently, on days when there is no significant rainfall, there is a slow approach to equilibrium between the mobile and immobile phases, driven by a difference in water content between the two domains.

Modelling Pesticide fate

Pesticide adsorption

Once a surface-applied pesticide enters the soil environment, it may reside in either the vapour, liquid or adsorbed phase. The mobility of that pesticide, and its propensity to leach, depends on how the given quantity of pesticide is partitioned into the three phases. SPASMO assumes a linear, equilibrium partitioning between the three chemical phases. The adsorbed-liquid partitioning is expressed through an isotherm:

$$C_S = K_D C_L , \qquad \text{[Eq. 1]}$$

where C_S is the adsorbed concentration [g-ai/kg-soil], C_L is the solution concentration [g/m^3 soil solution], and K_D [m^3/kg] is the distribution coefficient found from the adsorption isotherm. Since the distribution coefficient (for non-ionic pesticides, at least) primarily represents adsorption to organic matter, variability between soils may be reduced to an extent by defining an organic-carbon distribution coefficient,

$$K_{OC} = K_D \,/\, f_{OC} , \qquad \text{[Eq. 2]}$$

where f_{OC} is the fraction of organic C in the soil. In general, pesticides will show a greater propensity to leach if they have a low K_{OC} value, or if they are applied to soils that have a low organic C content, all other factors being equal. The liquid-vapour partition for a pesticide is generally represented through Henry's Law,

$$C_G = K_H C_L , \qquad \text{[Eq. 3]}$$

where C_G is the concentration of pesticide in the vapour phase [g/m^3 soil air] and K_H is Henry's law constant which is dimensionless. USDA values for both K_D and K_H have been assumed in all cases. Because $C_G << C_L$ in most cases, we have ignored the vapour phase and any volatilisation losses that are associated with it.

Pesticide degradation

The natural rate of pesticide attenuation, via microbial degradation, is assumed to be a first-order process described by a single rate constant, μ [1/d]. The amount of pesticide remaining in the soil after some time, t [s], namely $M(t)$ [mg/L soil], is calculated as:

$$M(t) = M(0)\exp(-\mu t) \qquad \text{[Eq. 4]}$$

where $M(0)$ [mg-ai/L soil] is the initial resident mass in the soil. The degradation rate provides a direct assessment of the persistence of a pesticide, and so it is an essential parameter that will determine how much pesticide is left to leach after a given time. The corresponding half-life, T½ [d], is related to the rate constant, μ, by T ½ = 0.693/μ. This represents the time taken for half of the resident pesticide to be degraded. Standard abiotic functions F_W and F_T have been used to account for the effects of soil moisture and temperature on the degradation rate constants (Johnsson et al., 1987).

Results

Figure 2 compares the instantaneous rates of sap flow recorded in the trunk of a mature vine against the model calculations of vine transpiration. There is very good agreement between the measurements and the model calculations. On a sunny day (e.g. day 43) vine transpiration peaked at about 1.2 L/h. This occurred a few hours after solar noon when both air temperature and vapour pressure deficit were elevated. The total water use for day 43 was about 12 L per day. On the cloudy day (e.g day 47) the vines used about 4 L per day.

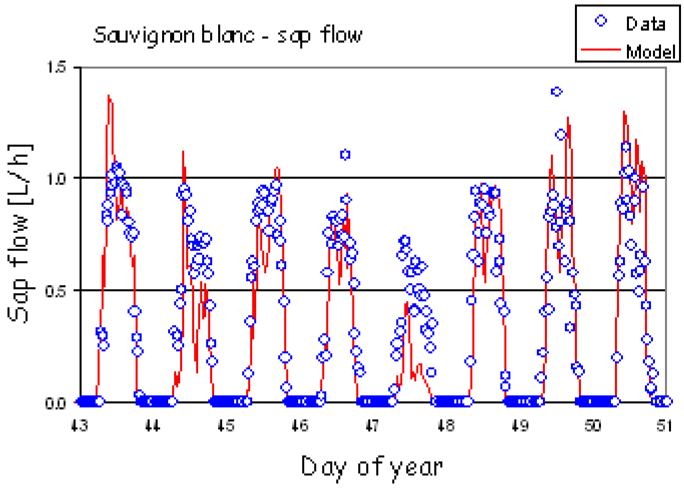

Figure 2. Diurnal variation in measured (open marker) and modelled (line) water use of a Sauvignon blanc grapevine at the Squire estate in Marlborough. The vine had a total leaf area of some 10 m^2. We note that some rain occurred on DOY 47.

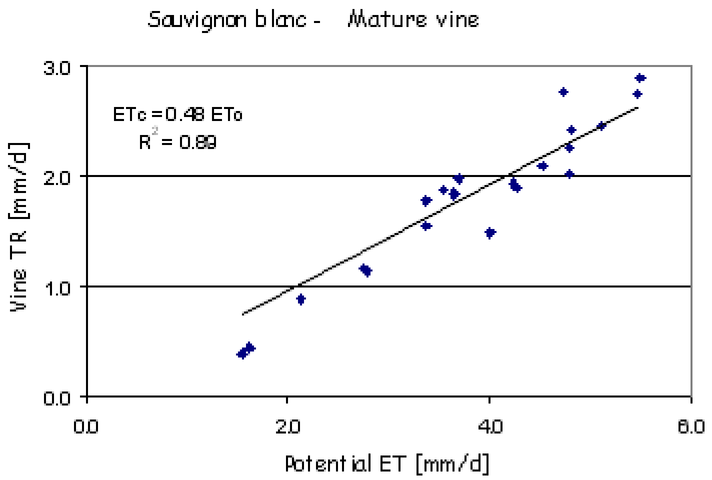

Figure 3. The relationship between vine transpiration, ET_C, and the potential evapotranspiration, ET_O. The slope of the line gives a direct measure of the 'crop factor', K_C, of these vines. Numerically the value of K_C = 0.48 is similar to the percentage light interception observed around verasion.

Rates of sap flow integrated over the course of a day can be used to establish a 'crop factor', K_C, by relating the vine water use to the potential ET. This can be done provided vine use is expressed in units of mm per day. By definition, 1.0 mm of water is equal 1.0 litre per square meter of ground area. The vines at the Squire Estate are planted at a spacing of 1.8 x 2.4 m and therefore have a ground area of 4.3 m^2 per vine. Their water use of 12 L is equivalent to a transpiration rate of 2.7 mm per day (from the vines only). Average transpiration rates during summer are likely to be much less than 2.7 mm per day because transpiration rates on a cloudy day (e.g. day 47) can drop by a factor of two or more.

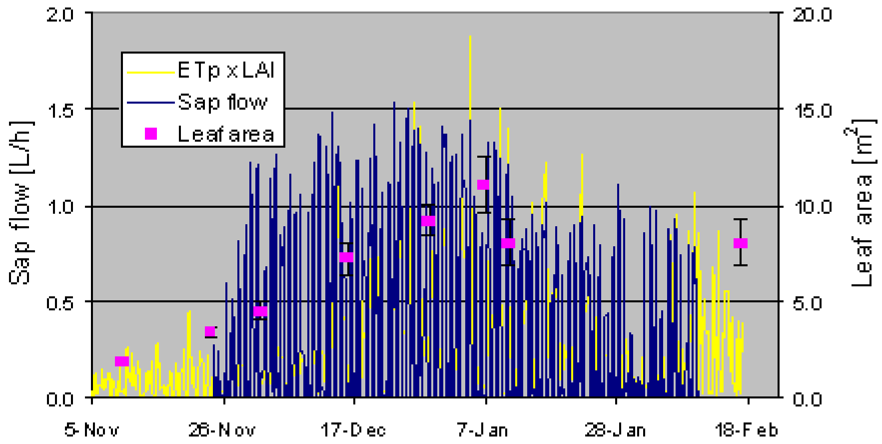

Figure 4. Seasonal pattern of vine water use by Sauvignon blanc vines at Squire Estate, Blenheim. These vines are planted at a spacing of 1.8 m, in rows that are 2.4 m apart. The daily water use of the vines in early January is about 12 L per day (~2.7 mm per day). The leaf area in early February has been reduced to just 8 m^2 and vine water use drops to about 1.8 mm per day.

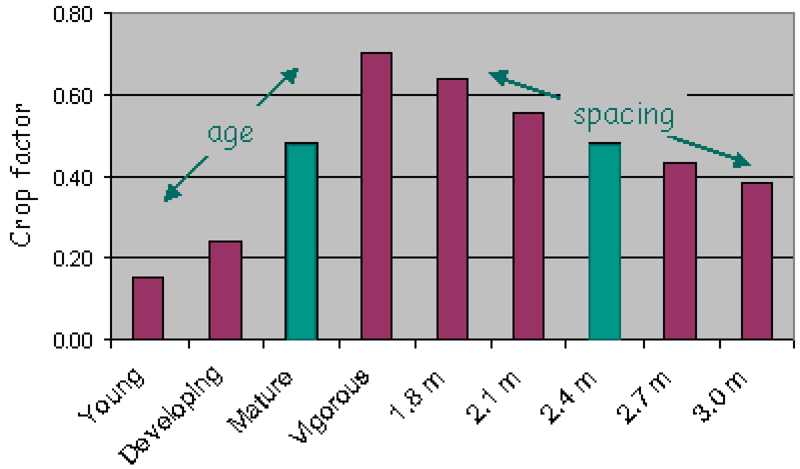

Figure 5. The influence of vine age and vine spacing on the maximum crop factor for sauvignon blanc vines in Marlborough. Vine age is represented by a different leaf area [young = 2.5 m^2, developing = 5 m^2, mature = 10 m^2, and vigorous = 15 m^2)]. Spacing refers to a range of row widths. The green bar represents the values measured from the Squires trial. Mature vines at a spacing of 2.4 m have a mid-season crop factor equal to about 0.5.

Our 3-d model of vine transpiration has been used to simulate the effect of vine spacing and canopy density on the crop factor (Figure 5). SPASMO was then used to calculate irrigation demand. The results are presented in Figure 6 for vines on a Wairau deep silt loam whose properties are defined in New Zealand Soil's Database (Series No.SB10131). The symbols represent the average irrigation amount that will meet the vines needs at least half of the time. The upper error bar represents the irrigation amount required to meet the vine's needs in four out of five years. This value represents the 20% probability of exceedence (PE_{20}). The annual irrigation needs are expected to exceed PE_{20} about 1 year in 5. The lower error bar represents the 80% probability of exceedence (PE_{80}). In this case the vine's annual irrigation needs are expected to be less than PE_{80} about 1 year in 5. Mature vines planted at a spacing of 2.4 m on a Wairau silt loam will need, on average, about 102 mm of irrigation each year. An irrigation allocation of 175 mm per year will meet the vine's water needs at least 80% of the time. At a closer spacing of 1.8 m the vines are expected to need about 50 mm per year more irrigation water, on average. However, in terms of an annual irrigation allocation, the PE_{20} value of the closed spaced vines is only about 10 mm per year greater than the standard calculation that is based on a mid-season crop factor of 0.5 for a row spacing of 2.4 m.

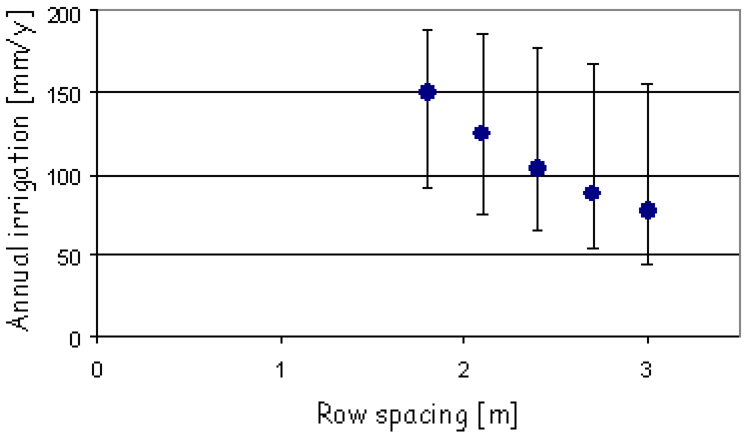

Figure 6. The influence of row spacing on the annual irrigation requirements of SB grapevines on a Wairau silt loam soil. The symbols represent the annual average irrigation demand. The error bars represent the range spanning 80% of the years.

Increasing vine density will have only a small influence (< 10%) on peak vine water demand. Differences in soil type are likely to have a much greater influence on annual water demand compared to the effect of different vine densities. For example, the average annual irrigation requirement for grapes at Rarangi, where the soil is a very coarse gravel below 30 cm, is calculated to be 140 mm per year. One in 5 years the grapes will need at least 195 mm of irrigation.

The soil at Rarangi is highly permeable and holds very little available soil moisture (Table 1). Drainage makes a significant contribution to the water balance of the vineyard and it occurs most frequently over winter when the soil is near field capacity and whenever large rainfall events (> 20 mm/day) occur. We calculate the average drainage rate under a vineyard at Rarangi will be about 540 mm per year, although the one in five years the total drainage could exceed 590 mm.

Modelling pesticide fate

Vineyards at Rarangi will spray a range of herbicides, once or twice a season, for general control of weeds under the vines and along the fence lines. Many vineyards have an herbicide strip of 1.0 to 1.5 m width under the rows, and the inter-row is in grass. Different herbicide products may be used for weed control. These range from low toxicity products (e.g. simazine and linuron) to products that are classified as harmful (e.g. amitrole) and even poisonous (e.g. paraquat and diquat). Herbicides also have a wide range of chemical properties that will affect both their persistence (amitrole has a half-life of 3 days and diquat has a half-life of 250 days), and mobility (amitrole has a K_{OC} of 200 and diquat has a K_{OC} of 10000) in the soil.

Simazine is one of the more mobile and persistent herbicides used in vineyards for general control of weeds and broadleaf grasses. A recent study of groundwater in the Wairau Plans has found traces of simazine in the shallow wells and springs of the Lower Fairhall-Brancott Valley. The source of contamination is thought to be viticulture since this is the predominant land use in the valley. Here we pose the question – what is the likelihood that simazine will leach into the shallow groundwater at Rarangi?

Model results for an annual application of simazine, applied at the label rate of 2.5 kg/ha, once every year on 15th August are shown in Figure 7. Most of the time the simazine concentration is expected to remain elevated well above a value of 2.0 µg/L (shown by the dotted line in Fig 7). Simazine is likely to leach rapidly though the soil profile, with very little absorption or attenuation. Elevated levels of simazine could be detected deep in the soil profile. At a depth of 3.0 m, the concentration is still about half the value expected at a depth of 1.0 m. If simazine was used on vineyards at Rarangi then it is very likely that some contamination of the shallow ground water would result.

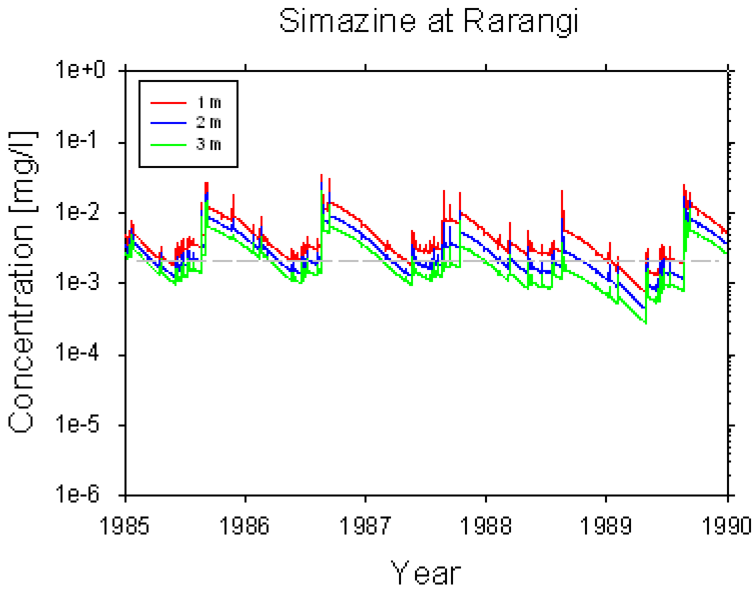

Figure 7. Predicted concentration of simazine under a Rarangi vineyard. Simazine was applied once per year, in mid August, at the label rate of 2.5 kg-ai/ha. The dotted line represents a maximum allowable value (MAV) of 2 ppb. Note: the y-axis is plotted on a log-scale.

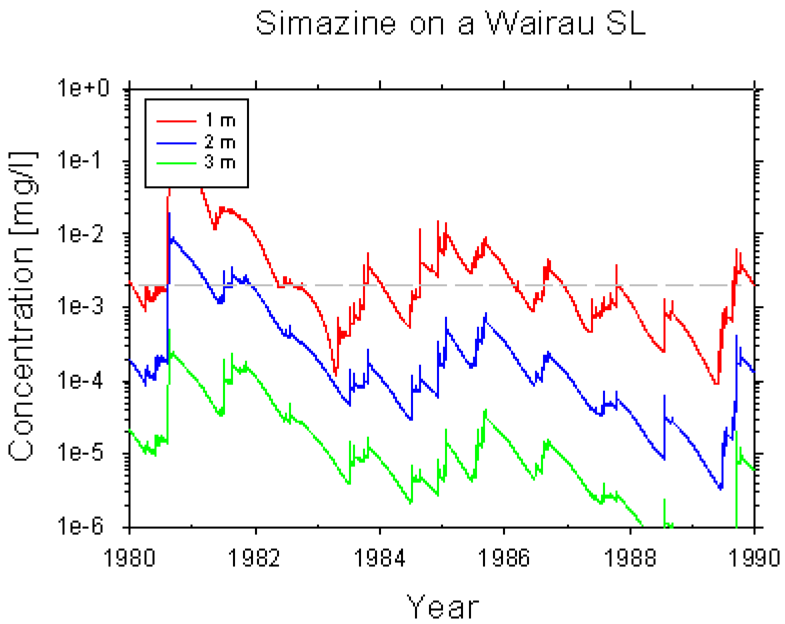

Figure 8. Concentration of simazine under a vineyard on a Wairau deep silt loam. Simazine was applied once per year, in mid August, at the label rate of 2.5 kg-ai/ha. The dotted line represents a maximum allowable value (MAV) of 2 ppb.

By comparison, simazine is less likely to leach into shallow groundwater under a vineyard on a Wairau soil (Figure 8). The Wairau silt loam has a greater water holding capacity than the Rarangi soil (Table 1), so that much less drainage water percolates though the soil profile. Furthermore, the Wairau silt loam also has much higher organic matter content so that a greater fraction of the active ingredient gets adsorbed in the upper layers of the soil profile. The simazine concentration at 3.0 m depth is 100 to 1000 times lower than at 1.0 m. A difference in soil physical and hydraulic properties means that it takes much longer for the simazine to travel through a Wairau soil, compared to a Rarangi soil, and so there is also more time for the pesticide to degrade. Pesticide mobility is much lower on a Wairau silt loam compared to a Rarangi soil. The same is true for other pesticides.

Table 1. Hydraulic and physical properties of Rarangi and Wairau soils. Here SAT, FC and WP represent the volumetric water content [l/l] at saturation, field capacity, and wilting point, respectively; RAW and TAW [mm] represent the readily-available and total-available soil moisture, respectively, for the fine-earth fraction of the soil; RHO [kg/l] represents the soil's dry bulk density; S represents the stone fraction, and OC represents the organic carbon content of the bulk soil.

Soil series	Depth [cm]	SAT [l/l]	FC [l/l]	WP [l/l]	RAW [mm]	TAW [mm]	RHO [kg/l]	S [%]	OC [%]
Rarangi	0-25	0.480	0.095	0.035	11.8	15.0	1.170	0.0	1.7
	25-50	0.400	0.073	0.030	5.4	7.7	1.410	25.0	0.3
	50-100	0.320	0.048	0.023	4.6	8.0	1.440	75.0	0.1
Wairau	0-25	0.513	0.339	0.158	12.4	45.1	1.295	0.0	2.0
	25-50	0.516	0.313	0.116	32.6	49.3	1.305	0.0	0.8
	50-100	0.517	0.225	0.052	68.3	83.3	1.313	0.0	0.2

Summary

The water balance and irrigation needs of a vineyard were determined using data from a three-year field experiment where vine water use was monitored using sap flow measurements in the vine trunk, and soil moisture was monitored using a combination of TDR and neutron probes. Model calculations for grapes on a Wairau silt loam indicate that mature vines at a spacing of 2.4 m will need, on average, about 102 mm of irrigation each year. An irrigation allocation of 175 mm per year will meet the vine's water needs at least 80% of the time. The same vines at a closer spacing of 1.8 m will use, on average, about 50 mm per year more water. However, the annual irrigation demand for these closer-spaced vines will be only about 10 mm per year greater than the standard (2.4 m) spacing because increased shading will reduce evaporation losses from the grassed inter-row.

Improvements in irrigation efficiency are possible by better defining when to irrigate and how much water to apply. Our field experiments are helping improve our understanding of those factors that impart grapes with the characteristics of yield and quality desired by the winemakers. With such information the grower has the opportunity to adapt his irrigation management to meet the market demand, whether that means a reduced yield of high quality grapes or simply a maximum production per hectare.

Improved understanding of pesticide fate is also providing regulators and growers with vital information to predict the impact of past and current pesticide practice so they can act now to reduce the likelihood of pesticide contamination occurring in the region's precious groundwater supplies. We have assembled our understanding of pesticide behaviour into a new decision support tool, the GROWSAFE® Calculator, to demonstrate the environmental fate pesticides used on a range of crops and soil in different regions of New Zealand. An accompanying paper (Snow et al., *ibid*.) shows the graphical outputs of this software tool. The key to reducing the negative impacts of pesticides is the provision of information to growers to encourage then purchase of those chemicals that are less likely to leach, or to accumulate in the soil.

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