Practical Considerations for Reducing Frost Damage in Vineyards

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"Warmth, warmth and more warmth,
for we are dying of cold, not darkness.
It is not the night that kills but the frost".

Miguel de Unamuno,
The Tragic Sense of Life

Report to New Zealand Winegrowers: 1999

Summary:

- *Frost is a significant hazard to grape production in many parts of New Zealand. In theory any crop can be protected, but economic and practical aspects limit the methods that can be used.*

- *The most effective weapon against frost damage is preventative action. We emphasise the comment by W.J. Humphries in 1914 who said, "The best time to protect an orchard (or vineyard) against frost is when it is being established". Geiger went on to say that "It is incomprehensible that even today, the most fundamental laws of microclimatology are disregarded time and again when vineyards are being established at great cost in areas subjected to repeated frost.*

  When developing a vineyard, three factors should be taken into consideration: "Location, Location, **Location***". Selecting a site is an on-going process, and however unpalatable, the best choice may be to pull up and walk away, rather than pour more money into an uncertain venture. This should be viewed as a positive choice.*

- *Characteristics of a site likely to be vulnerable to frost damage are presented. Of particular note is the impact and aspect of slope, altitude and factors such as shelterbelts.*

- *The report contains a model developed during the course of writing this review for evaluating the potential risk of a site. The model is based on predicted phenology of the vine and the probability of the frost at any stage of the season and can be used where long-term temperature records are available. Alternatively, where a risk analysis of a new site is required, a limited temperature data set can be used, by relating the new site to a nearby meteorological station with a long-term temperature record.*

- *Best practice management of vineyards in a frost vulnerable sites is to:*

  - ❑ *Ensure inter-row herbage is closely mown, and soils are moist and firm. Cultivated soils or deep inter-row herbage provide an insulated layer on the soil surface, minimising the heat accumulation by soils during the day, and increasing re-radiation of stored heat energy at night.*
  - ❑ *Employ late spur pruning to delay bud break reducing the vulnerability of developing shoots to frosts.*
  - ❑ *Leave additional canes post-pruning, which may or may not be used in event of a frost. This will allow additional shoot selection should a frost, optimising vine yield.*
  - ❑ *Provide significant protection to radiation frosts by establishing vines on a high cordon (2 metre), and hanging curtain training systems and may be preferred at a frost vulnerable site.*
  - ❑ *Monitor temperatures at 3.00pm provides a method of predicting whether a radiation frost is likely to occur. This enables growers to decide whether frost protection systems (in particular helicopters) need to be organised.*

- *Understanding the form of the frost event is necessary before effective frost control* *mechanisms can be used. Most literature is concerned with radiation frost events (section2.1), which generally occur on clear nights. Understanding the impact of inversion layer strength and height is important if effective frost control using heaters or wind machines are to be used (sections 2.1, 6.5 and 6.6). Advection frosts, where cold air mass moves into a vineyard, generally from the south are more difficult to manage. The most effective control mechanism is overhead sprinkler systems using water. These are expensive, and require considerable quantities of water. The possibility of using targeted sprinklers (where only the vulnerable tissues are protected) and pulsed sprinklers, where water is used intermittently are discussed. These may be the most effective forms of protection in vulnerable sites.*

- *Before investing in a frost protection system, growers need to be sure that it will meet their needs. In particular:*
  - ☐ *Will it provide the level of protection necessary, are frosts likely to be advective or radiative?*
  - ☐ *Is it reliable? There is no point investing in a system, which fails when it is most needed.*
  - ☐ *Risk and cost: benefit analyses are needed. Unfortunately the better the protection from the system, the more expensive it is likely to be*

- *Critical damage temperatures (T_{50} °C) have been determined for a limited number of cultivars, predominantly those grown in the NE of the USA. Little information is available for Vitis vinifera cultivars. Further research is needed to identify the temperatures, and the impact of management and bud phenology on these temperatures.*

Contents:

1 Introduction:

Frost is a significant hazard to many viticultural regions in New Zealand. Theoretically, any crop can be protected from any frost event, but economic and practical aspects limit the methods that can be used. Profitability ultimately determines whether frost protection techniques can be used. An understanding and ability to minimise the risk of crop loss or damage[1] is fundamental to managing a profitable enterprise. Damage not only puts at risk the current season's crop, but also because of the perennial nature of grapevines, can influence the productivity of vines for several seasons in the future.

In practice managing frost injury can be divided into three broad sections:

- Understanding the factors that affect the frost sensitivity of a particular site.
  This is particularly important in the planning phases of vineyard development, as selecting a site that is inherently frost free will minimise costs associated with damage or control during the life of the vineyard

- Managing a site and vines to minimise risk in a particular season.
  Most sites will be potentially vulnerable under some circumstances. Cultural techniques can be employed to modify the site or reduce the susceptibility of vines to damage on a particular date.

- Managing vines that have been damaged to reduce immediate and long-term impact.

Vines are perennial plants. Should they be damaged, the consequence of that event may have impact on growth and yield for three years. Appropriate cultural techniques will enable damage to be minimal. As a consequence yield and fruit composition return to maximum levels as quickly as possible.

The degree of injury depends on the minimum temperature reached the rate at which the temperature falls and the amount of time below a critical temperature.

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[1] *Note: Damage implies death of the plant or plant organ, whereas injury causes damage to part of the organ. For example, individual shoots on a vine may be damaged (killed), but the vine as a whole is only injured. The higher proportion of the shoots damaged, the greater the injury. Likewise, plants or organs will recover as a whole from injury, but not damage.*

1.1 Critical temperatures

Young (1966) defined critical temperature as the lowest temperature a tissue could endure for 30 minutes or less without injury. This concept is valuable as we seek by various means to reduce damage to developing grape buds at growth's onset in the spring. Critical temperature is commonly represented as the temperature estimated to cause 50% bud mortality and is frequently expressed as lethal temperature – 50 (LT-50), simply T-50 (Johnson and Howell, 1981: Proebsting et al. 1978; Proebsting and Mills, 1971; Hewitt et al. 1978; Bittenbender and Howell, 1974). A further designation of the range over which damage may occur is expressed as T_{10} and T_{90}, or the temperature at which 10 and 90% of buds are killed, respectively.

There can be considerable variation in the amount of bud mortality resulting from a spring freeze episode, even when ambient air temperature is uniform. The literature proposes a number of reasons why this may occur:

(i) Differences among cultivars (Proebsting and Mills 1971; Hewitt *et al.* 1978);
(ii) Differences in dew point and surface moisture (Johnson and Howell 1981; Proebsting *et al.* 1978; Hewitt *et al.* 1978);
(iii) Pre-freeze environmental conditions (Johnson and Howell 1981);
(iv) Stage of bud phenology (Baggiolini 1952; Anderson et al. 1980; Howell and Wolpert 1978; Anderson and Seeley 1993; Howell and Wolpert 1979; Howell *et al.* 1981.); and
(v) The probability of an ice nucleation event occurring (Lindow, 1983).

Nucleating events are influenced by:
(i) The duration of exposure to temperatures (Johnson and Howell 1981);
(ii) Tissue temperature (Johnson and Howell 1981; Proebsting *et al.* 1978; Proebsting and Mills 1971; Howell *et al.* 1981);
(iii) Supercooling (Lindow, 1983);
(iv) The size and differentiation status of the tissue;
(v) The presence or absence of ice nucleating bacteria (Lindow, 1983); and
(vi) The presence of surface ice to seed the nucleation of water in the bud tissues(Johnson and Howell 1981).

2 Frost formation in the vineyard

Several adjectives are employed to describe the two kinds of frosts that are usually experienced in New Zealand vineyards. These include ground frost, screen frost, hoarfrost, black frost, radiation frost and advection frost.

A **ground frost** occurs when dew freezes. It is recorded in climatological records when the grass minimum is -1°C or less. Young vines, during establishment are particularly vulnerable to a ground frost. A **screen frost** occurs when the air temperature at screen height (1.3 m above ground level) is 0 °C or less. The sensitivity of vines depends on a number of factors, including the stage of development (see section 4.3). However, because of the low relative humidity conditions generally associated with frosts and radiation to the sky by the bud tissue, the buds may be 2-3 °C lower than the air temperature on still nights. Wind speeds of 3 to 4 km h^{-1} will negate this effect, and tissue and air temperatures will be the same.

Hoarfrost may occur during periods when air is below freezing and ice crystals form and grow on surfaces through sublimation. While this process of ice being formed from water vapour, without going through a liquid phase is unusual in most regions, it can result in large masses of ice forming on wires and branches, breaking them.

2.1 Radiation frost condition in the vineyard

All surfaces radiate according to their surface temperature and a characteristic of the surface, called the emissivity (Geiger *et al.* 1995). The Stefan-Bolzmann Law gives the intensity of the emission:

$$I = \varepsilon\ \sigma\ T^4\ [\mathrm{W\ m^2}] \qquad (1)$$

and the wavelength (λ_{max}) of the peak of the radiant spectrum is given by Wien's Law:

$$\lambda_{max} = 2897 / T\ [\mu\mathrm{m}] \qquad (2)$$

where ε is the emissivity and is close to 1.0 for most natural surfaces;
σ is Stefan's Constant and is 5.67×10^{-8} W m^2 - $^{o}C^4$;
T is the absolute temperature (K), T(K) = T(°C) + 273.2
W is watts
and m^2 is square metres

Terrestrial surfaces at around 10 °C (283.2 K) radiate in the infrared, $\lambda_{max} = 10.2$ µm, I = 354.7 W m^2, and the sky about -15 °C (258.2 K), $\lambda_{max} = 11.2$ µm, I = 252.0 W m^2.

On clear nights, the earth's surface radiates upwards and receives infrared radiation from the sky. Since the sky is generally colder than the ground, the ground radiates more than the sky, with a net loss of radiation that results in cooling. With the figures used above the net infrared loss is 364.7 - 252.0 = 112.7 W m^2. Equilibrium would eventually be reached when the ground cools to the sky's temperature. Usually the sun rises before this happens and provides a welcome heat input. On cloudy nights the net infrared loss is about 10 W m^2. Hence the cooling rate is very small, and the equilibrium temperature is almost always above zero (Geiger *et al.* 1995).

In summer, the daylight period is longer than the night-time. The sun is high in the sky, producing a more intense beam on the ground. In winter, the daylight period is shorter than the night-time, and the sun is low in the sky making a low intensity beam as it strikes the earth. In inland, sheltered areas, the solar input more than matches the infrared loss during the summer and so successive days get warmer until a colder air mass arrives. In winter, the clear sunny days do not provide sufficient solar energy to overcome the overnight infrared loss. Thus night-time temperatures are quite low and get colder night after night, until a warm air mass arrives. Under clear anticyclonic conditions, light winds prevail. Thus there is little chance of vertical mixing by turbulence, and the surface temperature can then easily drop below zero and frosts form.

Frosts which are formed by infrared radiation loss at night are called **radiation frosts**. They are generally more severe in inland sheltered areas. This is because the ocean can store a great deal of heat energy and air close to the ocean does not cool as quickly. Sheltered areas have lighter winds and thus the mass of air that is being cooled by the ground is quite small, because it is slow moving and shallow. A severe frost is more likely when a ridge or anticyclone replaces a cold southerly airflow, so that the temperature is already low.

Air temperatures are measured in a screen at 1.3 m above ground surface. This is generally just above cordon height for most vine training systems in New Zealand. Grass minimum temperatures are recorded immediately above the grass, and a comparison of screen and grass minimum temperatures give an indication of the strength of the near surface temperature and the stability of the layer. Table 1 shows the mean screen and grass minimum temperatures for September for a number of climate stations in important grape growing regions in New Zealand (Anon, 1980).

Table 1

The Mean Screen and Grass Minimum Temperatures for September for a selection of New Zealand Climate Stations

Site	Site number	Latitude (S)	Height above sea level (m)	Screen min. (°C)	Grass min. (°C)	Difference Ts-Tg (°C)	Influence of 10 cm height (°C)
Te Kauwhata	C75412	37° 25’	32	7.9	4.8	3.1	0.22
Gisborne	D87683	38° 41’	9	6.5	3.1	3.4	0.24
Hawkes Bay	D96681	39° 39’	14	4.8	1.6	3.2	0.23
Martinborough	D05964	40° 59’	114	4.6	1.2	3.4	0.24
Nelson	G12191	41° 06’	8	4.8	1.7	3.1	0.22
Marlborough	G13581	41° 31’	27	5.0	2.6	2.4	0.17
Waipara	H32073	43° 04’	64	4.2	-		
Canterbury	H32641	43° 39’	11	4.2	1.1	3.1	0.22
Central Otago							
Queenstown	I58061	45° 02’	329	3.1	-1.4	4.5	0.32
Cromwell	I59021	45° 02’	213	2.7	-2.4	5.1	0.36

From: Anon, 1980. Summaries of Climatological Observations to 1980. N.Z. Met. S. Misc. Pub. 177.

Making direct comparisons between regions is difficult, as bud break dates are later further south, but September probably represents a mean date for the whole country. The mean data, which includes windy, cloudy nights as well as clear, still night’s can only, illustrate the general pattern. In frosty weather the differences between ground and screen minimum temperatures are typically in the range of 4 to 5 °C while on cloudy, windy nights the differences will be less. As a consequence, the temperature gradients tend to be greater inland, and further south, because of the greater incidence of still, clear weather. As a consequence the height of the bud above ground level and alter the potential frost hazard (Dethier and Shaulis, 1964). Using the data in Table 1, the impact of altering the height of the cordon can be estimated from the change in temperature for each 10 cm from the soil surface. For example in Cromwell, buds on a high cordon training system at 2 m (e.g. Geneva Double

Curtain or High Sylvoz) would be at a temperature approximately 3.96 °C above those at a standard 0.9 m Vertical Shoot Positioned cordon and 7.2 °C above the ground temperature.

Radiation frosts form because of cooling of the ground surface (Geiger *et al.* 1995). Still air is a good insulator and so strong that cooling of air occurs near the soil surface. The air temperature then rises with height through a surface layer. Above this layer, the temperature declines again with height. The warm over cold air is called an **inversion layer**, and is very stable with little vertical motion or mixing. The depth of the stable layer generally lies between about 5 and 40 m, with 10 to 30 m being most likely. Information of the presence of an inversion layer is particularly important if air-mixing systems (helicopters or windmills) are to be used for frost control. If the inversion layer is not present, or out of reach of the mixer, then using an air mixing system can result in increased damage. Water will remain liquid at several degrees below 0°C in a **super-cooled** state (Johnson and Howell, 1981; Lindow, 1983). However, movement of tissues containing supercooled water can cause ice-nucleation, freezing, and tissue death.

The temperature differences between 1.3 and 14 m have been measured for three sites in the Hawkes Bay region (Heine and Carran, 1983). They measured the inversion strength by recording temperatures at these two heights and calculating the difference. During inversion conditions, the 14 m was much warmer than at 1.3 m level, by up to 6.0°C for short periods, but were typically 3 to 5°C. The temperature at 14 m remained above freezing (Table 2). While there should be sufficient heat in the upper air for a wind machine to keep the crop temperature above freezing, the most vulnerable time was 06.45, when the temperature dropped to 1.4°C. The G.Wake site was more vulnerable, with the upper temperature dropping to 0.3°C at 0630. In practice, however, there may have been warmer air between 14 and 20 m, which might have been accessed by a helicopter or wind machine.

Table 2

Examples of inversion strengths at 2 sites in Hawkes Bay on 18/9/1981

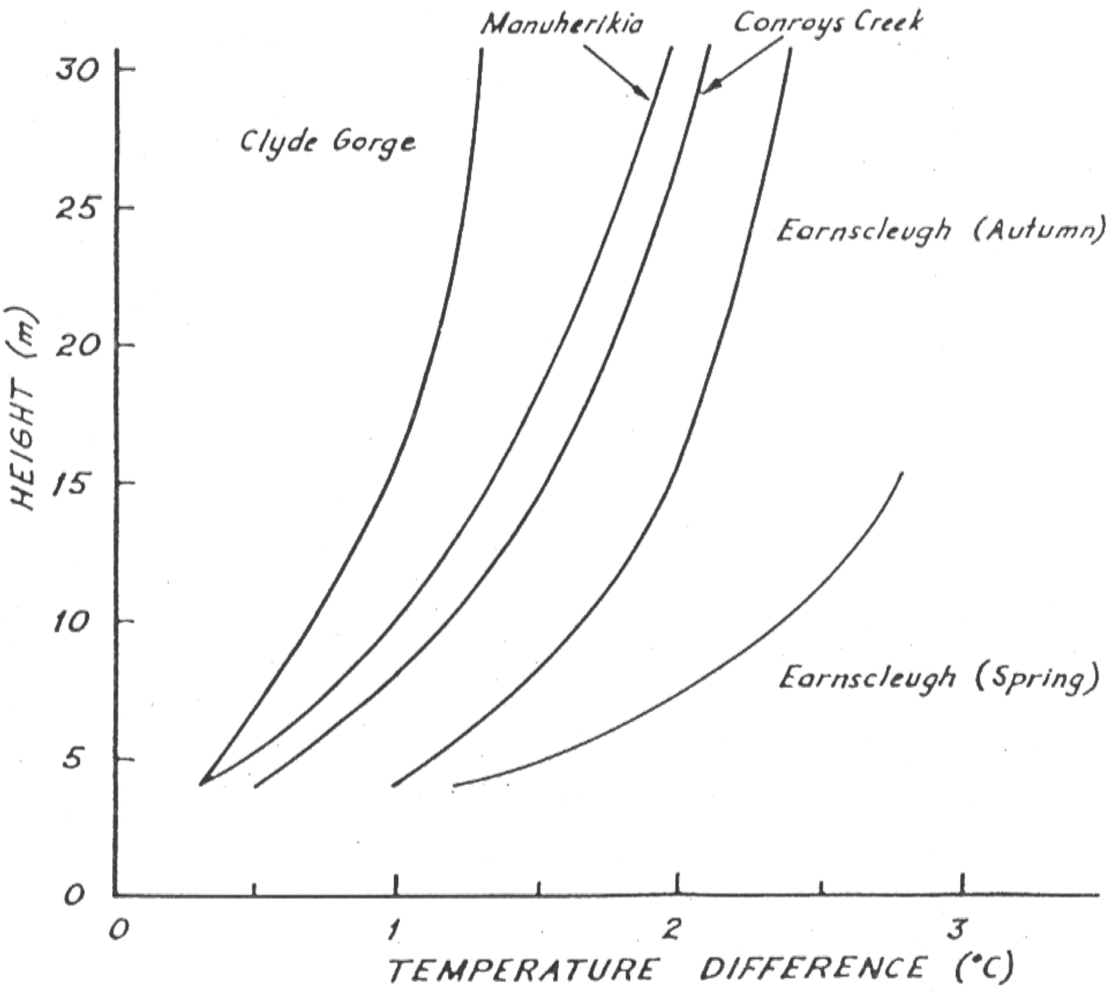
Site	Time	T (14m) ^{o}C	T (1.3m) ^{o}C	Difference ^{o}C
M.Aveling	0500	2.5	-0.7	3.2
	0515	2.3	-1.5	3.8
	0530	2.6	-1.5	4.1
	0545	2.2	-1.2	3.4
	0600	2.1	-0.7	2.8
	0615	2.3	-1.0	3.3
	0630	1.7	-1.1	2.8
	0645	1.4	-1.4	2.8
	0700	1.7	-0.7	2.4
G.Wake	0500	1.2	-1.5	2.7
	0515	1.1	-0.7	1.8
	0530	0.4	-1.4	1.8
	0545	0.6	-1.8	2.4
	0600	0.9	-2.0	2.4
	0615	0.9	-0.6	1.5
	0630	0.3	-2.0	2.3
	0645	0.5	-1.5	2.0
	0700	1.2	-0.2	1.4

From: Heine and Carran, 1983.

The strength of inversion layers can also vary over relatively small distances (Carran 1981) (see Figure 1). This suggests that growers need to evaluate the height, frequency of occurrence and strength of the inversion layer on any particular site before relying on an inversion layer for frost protection (see sections 6.5 and 6.6).

Figure 1

Average temperature profiles for various Central Otago areas expressed as the Temperature difference between any given height and 1.2 m
(Reproduced from Carran, 1981)



2.2 Advective frost conditions in the vineyard

Advection involves the horizontal movement of an air mass. When this air is below zero ^{o}C it causes an **advection frost** (Roger and Swift 1970; Howell et al. 1981; Cornford, 1938). In sheltered parts of New Zealand, advection can be associated with **katabatic** (drainage) winds from hills or mountains. The very cold radiation or snow cooled air slides down the slopes because it is denser than the air above it. Figure 2 shows typical katabatic wind flow down a valley, which, depending on the roughness of the terrain and the length of travel can form shallow surface flows of a few meters to tens of meters deep.

Figure 2

Schematic of katabatic flows in a valley

Figure 2: Schematic of katabatic flows in a valley.

2.3 Freeze damage in the vineyard

The loss of grapevine buds due to late winter-early spring temperatures is a result of the juxtaposing of buds to freeze episodes colder than their critical temperatures. The quantitative impact of such an episode depends on the differences between the tissue temperature and the range of critical temperature in the vineyard. This variability in the range of susceptibility will be dealt with in detail in Section 4.0.

3 Frost forecasting

3.1 Historical records

A useful frost climatology can be derived from daily data, which have been collected for several decades. These data can be used to derive the probability of a screen frost on a given day of the year, thus giving a statistical probability on the “frost free season”**.** Table 3 gives the date of the earliest and latest date of frost recorded on a range of sites, as well as the probability of frosts on given dates (from Goulter 1981). For example, for Ashburton (1951 to 1977) the earliest first frost was 3rd April and the latest last frost 21st November. The median (50% percentile) first frost was 1st May, and last frost was 18th October. If you wish to apply a 10% chance of having a frost the growing season must be between 14th November and the 4 April, giving 140 days.

Similar, statistically rigorous, frost risk information can be developed for any meteorological station in New Zealand. In many cases, data from a particular site of interest can, over a short time) be related to long-term meteorological stations, using temperature loggers. This potentially provides a long-term risk record for sites under consideration.

Table 3

Screen Frost Climatology for Selected Meteorological Stations in Canterbury, Goulter (1981)

Statistics of date of first frost (I), Date of last frost (II) and duration of frost free season (III)

		Min	0.10	0.25	0.50	0.75	0.90	Max	Mean
Ashburton	I	3Apr	4Apr	22Apr	1May	7May	24May	26May	30Apr
	II	10Sep	11Sep	26Sep	18Oct	31Oct	14Nov	21Nov	16Oct
	III	119	140	181	192	216	234	239	191
Darfield	I	13May	6May	25Apr	4May	11May	23May	7Jun	1May
	II	6Sep	14Sep	30Sep	15Oct	28Oct	11Nov	20Nov	15Oct
	III	122	159	182	201	219	233	237	197
Lincoln	I	7Apr	9Apr	25Apr	6May	18May	25May	26May	5May
	II	13Sep	18Sep	27Sep	11Oct	29Oct	5Nov	7Nov	11Oct
	III	150	158	187	207	226	242	252	205
Rakaia	I	15Jan	21Jan	9Apr	1May	10May	16May	18May	13Apr
	II	2Sep	3Sep	19Sep	9Nov	27Nov	3Dec	4Dec	25Dec
	III	92		144	166	212		240	170

3.2 Seasonal anomalies

Ocean temperatures also affect the seasonal temperature and hence the frost regime. La Nina brings more frequent northerly sector winds, warmer coastal waters and warmer than average water in the Tasman Sea. Cyclonic weather patterns eventuate, with cloudier and wetter conditions (Trenberth 1973) and fewer frosts. In contrast, El Nino is associated with more frequent southerly sector winds and cooler ocean water around New Zealand coasts, resulting in lower average land temperatures. The impact of early and late seasons on the sensitivity of the vineyard will be discussed in a later section (4.3), but as such relationships become better understood and real-time monitoring improves, individual frost forecasts and seasonal frost outlooks will become more reliable.

3.3 Determining risk from current day conditions

The weather conditions likely to precipitate a frost are reasonably well known, and several models have been developed to assess the frost risk from meteorological data taken during the day.

Smith (1973) produced and tested a simple forecast scheme, for use in Canterbury, to estimate the next morning's grass minimum temperature, using an understanding of the maximum rate of cooling prescribed by radiation physics and measuring the weather conditions at 15.00 hrs NZ standard time of the current day:

$$T_g = 1/3\ (T + T_d /2) - c \qquad (3)$$

where

T_g is the forecast grass minimum temperature (^oC)

T is the 15.00 dry-bulb temperature (^oC)

T_d is the 15.00 dew-point temperature (^oC)

c is a constant c=8 for May. Sept. and Oct.
c=9 for Jun. and Aug.

provided that:

1. the cloud amount is <1/4 of low or medium clouds and <3/4 high clouds
2. the wind speed is < 5 kt from E or NE (wind off the sea) or < 7 kt from any other direction.

For example, a psychrometer reading at 15.00 in September gives a temperature of 6 ^oC and a dew-point temperature of 3 ^oC.

$$T_g = 1/3\ (6 + 3/2) - 8 = -5.5$$

An analysis of the difference between ground a screen temperatures (Table 1) indicates that temperatures rise by 0.22 ^oC for each 10 cm from the soil surface in Canterbury. This suggests that on this particular occasion the minimum temperature at a 90 cm cordon height will be -5.5 + 1.98 or about -3.5 ^oC, and frost protection would be required if the vines were at a vulnerable stage of development.

3.4 Primary site effect on sensitivity to frost

The most effective weapon against frost protection is preventative action (Geiger *et al.* 1995). He went on to say that "It is incomprehensible that even today, the most fundamental laws of microclimatology are disregarded time and again when new vineyards are established at great cost in areas subjected to repeated frosts". W.J. Humphreys said in 1914 "The best time to protect an orchard (sic. Vineyard) against frost is when it is being established". An often quoted premise for land purchase can be used for vineyards "When developing a vineyard, three factors should be taken into consideration: *"Location,* Location, **Location***"*

3.4.1 Influence of altitude and aspect

Cold air, being denser than warm air, tends to remain close to the ground, and will accumulate in hollows. Small topographical undulations in vineyards can result in frost prone areas within a vineyard area. These undulations are often overlooked at ground level, but may be observed from the air. For example pilots flying for Safe Air from Blenheim airport early on spring mornings, quickly identified frost susceptible areas of the Wairau Plains in Marlborough, and chose "safe" sites for their vineyards (Mike Tiller pers. com. 1996).

On a larger scale, Kerner (1891) demonstrated the influence of aspect on soil temperatures at 70cm at different times of the year, with greatest temperature differences between equatorial facing and polar facing slopes in the autumn through to spring. Figure 3 shows the impact of slope, aspect and altitude on soil temperature. Soil temperature may influence early season vine growth in two ways:

1. The warmer soils of equatorial facing slopes will re-radiate more heat, and potentially be less frost sensitive.
2. Soil temperature is reported to influence vine development in the spring, particularly inflorescence development and fruit set (Woodham and Alexander 1966), and relatively warm soils at this time can lead to significant higher yields.

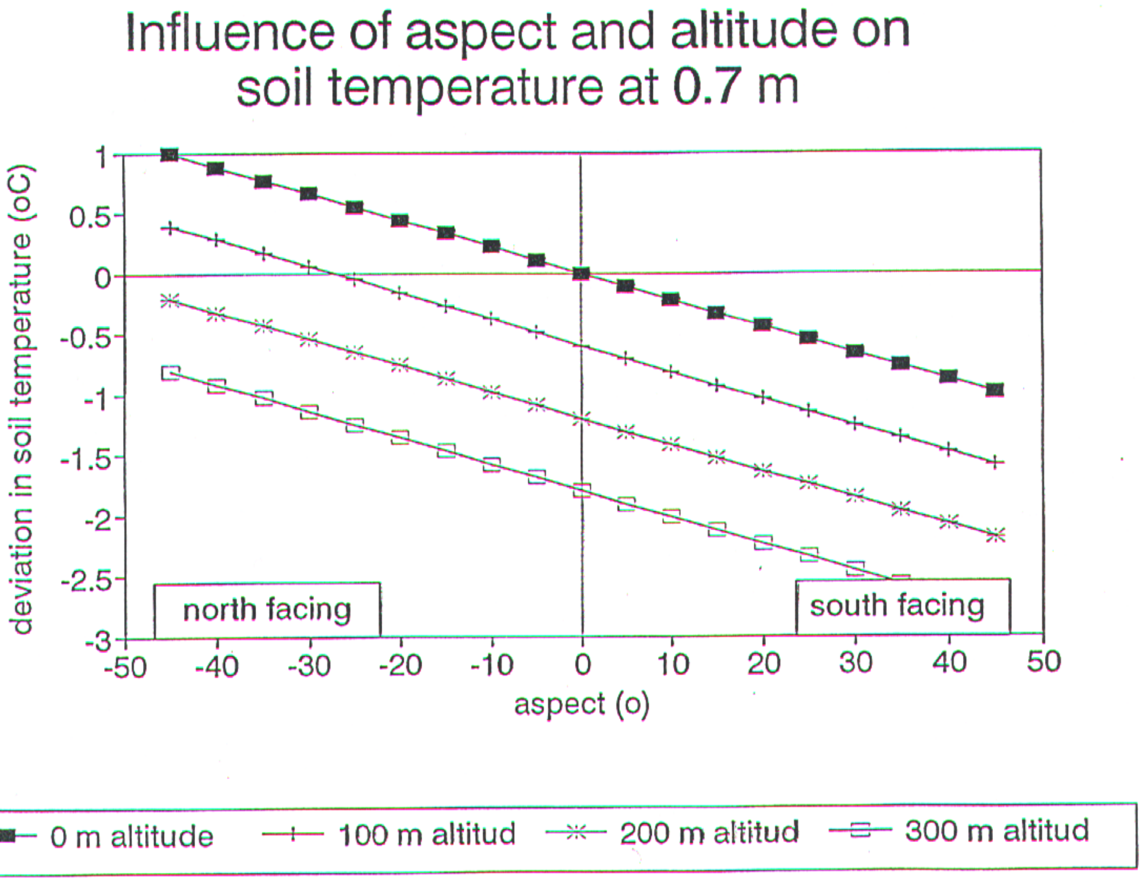
3.4.2 Proximity to water mass

The importance of large season variation in ocean temperatures on likelihood of conditions favouring spring freeze episode was discussed in 3.2. The impact of both ocean and more localised water masses near the vineyard also influence the likelihood of buds being frost damaged by other mechanisms.

Water possesses a greater heat capacity than does either soil or air. The result is a slower change in water temperature as compared to these two. A localised cold water mass can keep buds dormant later in the season and result in slower movement through the increasingly less frost resistant stages of bud phenological development. If the seasonal timing of late spring freezes and early autumn freezes is stable, such delays would reduce the incidence of vineyard temperatures below the critical level for buds growing there. That stability is an evaluation that must be carefully assessed.

The presence of a water mass near a vineyard is also useful as it promotes air movement. As noted by Dethier and Shaulis (1964) cold air flows down slope to the body of water where it is warmed and then rises. A vertical circulation pattern can build if other air movement patterns are not sufficiently strong to interfere.

Figure 3



3.4.3 Shelterbelts

The impact of shelterbelts on frost sensitivity depends on the density of the shelterbelt, site slope and time of year. It is clear (Daigo and Maruyama 1956) that a cold air dam on the up slope side of a shelter belt can produce lower temperatures than on the down slope side, and care must be taken to allow air drainage through the shelter belt in such situations. Where shelter is desirable for other vineyard reasons (prevention of spray drift, wind damage etc.), temporary, artificial shelter cloth, which can be lifted up during the period of frost sensitivity, may be considered. This can then be lowered into place once the risk of injury has passed.

What is less clear are the potential frost protection benefits that may be afforded on the down slope side of a shelterbelt. Anon, Jensen (1954) and Geiger *et al.* (1995) all reported increased temperatures near shelterbelts, while Kaminski (1968) observed an increase in temperature near a shelterbelt, and a decrease 4 to 16 *h* distant (where *h* is the height of the shelterbelt). Others (see Geiger *et al*. 1995 for a discussion) all report lower temperatures. Additional research is necessary to determine the exact conditions controlling minimum night temperatures around shelterbelts, but they are likely to be related to air movement, shelterbelt density and the differences between advective and radiation frosts.

4 Grapevine frost sensitivity

4.1 Factors influencing Spring frost damage

The onset of bud burst each spring is a period of anticipation and anxiety. Inflorescence primordia initiation in the previous summer and winter pruning establishes yield potential for the coming season. However, every year poses the possibility of a frost causing an economic disaster. While the compound bud of grapevines has three shoot primordia (Pratt, 1974), the fertility and hence potential productivity of the primordia decrease as secondary or tertiary buds develop. At the same time, frost damage to the primary bud results in the bud break process having to start again, later in the season. As all initial shoot growth, up until the shoot has approximately eight fully expanded leaves, depends on stored reserves within the vine, early season frosts can deplete stored reserves within the vine, potentially affecting subsequent development of shoots, and fruit set at flowering.

4.2 Damage mechanisms

Some herbaceous plants (e.g. wheat, cabbage etc.) tolerate frost conditions. During freezing these plants, water freezes and ice nucleation occurs outside the cells and then as the temperature declines further, water moves out of the cells and freezes in the intercellular spaces. In contrast, damage to vulnerable species is characterised by explosive ice formation inside the cells, which ruptures cell membranes and kills the cells, and hence the tissue or perhaps the entire plant.

In grapevines, buds and shoots which have not started to develop will tolerate temperatures as low as -15°C. At this stage, buds have no free space for ice nucleation, and effectively tolerate these low temperatures by supercooling. Supercooling occurs when water remains undisturbed, and their are no nucleation points for ice formation to occur. As the bud develops and starts to grow, xylem is produced that hydraulically connects the bud to the cane. Once connected, the capacity for supercooling is lost. While the dissolved solutes in cells of grapes may lower the freezing point of liquid in the vine by 1-2 °C through freezing point depression, the new leaves and shoots of the bud becomes susceptible to temperatures only slightly below 0 °C. These developing buds will be killed immediately upon ice crystal formation in these tissues. In general, younger tissues have a greater water content, and tend to freeze at a higher temperature, hence shoot tips, emerging leaves and developing inflorescences tend to be most sensitive to a frost.

4.3 Bud phenology

As the grape bud responds to environmental cues (predominantly warm temperatures) growth slowly begins and changes in development can be perceived visually. These are called phenological changes and Baggiolini (1952) has defined the individual stages as a bud passes from dormant bud to status as an elongating shoot.

The critical temperature of the expanding grape bud becomes warmer as bud development continues (Johnson and Howell 1981) (Table 4).

Table 4
Critical temperatures (°C) for developing buds of Concord Grapevines[1]

Stage of Phenological Development	Influence of Surface Moisture	
	Wet[2]	Dry
Scale Crack	-5.5	-9.5
First Swell	-4.5	-8.0
Full Swell	-3.5	-7.0
Burst	-3.0	-6.0

[1] Values are T_{50}

[2] Indicate presence of hoar frost, dew, ice or water from precipitation or irrigation

After: Johnson and Howell., 1981

Bud phenological stage at any given time during the initiation of spring growth can be influenced by a number of factors:

(i) temperature – within a given cultivar, vine response to temperature is straight forward – the warmer the temperature and the longer the duration of that temperature, the more rapidly a bud passes from dormant bud to shoot status;

(ii) cultivar – data suggest that different cultivars vary in their threshold temperature to stimulate bud growth (Anderson *et al.*, 1980). That work suggests that growing degree days required for onset of bud growth ranged from 290 to 640 across an array of cultivars. Further, the rate of development once growth was initiated was independent of threshold temperatures. In the years of this study a range of 14 days from earliest onset of bud growth existed (Table 5).

Table 5
Cultivar influences on bud phenological development

Cultivar	Onset of Bud Growth		Rate of Bud Growth
Marchal Foch	⇑	Early	Slow
Baco Noir		Early	Slow
Concord		Mid	Mid
Seyval	10-14 days	Mid	Mid
Vignoles		Mid	Fast
Vidal blanc	⇓	Late	Mid

After: Anderson *et al.* 1980

(iii) A second cultivar factor seems also to increase susceptibility to frost damage (Johnson and Howell 1981). At the same phenological stage differences in critical temperatures were demonstrated (Table 6). So, growers have cultivar choice based on delayed phenological development and greater frost resistance at a given stage of development. Before this can be made a part of the grower decision-making process, however, both bud phenology and definition of critical temperatures for important phenological stages is required. Similar research needs to conducted on *Vitis vinifera* cultivars, particularly in relation to spring carbohydrate levels in canes.

Table 6

Cultivar influence on critical temperatures (T_{50} °C) at a Common Stage of Phenological Development

	T_{50} (°C)		
	Stage of development		
Cultivar	First swell	full swell	Significant F
Baco Noir	3.0_a	2.5_a	*
Concord	4.0_b	3.5_b	*
Vidal blanc	3.5_{ab}	2.5_a	*
	*	*	

After: Johnson and Howell 1981

The potential damage in any season depends on the time of the frost in relation to the phenological stage of development of the vine. The greater the heat accumulation and the more developed the vine before the last frost of the season, the greater the susceptibility it will be to damage. Information regarding the range of bud break dates in New Zealand is limited. However, there is a long meteorological record in many of the main grape growing regions. Using a model describing bud development, developed by Moncur *et al.* (1989), mean and seasonal variation in bud break dates can be made (Trought unpublished data).

(1) $HU_d = ((T1-Tb)*8) + ((T2 - Tb)*16)$

(2) $HU_t = \Sigma HU_d$

Where HU_d = daily sum in degree hours
HU_t = total heat sum in degree hours
T1 = day temperature
T2 = night temperature
Tb = base temperature

Using four years of data from the Lincoln University vineyard, the observed bud break of Pinot noir was four days behind the date predicted by the model. Over 69 seasons, the estimated date of bud break ranged from 2 nd October in 1988 to10th November in 1959 (Figure 4). Using this modelling approach the point at which the vine becomes vulnerable to frost damage can be assessed (Figure 5). Comparing the date of budbreak to the date of the last significant frost (chosen as -0.5 °C), indicated that the years that had the later bud break often also have the later frosts (Figure 6). This suggested that a delayed bud break induced by a cool spring does not mean that the vines will be less vulnerable to frost damage or *visa versa.*

Figure 4

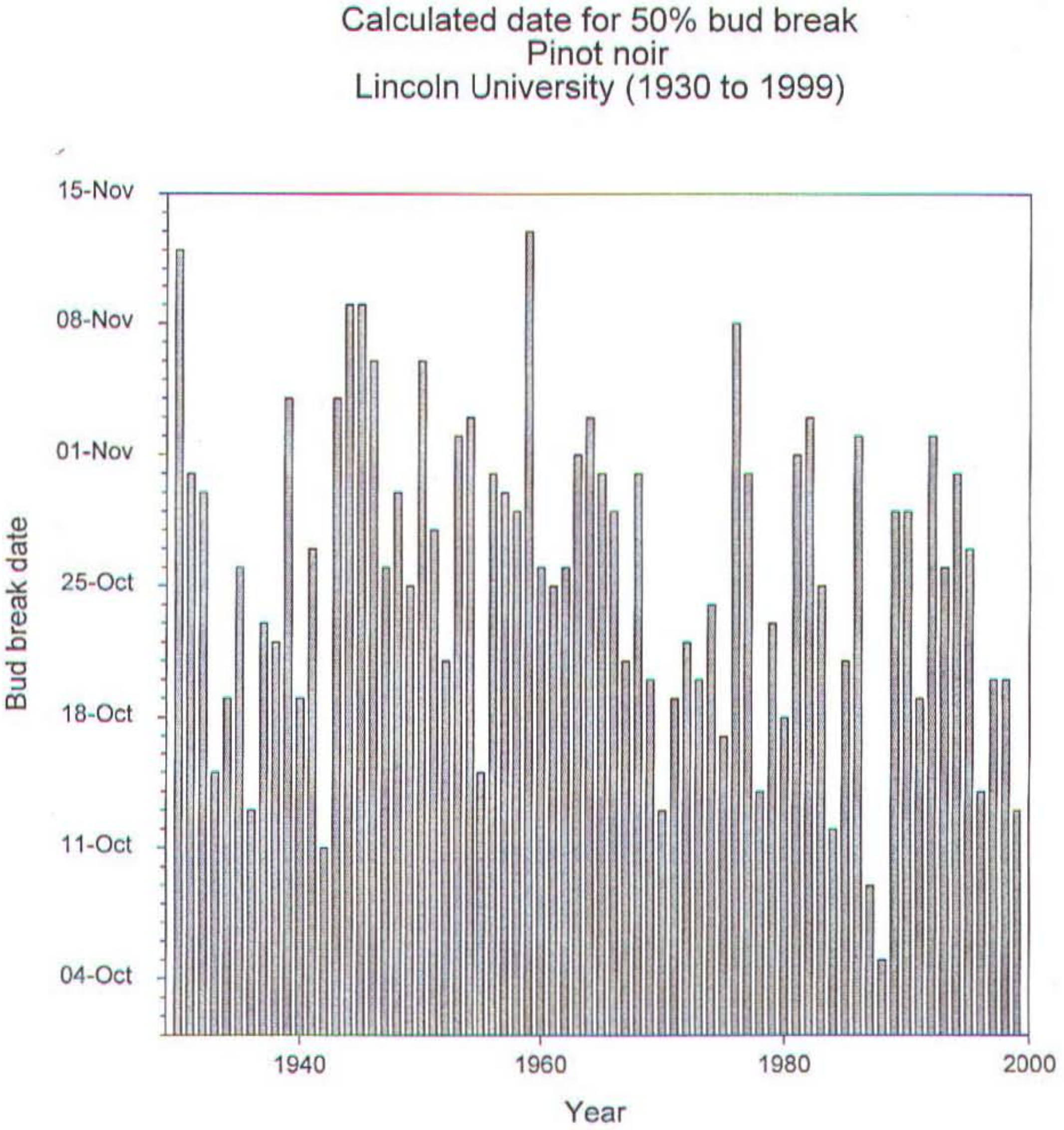


Figure 5

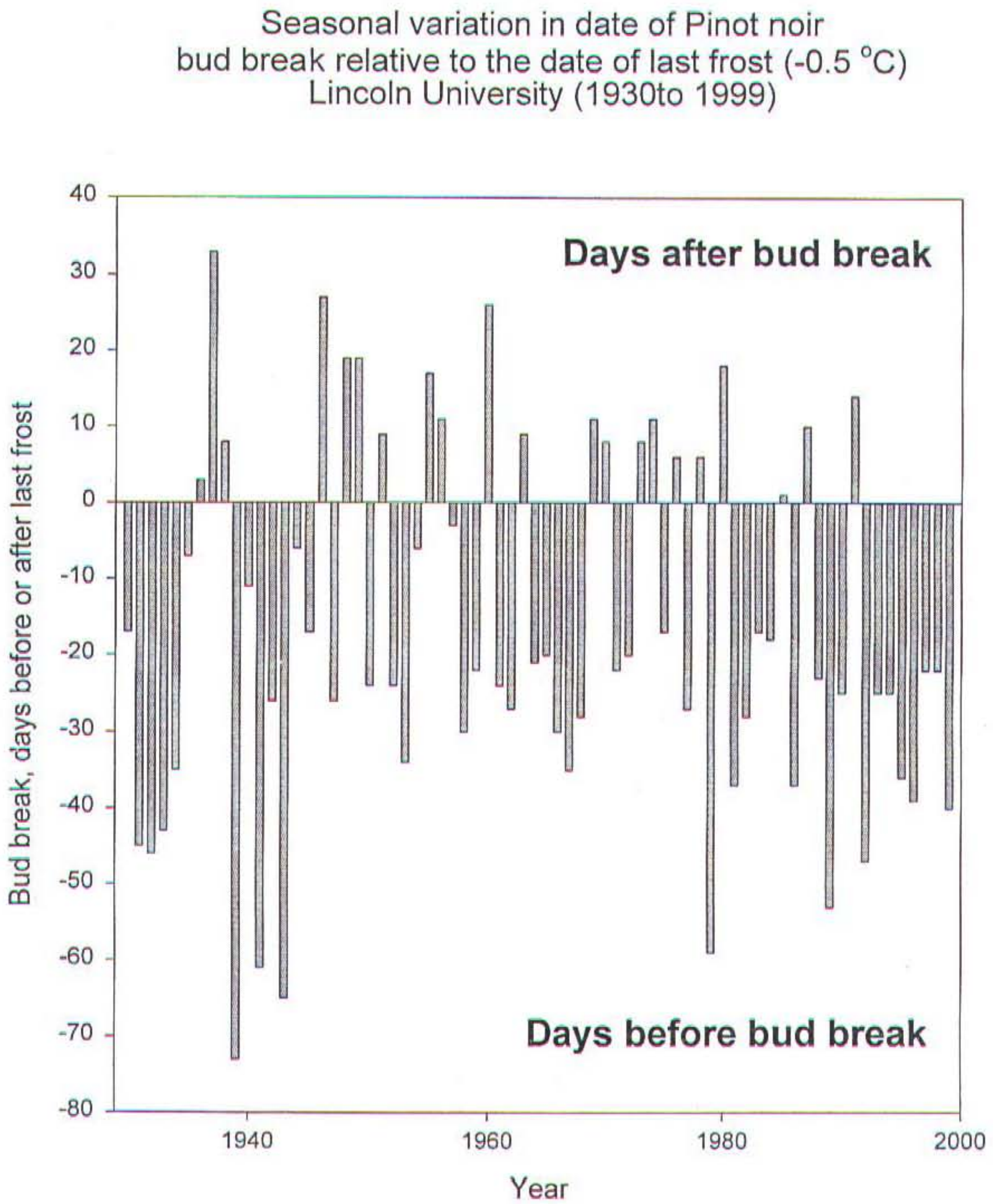
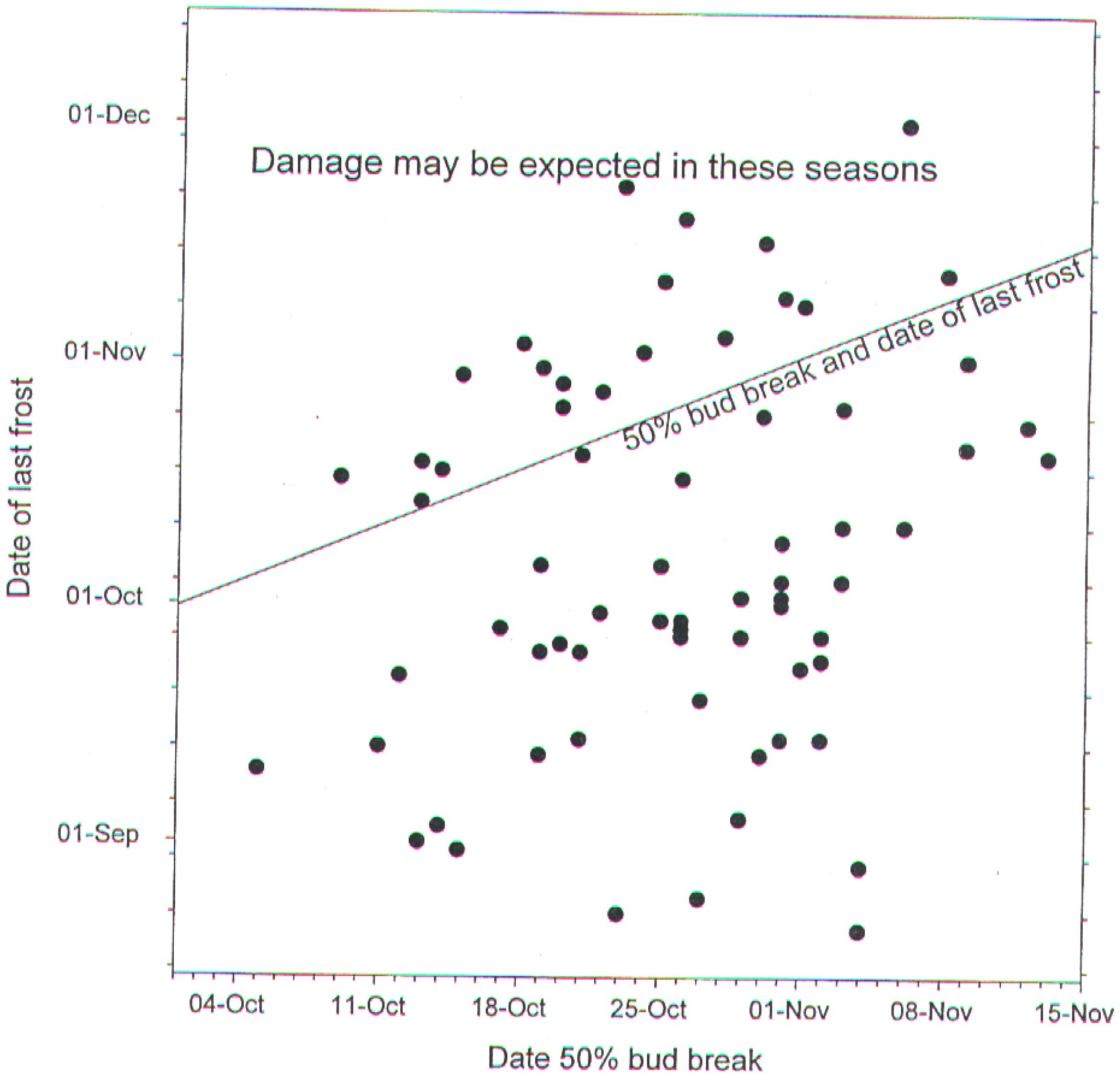

Seasonal variation in date of Pinot noir
bud break relative to the date of last frost (-0.5 °C)
Lincoln University (1930to 1999)
Days after bud break
Days before bud break
Bud break, days before or after last frost
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
1940
1960
1980
2000
Year

Figure 6

relationship between the date of 50% bud break (Pinot noir) and the date of the last frost (-0.5 °C)



Using the same approach, the sensitivity of various cultivars can be assessed. Table 7 shows the predicted bud break dates of four cultivars at Waipara (North Canterbury) over seven years. It is apparent from the analysis, that Gewurztraminer will be the most vulnerable cultivar and Sauvignon blanc the least at this site. However, a the lack of late frosts at this site would suggest that there is a low risk of damage to vines post-bud break.

Table 7

Estimated date of bud break for a range of cultivars at Waipara West Using the model of Moncur *et al.* 1989

Year	Pinot noir	Sauvignon blanc	Riesling	Gewurztraminer	Mean for cv. in year
1990-1	6 Oct	13 Oct	8 Oct	24 Sept	5 Oct
1991-2	6 Oct	12 Oct	7 Oct	23 Sept	4 Oct
1992-3	25 Oct	1 Nov	23 Oct	12 Oct	22 Oct
1993-4	12 Oct	20 Oct	12 Oct	4 Oct	12 Oct
1994-5	21 Oct	31 Oct	18 Oct	7 Oct	19 Oct
1995-6	21 Oct	28 Oct	19 Oct	8 Oct	19 Oct
1996-7	3 Oct	11 Oct	5 Oct	26 Sept	3 Oct
Mean	13 Oct	21 Oct	13 Oct	2 Oct	12 Oct

From the model, the impact of the Mt Pinotubo explosion in 1992 can be seen, with the mean predicted date for all cultivars not occurring until 22nd October, significantly later than 1990, 1991 and 1996 springs. At the same time, Gewürztraminer would appear to be the cultivar most vulnerable to a late frost having a mean bud break date of 2nd October over the seven years considered, and breaking bud as early as 23 rd September in some seasons.

4.4 Freeze duration

Since supercooling and the presence of ice nucleation sites in the bud vary from developing bud-to-bud, the amount of damage suffered will increase as the length of period of exposure to freezing conditions increases. It is a stochastic factor, much like rolling dice; the more throws of the dice the greater likelihood that a given result may occur. (Proebsting and Mills 1971; Howell et al. 1981).

4.5 Wind

The presence of wind during a spring frost episode can have impact upon both the damage and the degree to which protection may be effective (see section 6.6 and 6.71). Wind induced motion by buds or shoots can reduce supercooling by the agitation and result in freezing events at warmer temperatures.

In the course of discussion about freezing conditions, the topic of wind chill, and the influence it has on damage frequently arises. We personally experience wind chill, when the wind is blowing hard on a cold day, we are colder. Are our grape buds?

To answer this question we should consider the reason for our perception of "wind chill effect". First, humans are warm-bloodied and body temperature is generally above ambient air temperature. When a wind blows across a body there is convective heat loss and we perceive greater cold. Second, we release water through our pores and when a low humidity wind blows, water is evaporated from the skin, resulting in a lower surface temperature.

Grapevine buds are either at or very near ambient air temperature, so blowing wind does not lower this temperature. The case for water loss is more difficult to make in this early stage of spring bud growth. Previous work (Howell, 1981, unpublished) with a wind-tunnel at 145 km h^{-1} could not demonstrate a loss of water from buds in scale crack, first swell of full swell and there was no difference between bud tissues and air temperatures. Later stages of shoot growth were not measured, however, leaf expansions would possibly allow water loss and exacerbate frost damage either directly by temperature lowering, or indirectly via dehydration.

4.6 Pre-freeze temperatures

In winter, periodic warm temperature exposure is viewed with concern because of the potential for hardiness loss by buds and the portent of winter freeze damage when cold normal conditions return. This is not the case with regard to spring frost. The influence of temperature is on phenological stage only. Whether that stage is achieved very slowly at near growth threshold temperature or rapidly via greenhouse forcing, both have comparable critical temperatures at the same phenological stage.

4.7 Rainfall prior to freeze

Free water in the soil can serve as a heat sink and release heat to the air reducing a freeze on impact. Surface water on buds, however, can reduce supercooling as that water freezes and serves as a nucleator for ice within the bud (Johnson and Howell, 1981).

Relative humidity. High relative humidity can have a similar impact on supercooling as does surface water. Ice crystal formation on the bud surface can serve to inoculate the tissue and canes.

4.8 Ice nucleating bacteria

In the late 1970's Lindow and associates determined that supercooling was limited by the presence of certain bacteria. To date, two have been identified as having active ice nucleation capacity. These include the stone fruit bacterial canker organism *Pseudomonas syringae* and the relative of fireblight, *Erwinia herbicola*. Activity occurs when populations of the organism exceed 10,000 bacteria per cm^2 of tissue surface. The practical importance of these organisms varies with location and with the nature of spring bud development. If one has a location where the bacteria do not achieve this population during the spring phenological stages that are susceptible, or do not achieve such populations until the last frost hazard has passed, then they are of minimal concern. Where populations are high, copper sprays, to kill the bacteria may provide some protection. The important question is whether such knowledge is available in the specific viticultural region.

5.0 Autumn Frost

Autumn frosts affect a vine in a different way to spring frosts. Frosts before harvest will invariably cause death of leaves, which are already in the process of senescence, and will lead to premature leaf fall. This effectively prevents any further photosynthate accumulation by the vine, and any transfer of nutrients from the leaves into the vine. In some cases (when the frost is early enough), it may prevent wood from becoming fully mature, leading to a decreased tolerance of lower winter temperatures. In general fruit will not be adversely affected, unless the temperature falls to -8°C, when fruit will freeze.

In 1992, a frost in late March in Marlborough caused death of vine leaves, and this was followed by rain. The dead, wet leaves caused major problems with machine harvesters and excessive plant resides in the fruit.

6.0 Minimising and managing frost risk

Selecting a site is an on-going process. Abandoning an unacceptable site may be a positive choice.

The history of frost protection of grape vines is at least 2000 years old, when Roman grape growers protected their vines by burning heaps of dead vines and prunings (Blanc *et al.* 1963). Many alternative methods have been developed to manage and minimise risk to horticultural crops, and have been comprehensively review several times from the late 1880's (see Rieger 1989 for a recent review). We do not intend to cover all aspects here, but to focus on alternatives that we believe are realistic options for viticulturists.

Growers have used a wide range of frost protection methods over the years. Undoubtedly the most preferred is selecting a site that has minimal frost risk, and this was covered in previous sections. However, few sites in New Zealand can be considered to be truly free of frost risk in all seasons. An awareness of the risk of frost in any season (see section 3.3.2) may cause a grower to alter management strategies to accommodate the specific season under consideration.

6.1 Management options to ameliorate frost damage

There are an array of options and these may be subdivided into further categories.

6.1.1 Pre-plant options

a) Site selection based on appropriate macro-, local, and meso-climatic considerations.
b) Choose a site having as few limitations regarding growing season length, an advantageous aspect (faces the equator) and slope.
c) Cultivar selection is a tool that may be exercised as Table 7 shows Gewürztraminer to be an early budding cultivar while Sauvignon blanc is late. The latter would be less often damaged by frost.
d) Rootstock choice has been often suggested to influence date of bud burst. Critical experiments utilising reciprocal grafts of vines with 14 days difference in bud break showed no rootstock influence on scion bud phenology (Howell, Unpublished data).

6.1.2 Training system choice

Training which puts buds well above the soil may reduce frost hazard by up to 0.36 ºC for each 10 cm above the soil level. (See table 1).

6.1.3 Pruning choices

While the date of bud break is largely determined by the accumulated heat prior to bud break and the cultivar under consideration, vines can be managed to adjust the date of bud emergence.

a) Double pruning. In locations where spring frost losses are a frequent economic concern it is a practice to retain 2 to 3 times the number of cane per vine. These can be utilised to produce a crop when damage is severe, and be quickly removed if not needed. Figure 7 shows one approach seen in Swiss vineyards by one author.

Leaving extra bud numbers may allow yields to be maintained after a frost event. Vines will need to be repruned, after the danger of frost has passed, adjusting the shoot number to an appropriate level for good canopy structure, and appropriate cropping levels.

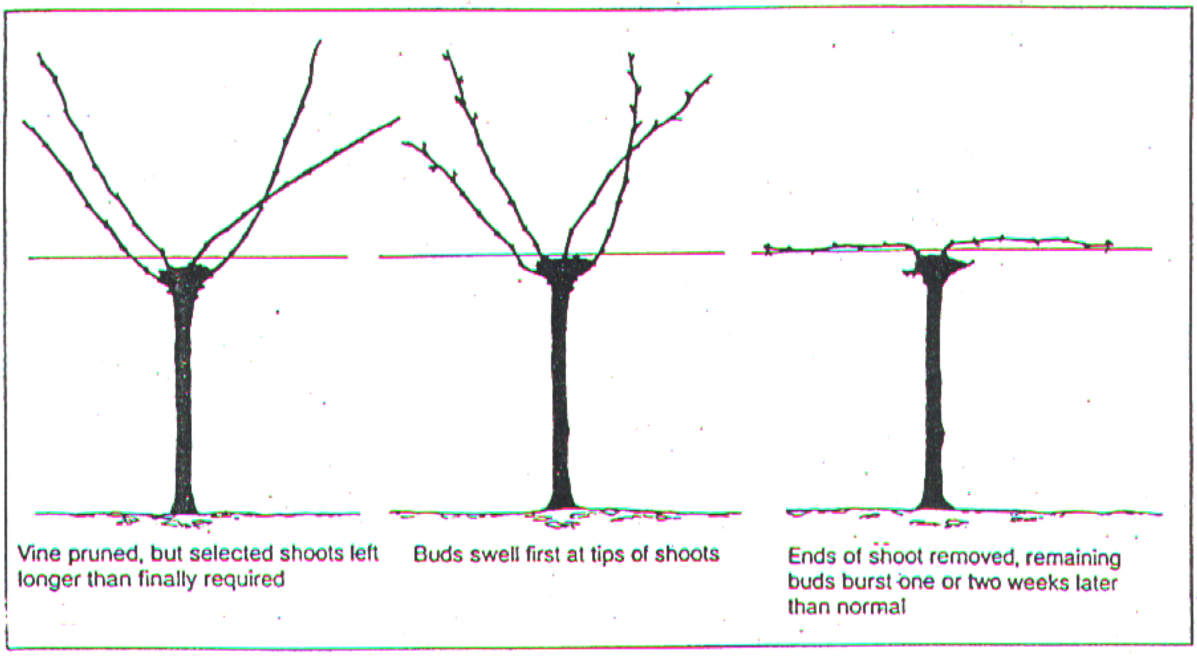
b) Late pruning spur-pruned vines will cause bud break to occur later in the season, resulting in buds being less sensitive to frost damage at any particular stage of development

(Whittles 1986; Friend *et al.* 1999).

c) Long cane pruning. As noted earlier, bud burst along grape canes is not uniform; it begins first at the cane apex and progresses basipetally. The larger the number of buds apical to a given bud the greater the delay (Howell and Wolpert 1978, 1979).

Figure 7

Method of retaining additional buds on a modified Guyot (VSP) system in anticipation of losses by spring frost.
a) typical VSP post pruning; b) retains 1-3 additional canes at the head to augment bud number if required, or cut back to renewal spurs if not required.



Figures after Jackson, 1997.

This response is best seen by using data on the subject comparing number of nodes apical to buds in question, their stage of phenological development, and the resulting bud mortality.

6.1.4 Delaying bud-break by chemical means

There have been few reports of chemicals used to delay the onset of bud break. Potassium alpha-napthaleneacetate (PNA) significantly retarded bud burst by five days when applied at 200 and 400 ppm in the autumn (Di Cesare, 1968). An unnamed gel product was reported to delay bud-break of Chardonnay, Pinot noir and Vignoles by up to 14 days (Dami *et al.* 1996). This treatment enhanced freeze resistance of both buds and canes, although the mechanism(s) remain unknown. The authors speculate that the gel may inhibit gas diffusion into and out of the bud, causing both an increase and decrease in CO_2 and O_2 concentrations respectively. Myers *et al.* (1996) found that applications of soybean oil to dormant peach trees increased internal CO_2 concentrations in buds and delayed flowering.

Despite a tremendous amount of effort into delaying bud break by using a range of chemicals, the lack of practical application of any technology suggests that to date, few have proved to give a reliable response.

6.2 Inter-row management

Inter-row management can have a marked influence on the minimum temperature reached in a vineyard. Ground cover, and the thermal properties of the soil, i.e. its thermal conductivity, density and specific heat, can influence air temperatures during radiation frosts. For example, loosely packed soils or those with high organic matter levels have poor conductivity, and low heat capacity. They store little heat during the day and radiate little at night when compared to densely packed soils (Hamer, 1978). Slater and Ruxton (1954) showed that temperatures 7.5 cm above a firm surface could be ~1.0 °C higher than over loose soil. Likewise, ground cover can have a major influence and grass cover or mulches may reduce temperatures by 4-6°F (Cornford, 1938; Rogers, 1957). Similar differences have been observed in vineyards where minimum temperatures were 0.3 to 0.6 °C higher where the inter-row was managed using a herbicide regime when compared to one that was disked or closely mown (Donaldson *et al.* 1993). Disking creates an insulated layer between the soil and the air, and vegetation increases evaporation from the soil surface, which reduces the ability of the soil to absorb heat during the day. Treatments had greater differences on colder nights, while Snyder and Connell (1992) suggested that taller vegetation leads to colder minimum temperatures.

6.3 Soil moisture

As noted in 6.2, soil characteristics that increase a soil's heat capacity will influence thermal conductivity and specific heat. Soil profiles with high water content will store heat during the day for release at night.

6.4 Vineyard covering

Covering plants with material that is opaque to long-wave radiation may reduce radiation heat loss from the vineyard to the sky. To be effective, the material should have a low infra-red transparency (e.g. polyvinyl chloride), (polyethylene and polypropylene have high infra-red transparency), and need to be of sufficient width to trap the heat. Rogers and Beakbane (1951) found that string netting, which impeded only 6.25% of the radiation had little effect, however, other materials giving 40% shade would provide a temperature lift of typically 0.5-1.1 oC (Hamer 1978). The possibility of using bird protection nets, folded over the vines at a vulnerable time of the year, may be worth investigation.

6.5 Frost pots and heating

Frost protection by heating may be provided from many alternative sources has been employed for centuries. In general however, oil stoves, because of ease of lighting are preferred, although high fuel costs have limited their use in recent years. Heating provides protection by raising air temperature within the planting and through radiant heat transfer from the heater chimney (Perry *et al.* 1977). Radiant heat is particularly important in an advective freeze because the convective-conductive head component is reduced by windspeed. Strong inversions increase the efficiency of heading by preventing the heated, buoyant air from rising above the area being protected. A larger number of small heaters are more effective than a fewer large ones. The greater number provides more uniform heating, and lowers the risk of intense heat “puncturing” the inversion layer. Between 80 and 100 heaters per hectare are required to provide 2 to 4 ^{o}C protection, although protection may be higher under ideal conditions, and less under windy conditions. Additional heating around the border is important. The ascending warm air from the middle of the vineyard produces an inflow of cold air from the periphery, which needs to be heated to prevent damage at the edges of the vineyard. Similarly, if there is air movement across the vineyard, additional heat needs to be supplied on the upwind side of the vineyard.

In a frost event, a small proportion of heaters can be lit initially, and temperatures monitored to maintain temperatures above a safe level. Additional heaters can be lit if temperatures continue to fall.

The combination of heaters and wind machines (see section 6.6) is much more energy efficient (Gerber, 1970). The investment required for heaters and wind machines in combination is less than their combined costs, because the number of heaters is less. At the same time, the risks are lower than depending on wind machines alone.

6.6 Wind machines and helicopters

The use of devices to mix warm upper layer air strata into the cool vineyard is common. Wind machines and helicopters are popular because they require low labour input and have low operational cost per unit area of land protected. The choice between wine machines and helicopters largely depends on the frequency with of frost events. Wind machines will tend to have a high capital cost, but once installed will provide reliable control (providing the inversion layer is sufficiently strong (see section 2.1), and within reach of the machine). In contrast, helicopters are generally hired by vineyards for particular events, and will remain on standby either in the vineyard or close by, until required. This can be relatively expensive in operation, although capital cost is minimal. A reliable prediction system (e.g. see section 3.3) which allows decisions to be made on the need to have a machine on standby will greatly influence the overall cost of this system.

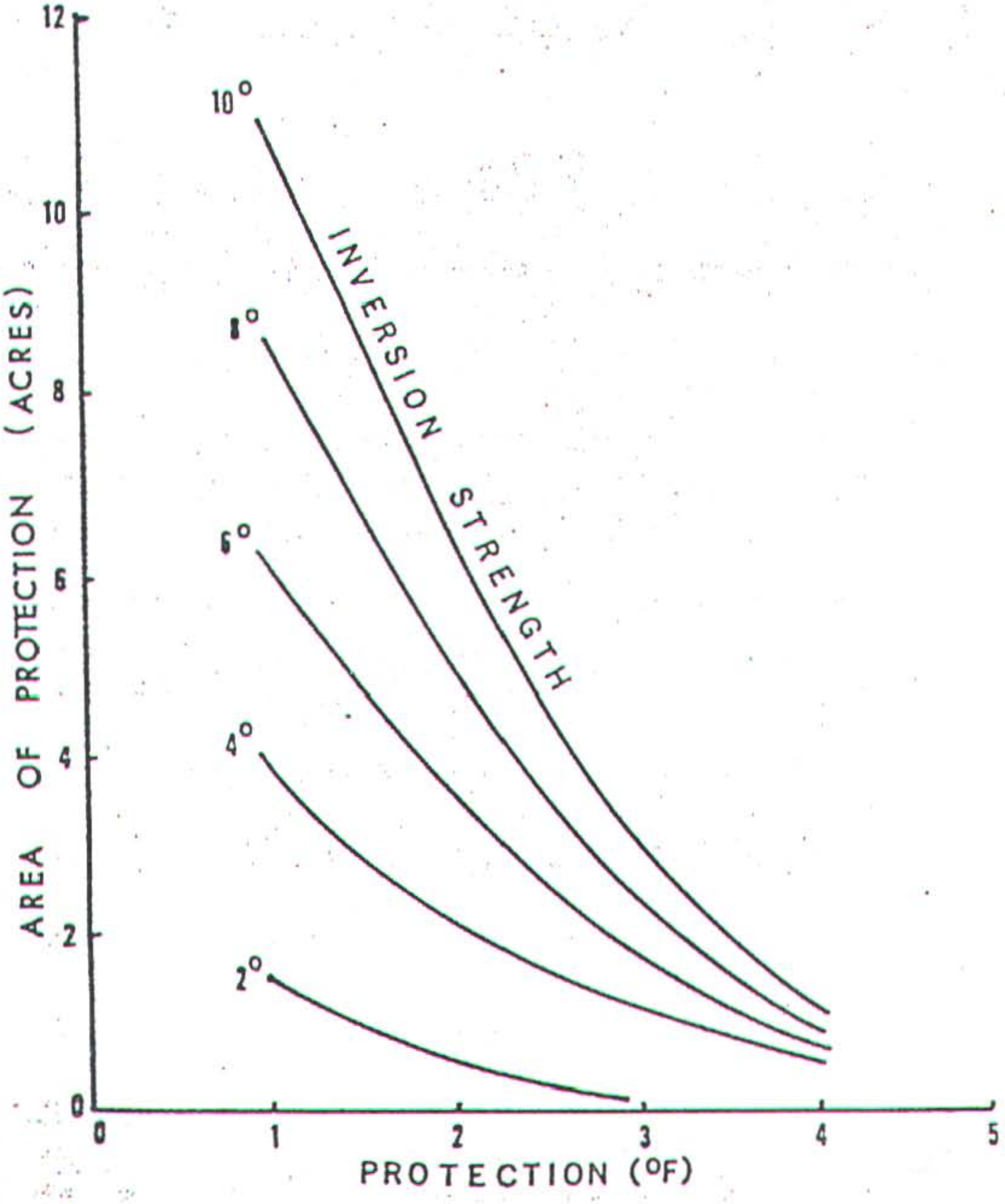
The area that can be protect depends on the strength of the inversion layer. Work in Florida (Gerber, 1970) has demonstrated both the level and area that may be protected by a typical wind machine under varying inversion strengths (Figure 8).

It is important to note that under advective conditions, wind machines and helicopters will give no cold protection, and can potentially make matters worse.

Figure 8

The area and amount of protection provided with an 85-brake hp. Wind machine as related to inversion strength

(From Gerber 1970)



6.7 Sprinklers

Sprinklers that spray water on plants provide the most reliable frost protection. Latent heat of freezing generally provides heat required to prevent temperatures falling below 0 ^{o}C. Unlike other systems, protection can be afforded in advection and radiation frost conditions.

6.7.1 Overhead sprinklers

Overhead sprinkler protection is probably the most reliable form of protection. Heat is gained both as water-cools to freezing (1 cal g^{-1} $^{o}C^{-1}$) and as the water begins to freeze (80 cal g^{-1}). When temperatures are below 0^{o}C, buds and developing shoots will have a layer of ice inside, but free water on top. As freezing of the free water continues, latent heat is liberated, maintaining the boundary at a temperature of 0^{o}C, a temperature tolerated by vines. It is important to apply sufficient water to maintain the free water on the ice surrounding the tissue (Gerber 1970) (Table 8). If the ice is allowed to dry, then the temperature rapidly falls to below 0^{o}C, and sensitive tissues will be killed (ice is a good conductor of heat).

Table 8

Sprinkling rate (mm h-1) necessary for cold protection

Tissue Temperature [a]	Wind Speed (Km h^{-1})					
	0-1.5	3.0-6.5	8-13	15-22	29-32	48
-2	-	-	-	-	-	-
-3	0.25	0.25	0.36	0.50	1.00	1.50
-4	0.25	0.40	0.75	1.00	2.00	4.00
-5	0.30	0.60	1.25	1.50	3.00	4.50
-6	0.35	0.70	1.40	1.80	3.65	5.25
-7	0.40	0.75	1.50	2.00	4.00	6.00
-8	0.50	1.00	1.75	2.50	5.00	7.50
-9	0.65	1.75	2.25	3.30	6.60	10.00

[a] Tissue will prevent freezing 0 to -2 by freezing point depression resulting from dissolved solutes in cell sap. Note: *This is tissue temperature, not air temperature*
Modified after Gerber, (1970)

It is important therefore that the rotation speed of sprinklers must not be long enough to allow the ice to freeze on the target between rotations (Pogrell (1958). The degree to which sensitive tissues can be protected depends on the spray density and period of interruption. Generally greater frequency of application or higher intensity will give better protection (Table 9). However, when considering application rates the distribution of water from the sprinkler has to be taken into account, and designed provide sufficient coverage to the area of minimum application rate.

It is important to start and cease watering at the right time. The first application cools the tissues to the wet-bulb temperature, and under dry, motionless conditions, cooling can be to a level substantially below the air temperature at that time. So water applications have to be started before the air or tissue temperatures reach a critical value. If spraying is started at that time, the drop in temperature experienced at that time may kill the tissues, before the latent heat becomes effective. Likewise, sprinkling should only be stopped when temperatures are well above freezing. If applications are discontinued too soon, heat may be drawn from the plant to melt the ice, causing damage.

Table 9

Minimum temperatures (^oC) for different spray densities and interruption times

Spray Density (mm h^{-1})	Interruption time (min)			
	3	2	1	0.5
<1.5	-2.5 to –3.0	-3.0	--	--
1.8 to 3.0	-4.5	-4.0 to –5.0	-5.0 to –6.0	--
3.4 to 4.1	--	--	-6.5	-7.5
11.3	--	--	--	9.0

From: Geiger *et al.* (1995)

6.7.2 Targeted and Intermittent Sprinklers

Traditional overhead sprinkler systems will use a considerable quantity of water (e.g. 4 mm h^{-1} for six hours represents 240 m^3 water per hectare). In vineyards, much of this is falling on non-target areas. Targeting water, using micro-sprinkler technology has been shown to provide good protection and water use by 25 to 45% (on peach trees. One could anticipate greater savings in vineyards, where the target area is possibly a row 30 cm wide or only 10% if a 3 m wide row) (John 1985). In practice a wider band of water would be needed to allow some drift in water spread under windy conditions. However, because water is applied continuously, the application rate would be minimal (see Table 9 for the impact of interruption time [which in this case is zero] spray density and minimum temperatures). Little work has been done to investigate the performance or economic worth of such systems. While targeted sprinklers may be used for irrigation, a secondary irrigation system would probably need to be considered, and micro-jets established at ~6m centres to provide sufficient overlap along the rows.

An alternative approach is to provide intermittent application. Again, this will reduce water use, but provides less protection. Care should also be taken to prevent the sprinkler heads from freezing between pulses or the whole system may become ineffective. Using Table 9, the interval between pulses may be adjusted to provide appropriate protection at different temperatures. Like targeted irrigation, little research has been undertaken to evaluate the performance or cost:benefit of such systems, and this may be worth further research.

An additional use of sprinkler systems is to apply water to buds on warm days in the spring. Under conditions of relatively low humidity, evaporation from the buds causes the temperature of the bud to be reduced. As a consequence the dormancy period will be prolonged, causing a later bud break and lowering the risk of spring frosts.

6.7.3 Under tree sprinklers

Under tree sprinklers have been tried as a means of frost protection. Generally heating benefits are small, the heating benefit relying on the calorific value of the water, which is considerably lower than the heating benefit from latent heat as water freezes (see section 6.7.1). However, unlike overhead sprinkler systems, there is no risk of shoot breakage caused by an accumulation of ice on the vines. Parsons *et al.* (1982) reported a 0.5 to 1.5 ^{o}C lift in temperature above the spray zone in Florida citrus orchards, however it should be noted that the temperature of the well water used in this experiment was 20 ^{o}C! John *et al.* (1986) reported little benefit with application rates of 4.3 mm h^{-1} in fruit orchards at Lincoln.

6.7.4 Artificial fogs

When the dew point is close to air temperature, fog can form. Water droplets 10 :m in diameter are most effective in reducing long wave radiation loss (Mee and Bartholic 1979). McGill (1984) described a man-made fog system to protect Californian orchards. The fog, which requires relatively little water, is produced using micro-sprays in a line across the upwind part of the orchard. Wind carries the fog across the orchard. Little water is deposited, minimising the potential for ice-load damage. Energy costs were minimal ($US 0.27 h^{-1}) compared to $US 0.80, 1.35 and 2.71 h^{-1} for direct heating, sprinklers and wind machines respectively. [Note: these values need to be recalculated for today's New Zealand conditions]. In the USA, fogs are seldom used because of potential liability by the operator in event of the fog causing accidents by drifting onto adjacent properties, in particular roads.

7.0 Resource management issues

It is beyond the scope of this report to consider in detail the impact of various protection systems on the wider environment. Suffice it to say that systems, which impact on areas outside the vineyard being treated, will need to be dealt with under the Resource Management Act. Frost protection systems, which produce noise (Wind machines, helicopters), smoke (frost pots) or require water resources (sprinkler systems) will need RMA approval.

8.0 Vineyard management after a frost episode

Assess cropping potential. The potential crop after an economically significant spring frost may be quite varied depending on cultivar, training system and location within the vineyard. Some cultivars will produce minimal crops from clusters on secondary shoots (arising from secondary buds, not laterals) while others can produce 30-40% of the crop from primaries. Growing conditions and crop load the previous season also influences this response. Another cultivar and training system related factor is the capacity to produce fruitful shoots from bud positions other than those on canes retained and counted at pruning. These fruitful "non-count" (Howell *et al.* 1987; Wolpert *et al.* 1983) shoots can also augment the crop. The approach best taken is to do a careful vineyard assessment and modify management programmes accordingly. The extent to which this secondary crop is useful to the grower will also depend on the expected time from the damage event to harvest. The more developed the vines at the time of the frost event, the shorter the time available to ripen any subsequent crop. On the other hand, the smaller crop might be expected to ripen and mature faster than an undamaged, full crop.

Preliminary experiments conducted after a frost event in Canterbury in 1998 indicated that removing all damaged material from vines 10-14 days after the event resulted in slightly higher yields of harvestable fruit in partially damaged vines. In severely damaged vines, removal of all shoots, except those around the head of the vine appeared to be the best option (Trought and Creasy 1999, unpublished data). However, this needs further investigation, as vines were not managed to select the best fruit. Likewise, studies need to include assessment of time to evaluate the cost:benefit responses.

If this crop is determined to be below levels acceptable for standard commercial practice there are several approaches that should be considered:

The first question that needs to be addressed is "Will the loss of crop create excessive shoot density during the on-going season with minimal crop?"

a) If no, then a standard programme of nutrition, water and pest control is suggested. Management options aimed at specific fruit concerns may be minimised, providing it does not result in a potential disease innoculum build up, which may lead to problems in the following season.
b) If the answer is yes, then several options to minimise excess growth should be considered. If the fertilisation programme is based on split application, especially of nitrogen, consider reducing or eliminating additional applications. Control of water also offers a means to reduce excessive vigour, but care should be taken to make sure vines are not severely stressed. Finally, as biodiversity is being encouraged in vineyards to support an increasing range of beneficial organisms, such encouragement in a frost year could be doubly advantageous as a competition for soil nutrients and water. The goal here is to reduce costs without putting next season's crops at risk.

9 Economic Factors in Frost Protection

The cost and return of any business operation finally determines the profitability of the enterprise. Whether or not some means of frost protection is needed requires a careful evaluation of the probability of a frost occurring on any particular day, the potential benefit and cost of preventing that event from occurring. Before investing in a frost protection system, growers need to be sure that it will meet there needs, in particular:

- Will it provide the level of protection necessary in an event, which is likely to occur? Are frosts likely to advective or radiative? A risk analysis is needed, unfortunately the better the protection from the system, the more expensive it is likely to be.
- Is it reliable? There is no point in investing in a system, which fails when it is most needed.

There are of course non-economic considerations, and these will depend on the individual. Investing in a wind machine may be considered worthwhile when compared to the stress of uncertainty and sleepless nights. ***Before any investment is made however, investigate the options carefully, it may be an unpalatable fact, but the best investment may be to pull up and walk away, rather than pour more money in an uncertain venture.***

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