Improving Sprinkler Frost Protection In New Zealand Vineyards

Summary Report from 2004-7 Data

Prepared for:
Hawke's Bay Grape Growers Assn (Inc) and other Stakeholders

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This work has been commissioned at the request of interested parties after the unsatisfactory results from our frost protection methods (more specifically sprinkler applied water), during several frost events in the spring of 2003. These parties include winegrowers (both grape growers and winemakers), Hawke's Bay Grape Growers Assn, irrigation design and installation companies through Hawkes Bay Irrigation Services and irrigation hardware supply companies through NaanDan and Deeco.

Through the HBGGA, the group applied for funding assistance, from both the Sustainable Farming Fund (SFF) and from industry suppliers and contractors, and with this support, has set up a major trial in Hawkes Bay, with the objective of evaluating numerous generic sprinkler types and configurations, with a view towards providing reliable guidelines for sprinkler frost protection installations. As the trial has proceeded, the team has included several aspects of the installation and operation that are important to providing optimal protection given the inevitable constraints of an existing installation, the site, available water or the prevailing conditions.

Data were collected during the winter and spring of 2004, and reported in Report No LTE02129/1, "Improving Sprinkler Frost Protection In New Zealand Vineyards, Summary Report from 2004 Data". This report includes the original information and findings, subsequent data for additional configurations, and findings from the Hawkes Bay and other trials established to test and/or verify other concepts.

Project Team

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1 SUMMARY

The key question that was asked from this trial was how the monitored sprinkler configurations performed for frost protection. We conclude that the configurations provide protection as summarised in Table 1.

Table 1 Summary of protected areas for specified sprinkler configurations.

Sprinkler	**Pressure (kPa)**	**Spacing (m)**	**Est. rate (mm/hr)**	**Protection (ºC/mm/hr)**	**Protection (ºC)**
SMamkad yellow	250	13.2 x 9	3.8	0.9	3.5
SMamkad yellow	300	13.2 x 9	4.1	1	4
SMamkad yellow	350	13.2 x 9	4.5	1.1	5
501-U t'hammer	250	4.4 x 9	6.7	0.5	3.5
501-U t'hammer	300	4.4 x 9	7.4	0.6	4.5
501-U t'hammer	300, 3-3	4.4 x 9	3.7	0.5	2
501-U t'hammer	300, 2-2	4.4 x 9	3.7	0.7	2.5
Flipper, black , new	250	2.2 x 6	2.5	0.8	2
Flipper, violet	300	2.2 x 6	3.3	0.8	2.5
Flipper, black	250	2.2 x 7.2	2.5	1	2.5
Flipper, black, new	250	2.2 x 7.2	2.5	0.8	2
Flipper, violet	250	2.2 x 7.2	2.5	1.6	4
Flipper, violet	300	2.2 x 7.2	2.7	1.1	3
Flipper, brown	300	2.2 x 7.2	3.4	0.9	3
Flipper, violet	250	2.2 x 9	2	1.8	3.5
Flipper, violet	300	2.2 x 9	2.2	1.1	2.5
Flipper, brown	300	2.2 x 9	2.7	1.3	3.5

Mean application rate for comparison with full cover

Key results from Table 1 are the protection efficiency (ºC/mm/hr) and protection (ºC), where in each case higher values are better. The violet NaanDan Flipper (spaced at 7.2 metres and operated at 250 kPa provides the highest protection efficiency of 1.6 ºC/mm/hr for protection down to -4 ºC. The Super Mamkad at 350 kPa on a 13.2 by 9 metre grid provides the best protection, down to at least -5 ºC, but water use is higher.

We also draw attention to the influence of factors that can significantly compromise the performance of a sprinkler frost protection system, and are discussed in this report.

- Air movement which distorts sprinkler distribution patterns and hence alters application depth, especially mid-way between targeted sprinklers.
- Sprinkler alignment – affects targeted systems in a similar manner to air movement.
- Shading of buds and florets by ice-encased wires, buds and vines.
- Startup temperature is frequently incorrectly set, and as well as allowing frost damage if set too low, may also allow damage if too high, as well as unnecessary use of water.
- Freezing of irrigation laterals may occur at stagnation points, but only affects a small portion of a vineyard.

2 INTRODUCTION

2.1 Overview

This report covers the 2004 to 2007 seasons. During 2005, there were additional data collected but just added confirmation to the existing results from 2004. However during that year, additional side-trials were performed to address issues that arose from the trial itself and from workshops with growers. These additional trials continued through 2006 and 2007, and here we report on all these additional findings and the data from 2006 growing season with a new series of sprinkler configurations.

This report includes results and findings from the 2004 report, so may be used as a complete report, avoiding any necessity to refer to the 2004 report.

2.2 Objectives

The original intent of the project was detailed in the application by Hawkes Bay Grape Growers Assn. (Inc) to the Sustainable farming Fund (SFF); "Improving sprinkler frost protection in New Zealand vineyards". An extract outlining the essential elements is given below.

> "The intention of the project is to evaluate and quantify the performance of existing configurations of sprinkler frost protection systems to define bounding conditions for effective frost protection. This information will:
>
> - Provide a key set of performance data for identifying deficiencies in current installations
> - Allow tighter specifications on the performance of new installations
> - Identify local characteristics of different frost conditions
> - Provide better recommendations on trigger temperatures for starting frost protection
> - Enable savings in water use by optimising the use of low application rate systems and investigating pulsing.
> - Standardise a risk analysis procedure enabling growers and designers to make informed decisions trading-off likely damage rates against system cost and/or water use, and providing confidence in the frost protection system.
>
> Project phase 1 involves an extensive, on-going trial within a particular vineyard. A large trial block will include a control section, at least 15 sprinkler configurations, and a phenology/physiology block where vines will be unprotected from just one frost event. The trial will continue through winter (when frost protection is unnecessary) to provide data from a wider range of frosts than normally experienced during the critical growth stages. The physiological response of the vines to each treatment will be monitored using the assistance of the viticulture staff of the participating companies and any adjustments to the engineering of the project will be made accordingly. Trial outputs will be delivered to the industry through seminars, field days and articles in industry publications.
>
> Phase 2 of the project has the goal of transferring results directly to individual growers through analysis of their vineyard and frost protection system. The outcomes will include promotion of (currently non-existent) standardised temperature measurement and recording, sensor placement, and tailoring system parameters to individual sites for optimum frost management. Apart from the preparation of data sheets and check lists that can be used by individual growers, much of this grower-targeted knowledge transfer phase is expected to be funded directly from growers or regional grower associations."

This report marks the formal completion of the project for the SFF contract, but we hope to continue work, as sources of other funding allow, since a valuable trial site has been established, and has provided useful insights, findings and recommendations for installation and management of sprinkler frost protection systems.

2.3 Additional Findings

As noted above, as the trials proceeded and discussions with growers proceeded, new questions were raised and were added to the scope of the trial and the list of findings to be reported on. Many of these have already been reported in various media; seminars, workshops and industry journals, and are included here in the next section.

The additional findings, determined from further trials and research are:

- Freezing rate of laterals
- evaporative cooling
- frost prediction
- start-up and shut-down
- tissue temperature vs air temperature.

2.4 Background

Frost damage to crops has long plagued mankind's efforts to expand the range of crops grown for food or fibre. Some of the earliest accounts of frost protection go back as far as AD77, and it seems likely that the practise dates back even earlier than this. By the late 1800's, frost protection for horticultural crops (including grapes) was well established in Europe and in the USA.

In New Zealand, areas such as Central Otago regularly experience damaging frosts, and frost protection has been practised since the early 1930's. Some of the earliest reported New Zealand research into frost protection techniques was undertaken in Auckland vineyards in the late 1940's (Palmer, 1949).

Nearly all the horticulturally significant frosts in New Zealand are of the radiation type. Radiation frosts occur on nights with clear skies and little or no wind. As heat is radiated away from the surface of vegetation (or other objects) the surface cools and draws heat from the plant material and the surrounding air. If suitable conditions remain long enough, the temperature of the object falls to a point where irreversible damage takes place to the plant tissue. For grapes, the most sensitive period for frost damage is at the point where the new buds and florets are emerging in the early spring. Damage to these buds occurs if temperatures fall to zero and substantially reduces the subsequent flower set and hence directly influences the subsequent crop. Losses of up 30% in total yield due to frost damage are not uncommon.

A wide range of methods is presently used to protect horticultural crops against frost damage. These can be loosely grouped into three main methods which are summarised as follows.

Directly heating the orchard area. This may be achieved by burners fuelled by oil, natural gas, LPG or by special solid fuel blocks or candles made from wax, compressed wood-waste or other similar materials. Orchard heaters are probably one of the oldest form of frost protection ever used. Their use in NZ is presently restricted to relatively small areas because of the relatively high fuel costs and the large labour input required to operate the system. Fully automatic systems are in use in some parts of the world but the high capital cost of such systems has so far precluded their use in New Zealand.

The second general class of protection methods utilises the inverted temperature gradient that exists under radiation frost conditions (the type experienced in spring in New Zealand). Under these conditions, the air temperature rises with increasing height above the ground up to a limiting height, which is dependent largely on topography and the climate of the area concerned. In many horticulturally important areas of New Zealand the temperature 15 metres above the ground is often three to four degrees warmer than the temperature one and half metres above the ground. By mixing this warmer air from above the orchard with the lower air, the overall temperature within the fruiting area can be increased sufficiently to provide protection against damage.

Two methods are commonly used to perform the required mixing operation - wind machines and helicopters. A wind machine is essentially a large fan (with a horizontal axis) which rotates around the top of a 10 metre high tower located in the centre of the area to be protected. The ‘jet’ of air produced by the fan entrains the warm air above the orchard and mixes this into the colder air closer to the ground. The area protected is circular in shape although this can be significantly distorted by even low wind speeds. Other problems include high noise levels (which can cause problems with neighbouring properties) and the dependence of a strong enough inversion to allow significant warming to be achieved. Flying a heavily laden helicopter at relatively slow speed across the orchard area can achieve a similar effect. By flying in a pre-determined pattern of closely spaced tracks, areas of almost any shape can be protected. However, this method is also relatively noisy, requires considerable forward planning to ensure availability of machines and pilots, and is similarly dependent on the presence of a sufficiently developed inversion condition. Despite these problems, the last decade has seen widespread use of both of these methods in various parts of New Zealand.

The third, and probably most common method utilises the heat released when water changes state from a liquid to a solid. By spraying water at the correct rate onto a crop under frost conditions, a layer of ice slowly develops over the plants. Provided the surface of this ice layer is kept wet, the temperature of the enclosed plant tissue will generally be greater than minus half a degree, even though the surrounding air may be at a much lower temperature. The method requires a continuous supply of water (typically 3 to 4 mm/hr) all of which ultimately ends up on the ground. Unless good drainage is available, the potential for water-logging the soil with subsequent plant health problems is high. Although high levels of reliable protection can be obtained, the use of this method is largely confined to those areas where adequate water is available, and soils are free draining.

3 EXPERIMENTAL DETAILS

3.1 Overview

The key aspect of the project is real-time monitoring of temperature and other frost-related weather parameters over an extensive trial site on the Keruru block at the Sileni vineyard, using a number of frost protection sprinkler types and layouts. Analysis of the data along with real-time collection of sprinkler distribution patterns and hence application rate distribution is intended to enable relationships to be formed between in-vineyard conditions, real application rates, and the prevailing conditions. A second phase of the project is concerned with technology transfer: ensuring that the knowledge gained is effectively relayed in useable form to vineyard managers. Hence the indicators of success will be:

- Identify the conditions under which each frost protection treatment fails
- Provide solutions to rectify or alleviate the failure
- Provide new frost protection design criteria, and which may be related to prevailing conditions and quantitative measures of risk
- Transfer knowledge to vineyard managers through analysis of individual vineyards and recommend changes to frost protection systems and/or management.
- Provide recommendations for on-vineyard monitoring that enable consistent, inter-vineyard comparison of frost conditions and performance of frost protection systems (ie future-proofing).

3.2 Measurements

There are a number of useful measurements for characterising frost conditions, but when assessing frost for damage to plant tissue, it is most appropriate to measure the exposed temperature of the plant tissue itself, or an object that has similar radiative and convective characteristics to the plant tissue. Since most damage to NZ grapevines arises during spring when buds are swelling or bursting, or florets are exposed, a temperature sensor several millimetres in diameter has been shown (eg Hamer, 1980) to replicate bud or florets quite well. Under frost conditions, the temperature of a bud will typically be 1 or 2 degrees lower than air (screen) temperature, depending predominantly on wind speed (Trought et. al., 1999).

For these reasons, the trial block measurements were made using artificial buds, comprising precision thermistors moulded to form 8 mm diameter plastic cylinders (Figure 3).

3.3 Trial design

The trial was conducted on the Sileni vineyard Kereru block around 20km West of Hastings (
Figure 1), and covering rows 136 to 177 of Block A.

Figure 1 Location of trial site in Kereru Rd, near Maraekakah, Hawkes Bay.

The concept of the trial was to employ two weather stations, one stationary and one which could be moved around the trial block if required. The weather stations (
Figure 2) comprised screened (air temperature) and exposed temperature sensors at the standard meteorological height of 1.2 m, and at 0.9m above the canopy (ie at 2m). Wind speed and direction were also measured at approximately 2m, and weather station 1 monitored relative humidity (RH) and line pressure.

Figure 2 The weather stations comprised a mast for measurements of air temperature, exposed temperature, wind speed and wind direction at two metres, and air temperature, exposed temperature and relative humidity at 1.2 metres (standard meteorological screen height).

Nine in-vineyard stations were used to monitor the effectiveness of different sprinkler frost protection configurations, and could be easily moved throughout the trial block. They comprised a weatherproof box containing the data logger, power supply and connector for data retrieval. The box was fixed to a semi-flexible 5m boom with temperature sensors at 65 cm spacing, and which could be secured along the canopy. The height of these sensors was typically 0.8 m. The data collection equipment also included a sprinkler distribution measurement station comprising eight collecting funnels (0.5 by 0.5 m) complete with stands (2 groups of four in a row) which could be positioned alongside the canopy to monitor application rate distribution. The system provided a time resolution of 2 minutes and sensitivity of 0.02 mm (ie equivalent to 0.6 mm/hr). Further details of the data logging systems are provided in Appendix A.

Figure 3 In-vineyard bud temperature sensor with label referring to sensor number and distance from data logger (and hence sprinkler) of 4.7m

3.4 Trial Layout for 2004/5

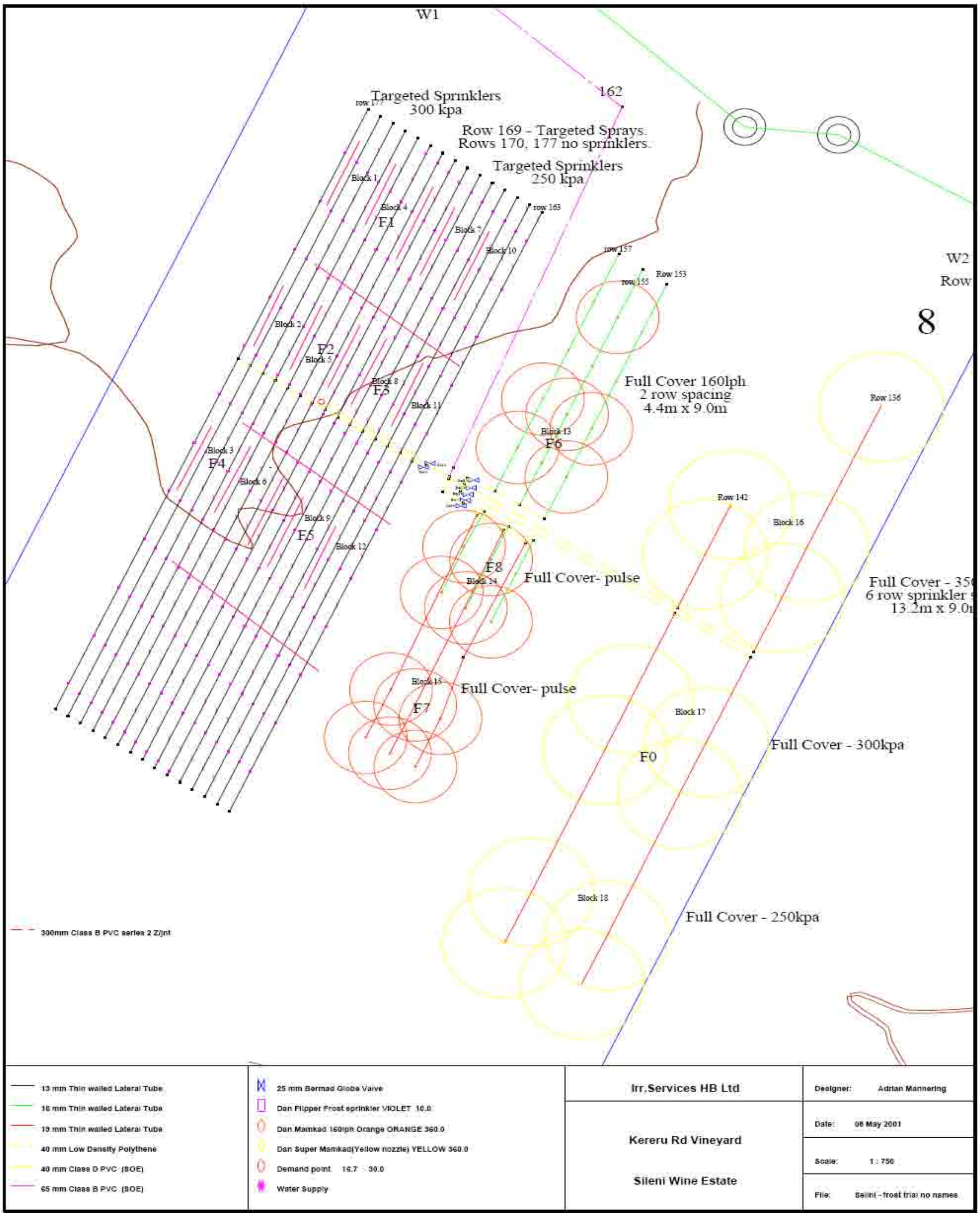


Figure 4 Layout of trial block showing trial sprinklers, and data loggers (F0..F9).

3.5 Changes for 2006/7 Season

On August 7th 2006, the configuration was changed from that reported in the 2004 report. The changes were:

The two pulse turbo hammer blocks (14,15) at three min on three min off have been replaced with one turbo hammer block (15) at two min on two min off and a super ten block (14) running at the same times.
New sways that were installed in all the targeted flipper blocks
Logger F0 moved into block 17
Loggers F1 and F2 were moved to blocks 4 and 5; 43 l/hr @ 300kpa and 7.2m @ 9.0m.
Logger F3 remained in block 8
Logger F4 relocated to block 3.
Logger F5 was moved to block 9 for the 25 l/hr @ 250kpa and 7.2m @ 6.0m
Logger F6 remained in block 13 and pressure was reduced from 300kpa to 250kpa
Logger F7 remained in the turbo hammer block
Logger F8 was moved from block 16 to go into the newly created pulsed super tens in block 14.

Logger #	**Row #**
1	172
2	172
3	167
4	175
5	167
6	155
7	155
8	155
0	139

Tipper array is now located at Lawn Rd and operated manually. Flipper is new style flipper 35 lph @ 300kpa.

4 ANALYSIS PROCEDURE

4.1 Data Records

This trial has generated very large data sets. Programs were written to automatically generate plots based on selectable criteria, and to automatically generate data summaries and time-based plots. Although these tools eased the analysis burden, there remained a significant task of manual assessment and interpretation.

A key aspect was to establish criteria for judging the performance of the frost protections systems. In past studies we have utilised chosen damage thresholds, but in this industry-wide study, it is important that all stakeholders are able to apply their own damage criteria when assessing the performance of a particular configuration. For this reason, we elected to report on performance at four levels.

- Provide an assessment of each sprinkler configuration as satisfactory or not, and under what circumstances the configuration failed
- Provide graphical and tabular data supporting the assessment and enabling readers to make their own assessments
- Enable access to time-at-temperature results, since actual damage is dependent on variety, development stage, air speed, humidity, etc. We envisage these data would be used for detailed comparisons based on crop sensitivity
- Unprocessed data with sufficient detail for others to analyse in different ways.

Data at levels three and four are not provided in this report, but available from Lincoln Ventures Ltd. A small handling charge may apply.

Sileni Vineyard has allowed the project full access and discretion over the trial plot, operation of the frost protection trial continued through the winters, providing a broader range of frosts than would otherwise be the case. One example of a temperature record for a winter frost event and one sprinkler configuration (NaanDan Mamkad full cover) is shown in Figure 5. Although the frost is more severe than the usual damaging spring frosts, the recordings provide the means to compare different configurations and determine under what conditions, the system fails.

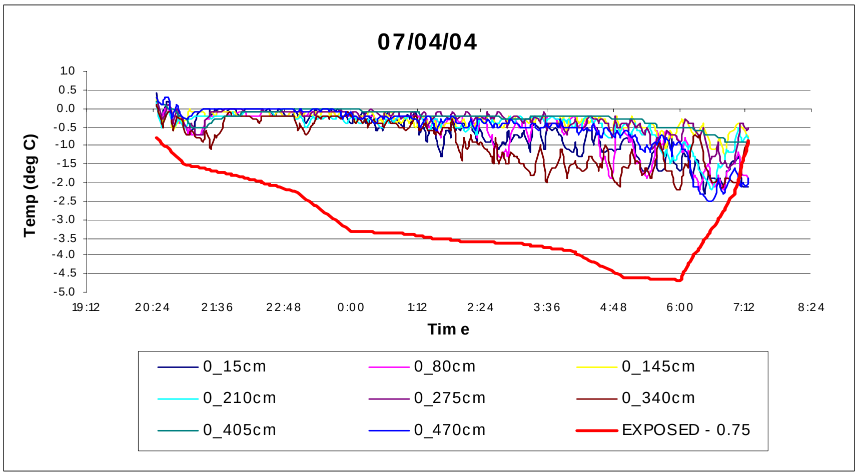


Figure 5 Example trace of artificial bud temperatures in Sileni vineyard on the night of the 4 July 2004 protected by a NaanDan Super Mamkad sprinkler operating at 300 kPa

4.2 Desired Output

From previous trials conducted by project team members, it was apparent that the rate of change of temperature of temperature sensors resembling grape buds in shape, size and colour, was quite rapid, even when heavily loaded with ice such as shown in Figure 6. Clearly, the rate of change of temperature of the bud can be quite high (eg the sudden drop in the second ice-encased sensor at around 0630).

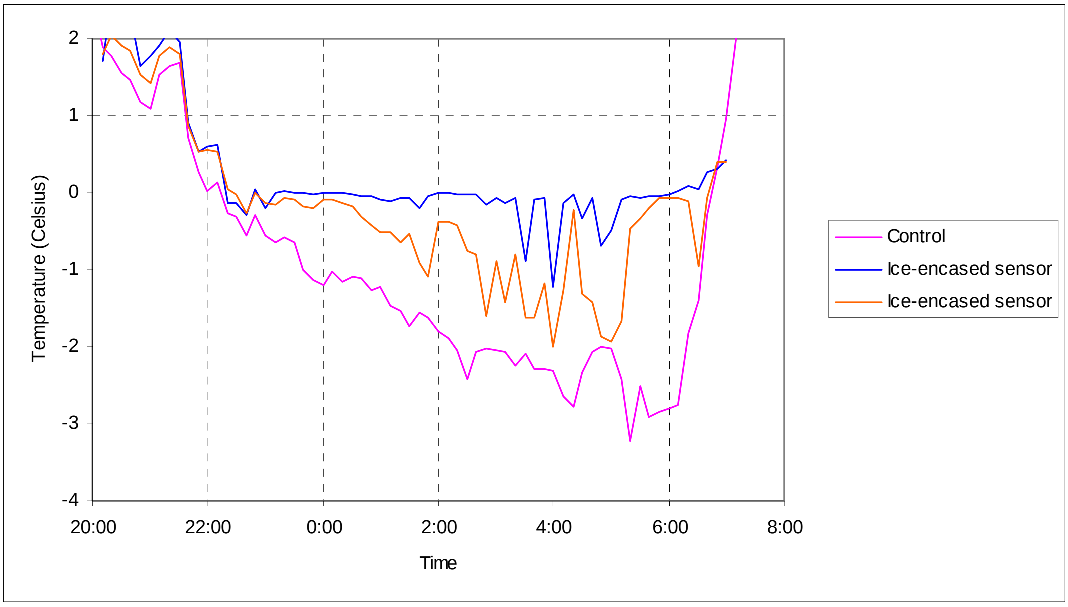


Figure 6 Plot of iced-covered sensor showing dynamic response

Given that the bud temperature may change quickly, a question remains about the rate of freezing of plant tissue. From Rajashekar (1989), it is apparent (e.g. Fig 1 of that paper) that ice nucleation at -2.5 °C causes immediate freezing, and that lowering temperature at 4 °C/hr results in a gradual increase in the quantity of ice inside the bud. Although not explicitly stated, it implies that there is little thermal lag at the 4 °C/hr freezing rate. Hence we assume from the implied precision of Fig 1 of

Rajashekar (1989) that a freezing rate of 4 ºC/hr causes an error or temperature skew, of less than 1ºC. This leads to the conclusion that the bud will always have reached the temperature of its surroundings and internal freezing will have stabilized, within 60 minutes of a step change in temperature. Hence, in formulating tabular data to enable independent assessment of the performance of different sprinkler configurations according to the frost sensitivity of different cultivars and at different developmental stages, we have elected to calculate time-at-temperature data within the time intervals defined as: 0-2, 2-4, 4-6, 6-8, 8-10, 10-14, 14-20 and >20 minutes.

Decisions were also required on how the data could be most usefully presented to provide the essential information about use of sprinklers and their failure modes. The main variables are listed in Table 2, with column two indicating whether the parameter was sufficiently influential to warrant its inclusion in charts or tables.

Table 2 Frost protection variables

Variable/parameter	Include?	Comment
Air temperature	No	Screen temperature, barely relevant
Exposed temperature	Yes	The control, unprotected bud temperature
Protected temperature	Yes	The crucial protected bud temperature
Time	Yes	Time at temperature is crucial
Wind speed and direction	Yes	A variable influence
Height	No	Sensors at one height, influences shading
Distance from nearest sprinkler	Yes	An axis on the plots
Distance from next sprinkler	Yes	May be inferred from sprinkler spacing
Shading	Yes/no	Not included in summary plots. Shading will change as vines grow.
Sprinkler type	No	Separate data plots for sprinkler type
Sprinkler flow rate	No	Separate data plots for sprinkler flow rate
Sprinkler spacing	No	Separate data plots for sprinkler spacing

5 REFERENCE DATA

A crucial aspect of the trial is measurement of the effectiveness of frost protection systems and configurations. As described earlier, the measurements of exposed temperatures in the form of artificial buds, which represent the temperature of the vine buds, were referenced to the exposed temperature at two control sites, outside the treatment area. For the 2004 season, the two weather stations providing the reference temperatures and other parameters were located towards the north of the trial block, near the river gully.

The dominant wind direction during frost conditions was in the easterly quarter, down the river valley, and there was little correlation with frost severity (Figure 7).

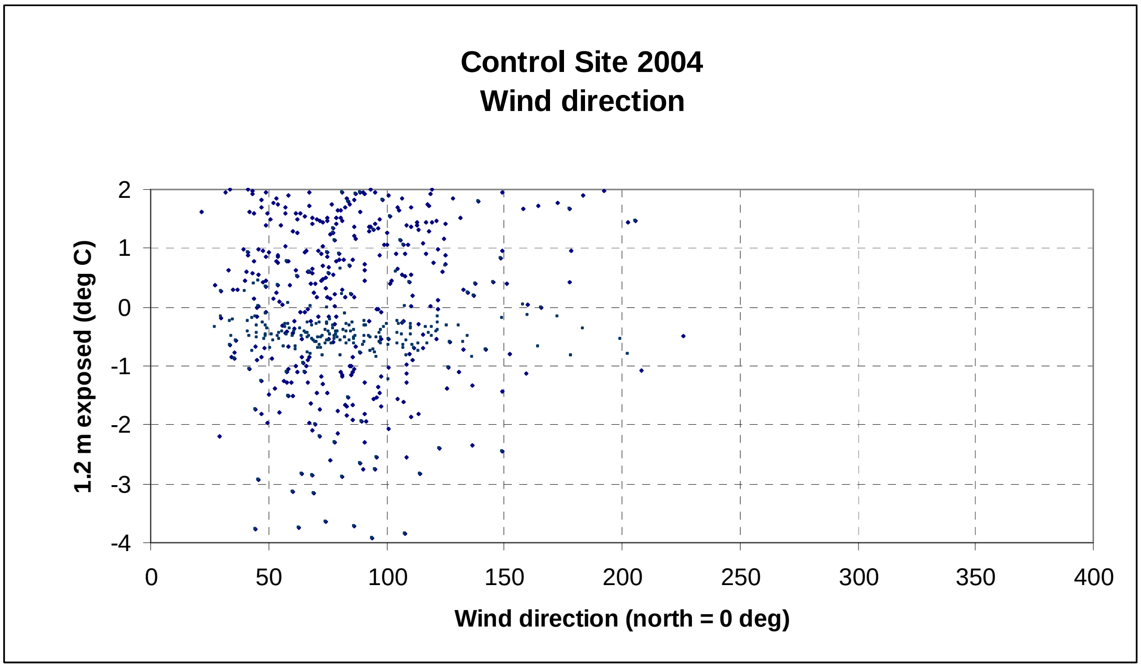


Figure 7 Dominant wind direction during frost conditions – uses 1.2m exposed temperature.

On two occasions, the pump/distribution system failed and hence provided the opportunity to examine the differences in temperature between the exposed temperatures at the control sites and those within the rows.

First, plots comparing site 1 with sites 0, 2, 7 and 8 (and Appendix C) demonstrate that there is no consistent difference in the exposed temperatures (at 77 cm above ground level) over the trial block. The differences at 2.7 ºC and 4.3 ºC were almost certainly due to early morning sun reaching the sensor at site 1 before site 0. The manually inserted line of best fit for the data (excluding the anomalous readings) has a slope very close to 1 indicating that the sites do experience very similar conditions. The comparison between sites 1 and 0 also reveals little consistent difference at two opposite corners of the trial block, although there is more scatter than between adjacent sites 1 and 2. The scatter was distributed throughout the recorded periods, indicating that it was most likely due to air movement, and was certainly of a short-term nature. Hence, we may conclude that without frost protection, there is no substantive difference in frost conditions over the trial block.

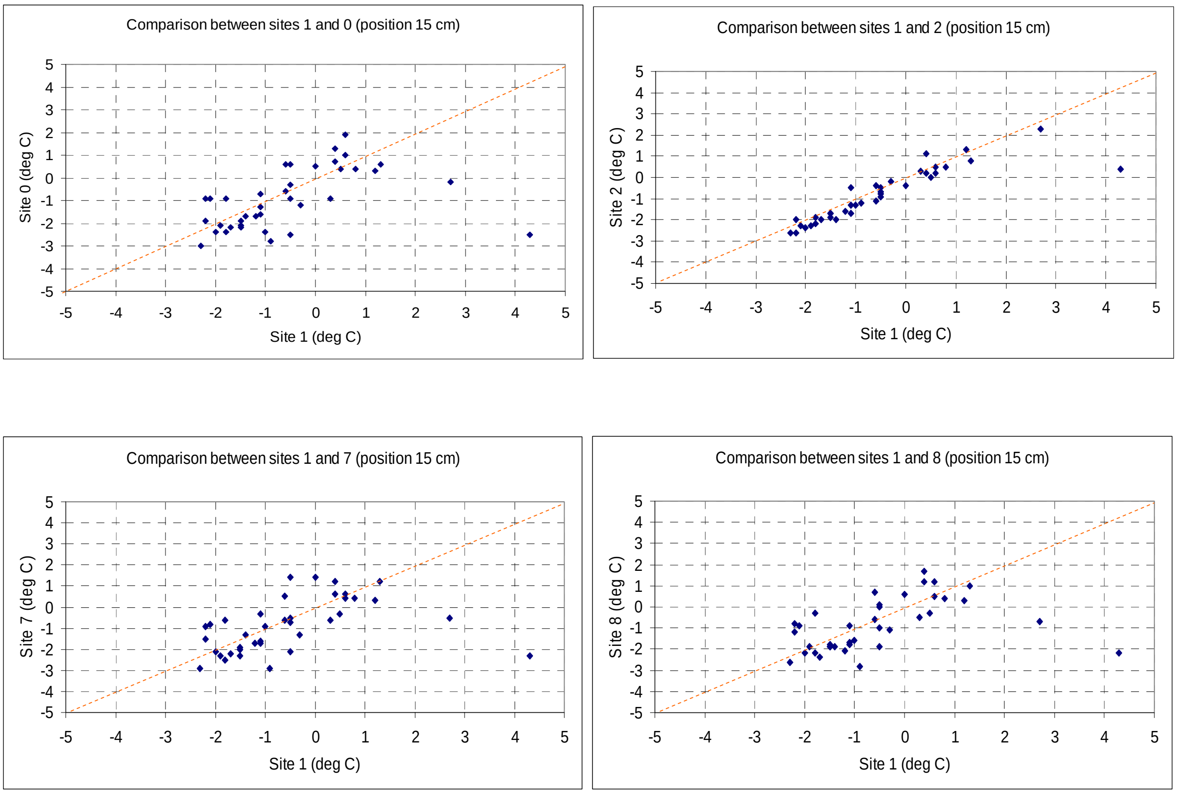


Figure 8 Differences between the 77 cm exposed vine temperatures at sites 1 and 0,2,7 and 8 without frost protection..

Turning now to a comparison of the control sites with the trial block, Figure 9 shows the differences between the mean of the 1.2 m exposed temperatures at the two control sites with the site 2 temperatures. The line through the data is an estimate of the real difference between the sites, and indicates that the mean of the 1.2 m exposed temperatures at each of the two control sites is between half and one Celsius degree warmer than site 2. Figure 9 is very similar to the control site comparisons for all other sites in the trial block, indicating that the control sites are consistently warmer than the trial block by 0.5 to 1 ºC. We attribute this to two factors: the vineyard sensors are approximately 0.8 m above ground level compared with the meteorological standard of 1.2m for the control site, and the proximity of the river gully and lack of canopy around the control site sensors allows greater airflow and hence warming of the exposed temperature sensors. The former factor is quite small, averaging approximately 0.2 ºC over the entire season, as determined by the difference between the 1.2 and 2 m exposed temperatures at the control sites.

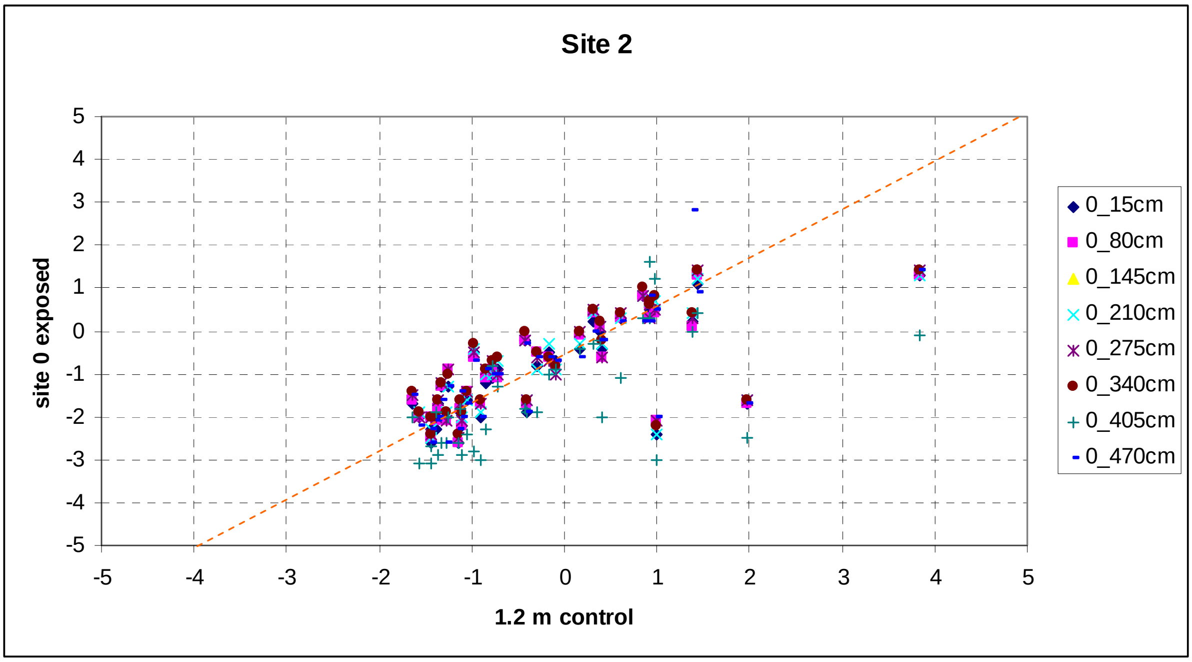


Figure 9 Comparison between the mean exposed temperature at the control sites and within the rows at site 0. The fitted line indicates the estimated difference between the sites (refer text).

6 SPRINKLER PERFORMANCE RESULTS

The results from each sprinkler configuration described below includes both a plot and tabular values of the mean level of protection. The data use corrected control temperatures consisting of the measured exposed 1.2m control temperature less 0.75 ºC for reasons discussed in §5. The percentage protection is calculated as follows:

$$P(\%) = \frac{\sum_{n} 100(t_c - t_p - 1)}{n.t_c}$$

where t_c is the corrected control temperature, n is the number of events and t_p is the protected temperature in the vineyard. The 1 ºC offset is used to define 100% protection when t_p is at -1 ºC, and only data where t_c was cooler than -1 ºC were included. In summary, the percentage protection is a measure of the effectiveness of frost protection, 100% when at or above -1 ºC, and 0% when at the exposed control (unprotected) temperature.

Tabular values of the time that protected sensors were at a particular temperature, expressed as a percentage of the time the unprotected sensor was at or below that temperature have also been prepared. These data are in Appendix A.

In Section **7**, the results are discussed and conclusions drawn about the performance of each sprinkler configuration.

Combining all results has provided a fairly complete set of frost performance data from a range of sprinklers, so we have grouped them in the following order:

1. Full-cover ball drive
2. Full cover turbohammer sprinkler
3. Targeted (flipper) sprinklers.

Within each type they were grouped by increasing span (targeted), then flow, then pressure.

Note that during the 2006/7 recording season, colder events were recorded so that the tables extend to -6 ºC. To highlight this difference and reduce the likelihood of mis-comparison, the additional data rows have been shaded light blue, but <u>all</u> graphs in this section are plotted from -1ºC down to -5ºC.

6.1 Full cover, Ball Drive

6.1.1 250 kPa at 13.2 by 9m (2006,7)

The full cover NaanDan Super Mamkad 445 sprinklers with yellow nozzle sprinklers at 250 kPa and spaced on a 13.2 by 9m grid were sited in block 18, and data recorded on data logger 0.

Table 3. Values of mean level of protection (%) provided by NaanDan Super Mamkad 445 sprinklers with yellow nozzle spaced on a 13.2 by 9m grid at 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	99	99	99	100	100	100	100	99
-1.5 to -2	98	100	98	100	100	100	100	99
-2 to -2.5	97	98	91	100	100	100	98	97
-2.5 to -3	93	94	78	98	98	99	96	94
-3 to -3.5	82	86	60	91	89	94	90	90
-3.5 to -4	79	81	58	85	85	91	87	89
-4 to -4.5	63	73	51	77	78	79	79	76
-4.5 to -5	57	64	47	68	74	69	67	63
-5 to -5.5	57	64	48	68	73	69	68	65
-5.5 to -6	57	58	51	66	69	74	71	75

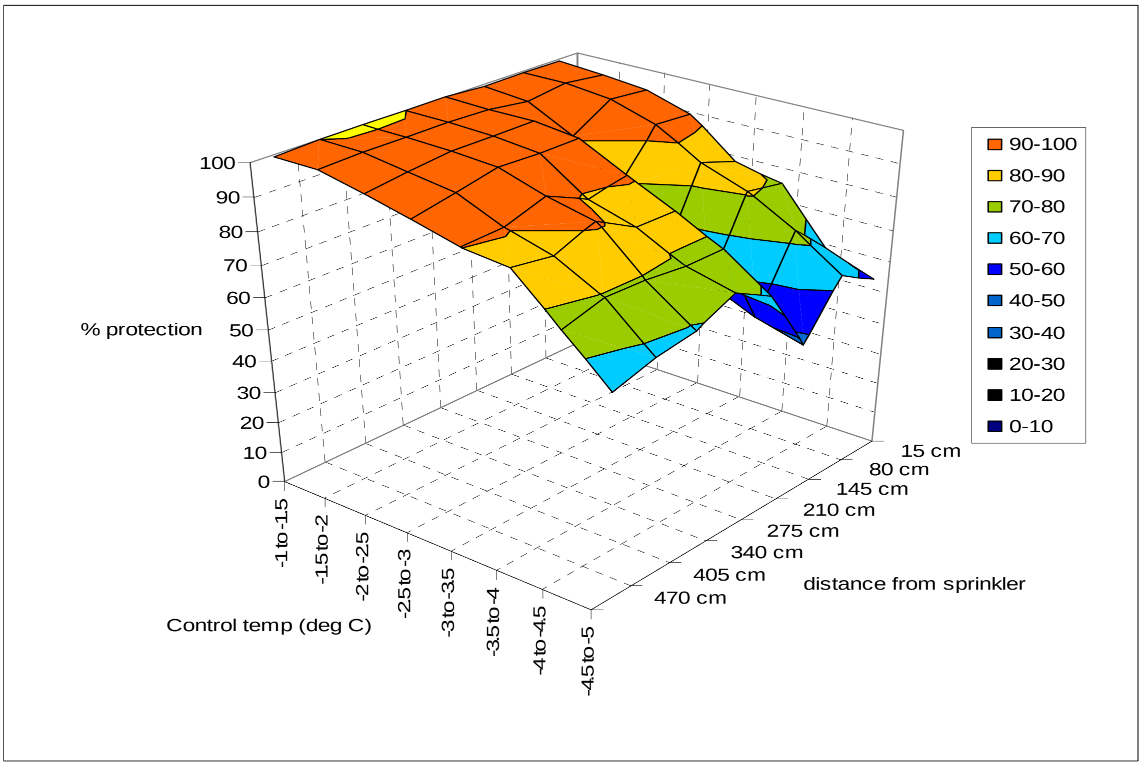


Figure 10. Mean level of protection (%) provided by NaanDan Super Mamkad 445 sprinklers with yellow nozzle spaced on a 13.2 by 9m grid and at 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.1.2 Full Cover, 300 kPa at 13.2 by 9 m (2004,5)

The full cover NaanDan Super Mamkad 445 sprinklers with yellow nozzle sprinklers at 300 kPa and spaced on a 13.2 by 9m grid were sited in block 17, and data recorded on data logger 0.

Table 4. Values of mean level of protection (%) provided by NaanDan Super Mamkad 445 sprinklers with yellow nozzle spaced on a 13.2 by 9m grid at 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (ºC)	**53 cm**	**118 cm**	**183 cm**	**248 cm**	**313 cm**	**378 cm**	**443 cm**	**508 cm**
-1 to -1.5	99	100	99	99	99	100	100	100
-1.5 to -2	99	100	100	99	100	99	99	99
-2 to -2.5	95	99	97	97	96	95	95	97
-2.5 to -3	99	99	99	99	99	99	99	99
-3 to -3.5	86	84	89	88	91	91	88	86
-3.5 to -4	86	89	100	97	100	100	99	89
-4 to -4.5	79	75	84	92	98	92	88	75
-4.5 to -5	76	70	74	86	78	83	76	66

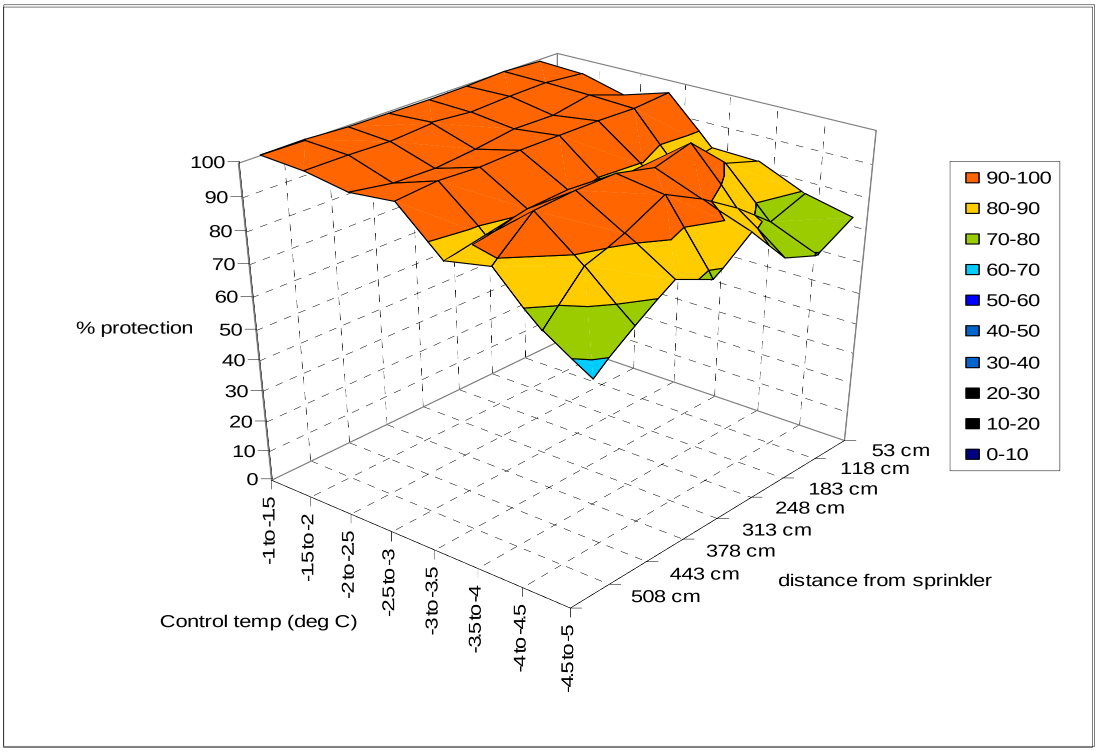


Figure 11. Mean level of protection (%) provided by NaanDan Super Mamkad 445 sprinklers with yellow nozzle spaced on a 13.2 by 9m grid and at 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.1.3 Full Cover, 350 kPa on 13.2 by 9 m grid (2004,5)

The full cover NaanDan Super Mamkad 445 sprinklers with yellow nozzle sprinklers located on a 13.2 by 9 m grid and operated at 350 kPa were sited in block 16, and data recorded on data logger 8.

Table 5. Values of mean level of protection (%) provided by NaanDan Super Mamkad sprinklers with yellow 445 nozzle sprinklers spaced on a 13.2 by 9 m grid and operating at 350 kPa. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	99	99	99	99	99	100	98	100
-1.5 to -2	98	98	98	98	97	98	98	89
-2 to -2.5	88	92	95	93	89	90	92	85
-2.5 to -3	99	99	99	99	99	97	100	98
-3 to -3.5	96	95	97	97	98	93	100	93
-3.5 to -4	97	100	100	100	100	96	100	100
-4 to -4.5	96	98	100	100	100	86	100	100
-4.5 to -5	94	96	100	94	100	75	100	88

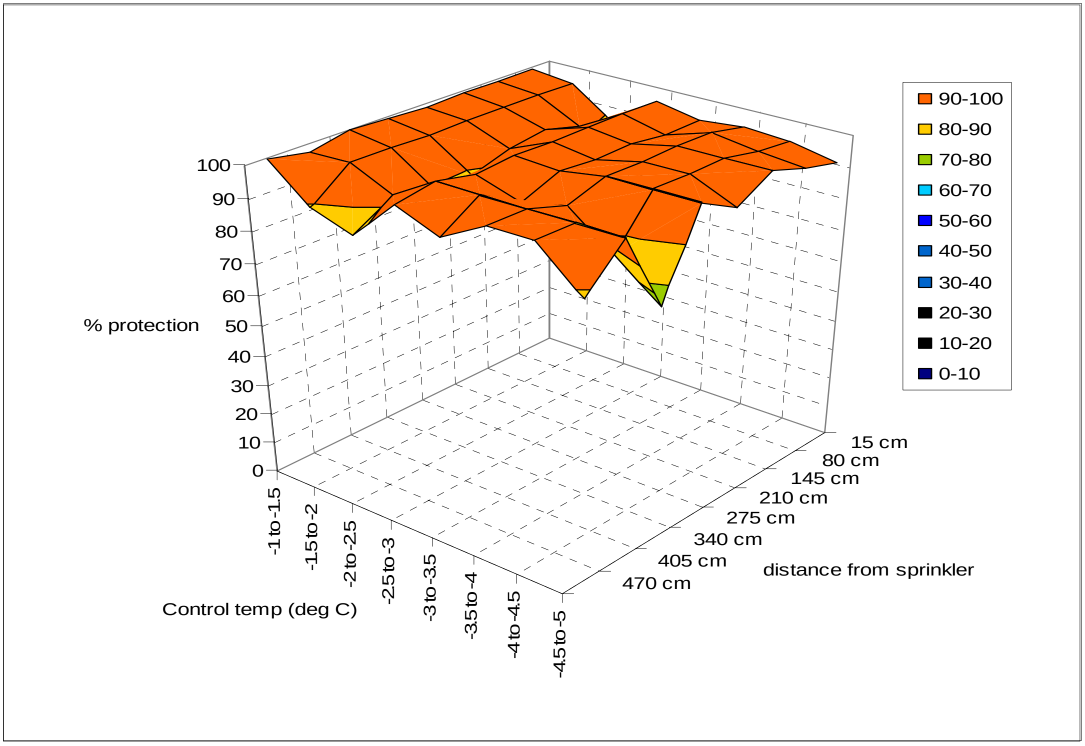


Figure 12. Values of mean level of protection (%) provided by NaanDan Super Mamkad sprinklers with yellow 445 nozzle sprinklers spaced on a 4.4 by 9 m grid and operating at 300 kPa. Data analysis uses corrected control temperatures (see text).

6.2 Full Cover, Turbohammer

6.2.1 250 kPa on 4.4 by 9 m grid (2006,7)

The full cover NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles located on a 4.4 by 9 m grid and operating at 250 kPa were sited in block 14, and data recorded on data logger 6.

Table 6. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at 250 kPa. Data analysis uses corrected control temperatures (see text). Data in red are interpolated due to defective sensor.

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	100	99	100	99	100	99	99	99
-1.5 to -2	99	99	99	99	99	99	99	99
-2 to -2.5	99	99	99	100	100	100	100	100
-2.5 to -3	96	96	95	100	100	99	100	100
-3 to -3.5	86	84	81	99	98	95	100	100
-3.5 to -4	79	75	70	97	93	91	100	100
-4 to -4.5	72	67	62	91	79	83	99	98
-4.5 to -5	63	59	55	87	71	74	96	96
-5 to -5.5	63	59	56	86	71	74	96	96
-5.5 to -6	65	61	57	89	70	78	99	99

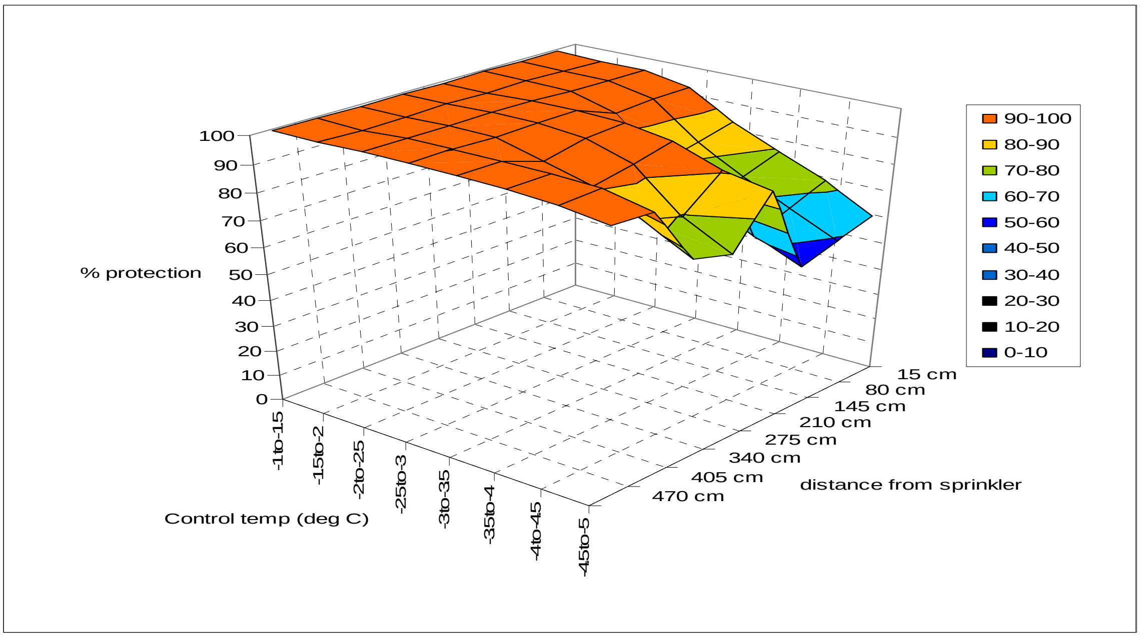


Figure 13. Mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at 250 kPa. Data analysis uses corrected control temperatures (see text).

6.2.2 Full Cover, 160 l/hr 300 kPa on 4.4 by 9 m grid (2004,5)

The full cover NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles located on a 4.4 by 9 m grid and operating at 300 kPa were sited in block 13, and data recorded on data logger 6.

Table 7. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at a line pressure of 300 kPa. Data analysis uses corrected control temperatures (see text). Data in red are interpolated due to defective sensor.

Control temp (°C)	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	100	100	100	100	100	100	100	100
-1.5 to -2	100	100	100	100	100	100	100	100
-2 to -2.5	95	95	96	95	96	97	96	95
-2.5 to -3	95	99	99	98	98	99	97	95
-3 to -3.5	91	94	94	94	94	97	92	87
-3.5 to -4	95	97	97	100	100	98	93	88
-4 to -4.5	83	90	100	94	96	91	84	78
-4.5 to -5	73	88	81	87	79	86	78	70

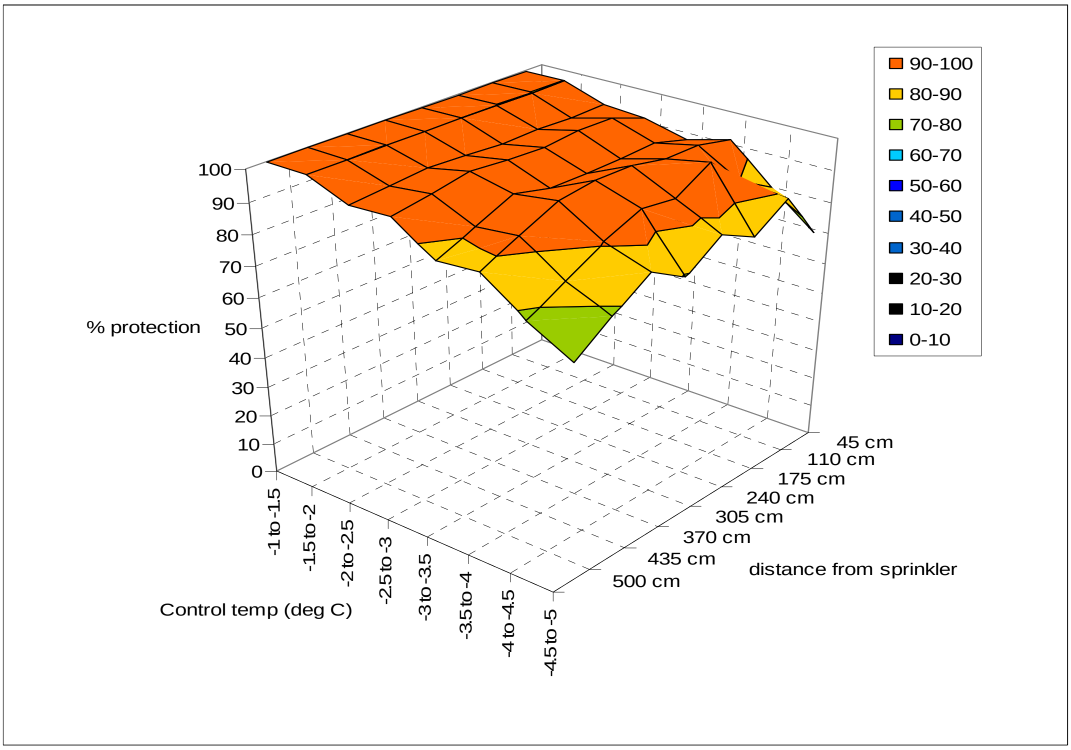


Figure 14. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at a line pressure of 300 kPa. Data analysis uses corrected control temperatures (see text).

6.2.3 Full Cover, Pulsed 300 kPa on 4.4 by 9 m grid (2004,5)

The full cover NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles located on a 4.4 by 9 m grid and pulsed at 300 kPa were sited in block 14, and data recorded on data logger 7.

Table 8. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and pulsed at 300 kPa. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	99	99	99	100	98	98	99	100
-1.5 to -2	90	89	91	91	93	91	100	94
-2 to -2.5	80	75	79	79	82	81	91	82
-2.5 to -3	72	64	72	76	87	84	93	85
-3 to -3.5	68	61	68	68	77	76	87	84
-3.5 to -4	73	63	69	73	79	77	96	86
-4 to -4.5	72	66	69	80	72	74	93	70
-4.5 to -5	59	54	56	67	62	64	85	55

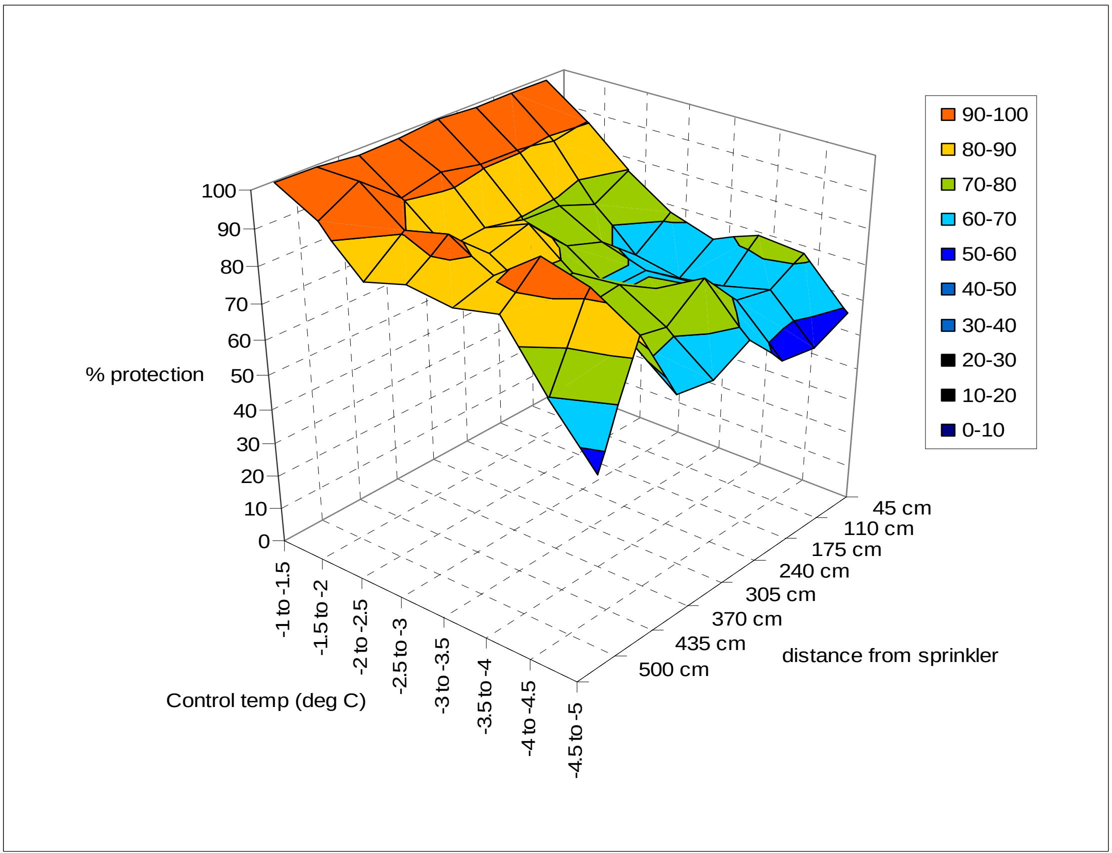


Figure 15. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at 300 kPa. Data analysis uses corrected control temperatures (see text).

6.2.4 Full Cover, Pulsed 300 kPa on 4.4 by 9 m grid (2006,7)

The full cover NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles located on a 4.4 by 9 m grid and pulsed (2 min on, 2 min off) at 300 kPa were sited in block 14, and data recorded on data logger 7.

Table 9. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and pulsed (2:2) at 300 kPa. Data analysis uses corrected control temperatures (see text).

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	100	99	99	99	99	100	99	98
-1.5 to -2	100	99	97	97	98	97	97	98
-2 to -2.5	99	99	85	91	96	87	92	94
-2.5 to -3	97	97	70	83	90	72	84	87
-3 to -3.5	86	91	53	66	76	56	64	71
-3.5 to -4	78	87	47	60	69	49	58	63
-4 to -4.5	71	86	60	58	58	44	50	53
-4.5 to -5	85	95	100	87	47	35	33	30
-5 to -5.5	91	99	100	86	42	35	33	30
-5.5 to -6	100	100	100	84	36	38	36	31

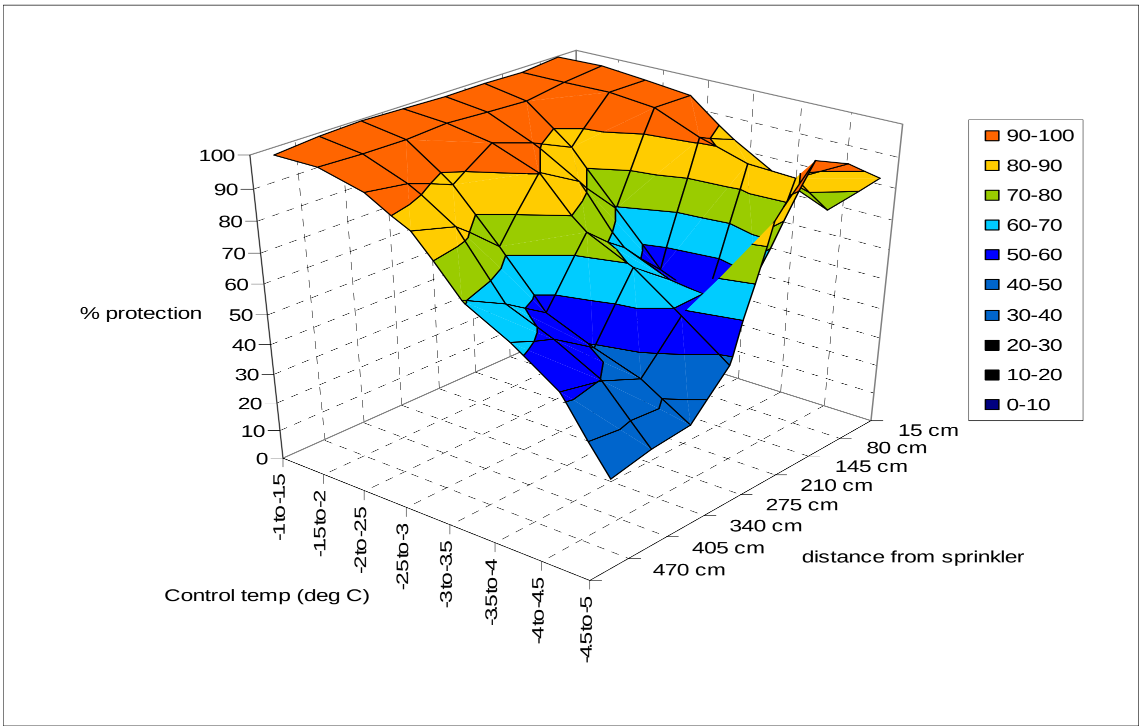


Figure 16. mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and pulsed (2:2) at 300 kPa. Data analysis uses corrected control temperatures (see text).

6.3 Targeted (Flipper) Sprinklers

6.3.1 Targeted, 25 l/hr 250 kPa at 6 m, new sway (2006,7)

The targeted NaanDan Flipper with black 25 l/hr nozzles spaced at 6 m and operating at 250 kPa were sited in block 8, and data recorded on data logger 5.

Table 10. Values of mean level of protection (%) provided by NaanDan Flipper with black 25 l/hr nozzles spaced at 6 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	95	100	99	98	99	99	98	99
-1.5 to -2	89	100	95	97	95	95	96	98
-2 to -2.5	85	98	78	81	75	79	81	89
-2.5 to -3	75	97	65	68	60	67	65	80
-3 to -3.5	65	88	50	54	47	51	48	66
-3.5 to -4	52	77	44	51	40	44	41	66
-4 to -4.5	43	69	40	49	38	41	42	66
-4.5 to -5	33	57	35	39	33	36	33	46
-5 to -5.5	37	58	37	44	35	38	36	45
-5.5 to -6	40	61	41	44	39	42	48	49

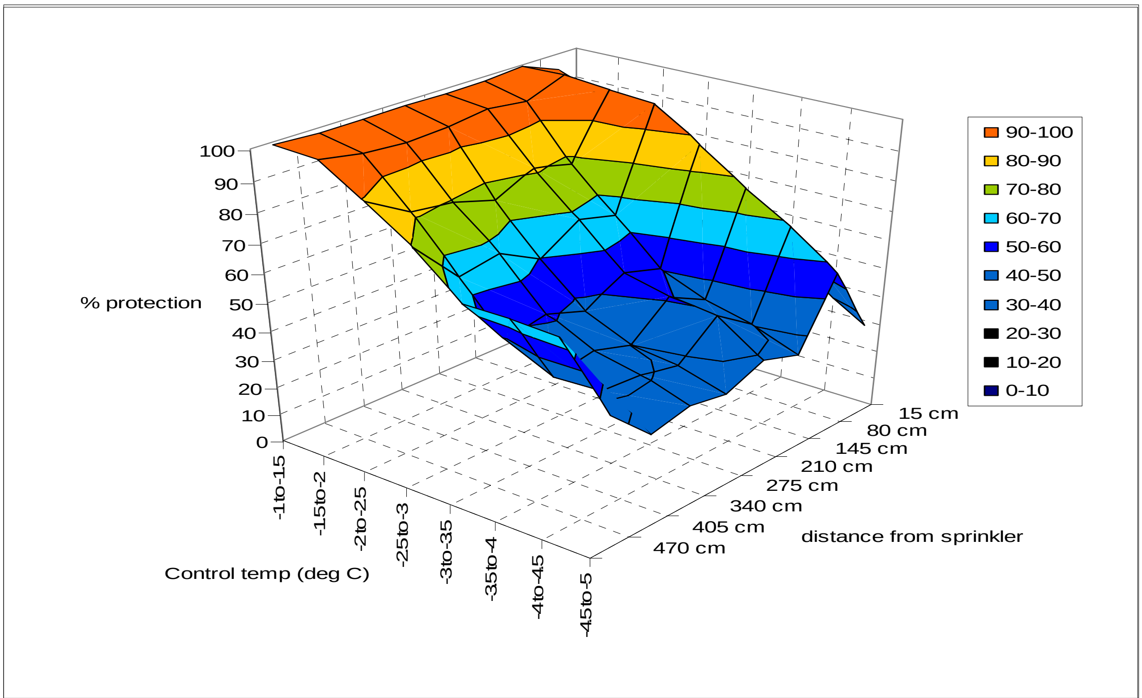


Figure 17. Mean level of protection (%) provided by NaanDan Flipper with black 25 l/hr nozzles spaced at 6m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text)

6.3.2 Targetted, 35 l/hr 300 kPa at 6 m (2006,7)

The targeted NaanDan Flipper with violet 35 l/hr nozzles spaced at 6 m and operating at 300 kPa were sited in block 3, and data recorded on data logger 4.

Table 11. Values of mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 6m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	99	98	98	98	99	100	99	99
-1.5 to -2	97	96	94	93	97	99	97	96
-2 to -2.5	90	86	85	85	90	90	88	85
-2.5 to -3	82	70	68	79	79	84	78	69
-3 to -3.5	69	55	50	73	75	82	72	55
-3.5 to -4	62	50	42	66	69	79	63	46
-4 to -4.5	55	46	39	64	59	70	53	41
-4.5 to -5	41	35	33	45	31	43	34	31
-5 to -5.5	42	36	34	48	38	51	38	33
-5.5 to -6	45	40	36	49	46	64	41	38

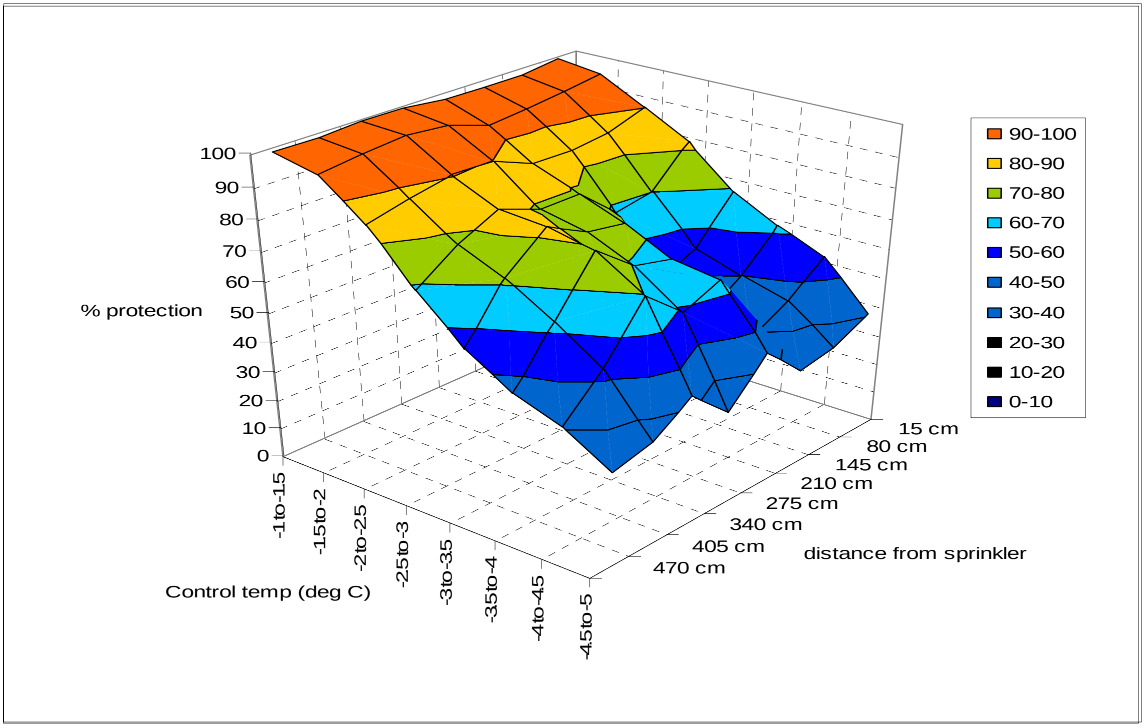


Figure 18. Mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 6m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.3.3 Targeted, 25 l/hr 250 kPa at 7.2 m (2004,5)

The targeted NaanDan Flipper with black 25 l/hr nozzles spaced at 7.2 m and operating at 250 kPa were sited in block 8, and data recorded on data logger 3.

Table 12. Values of mean level of protection (%) provided by NaanDan Flipper with black 25 l/hr nozzles spaced at 7.2 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (ºC)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	99	98	99	100	99	99	99	98
-1.5 to -2	95	94	95	97	94	96	98	95
-2 to -2.5	87	85	82	88	84	85	86	82
-2.5 to -3	80	74	69	88	85	90	94	78
-3 to -3.5	79	70	68	93	93	88	83	73
-3.5 to -4	80	63	59	93	100	93	86	74
-4 to -4.5	79	65	61	79	100	88	75	70
-4.5 to -5	72	55	52	80	100	87	75	65

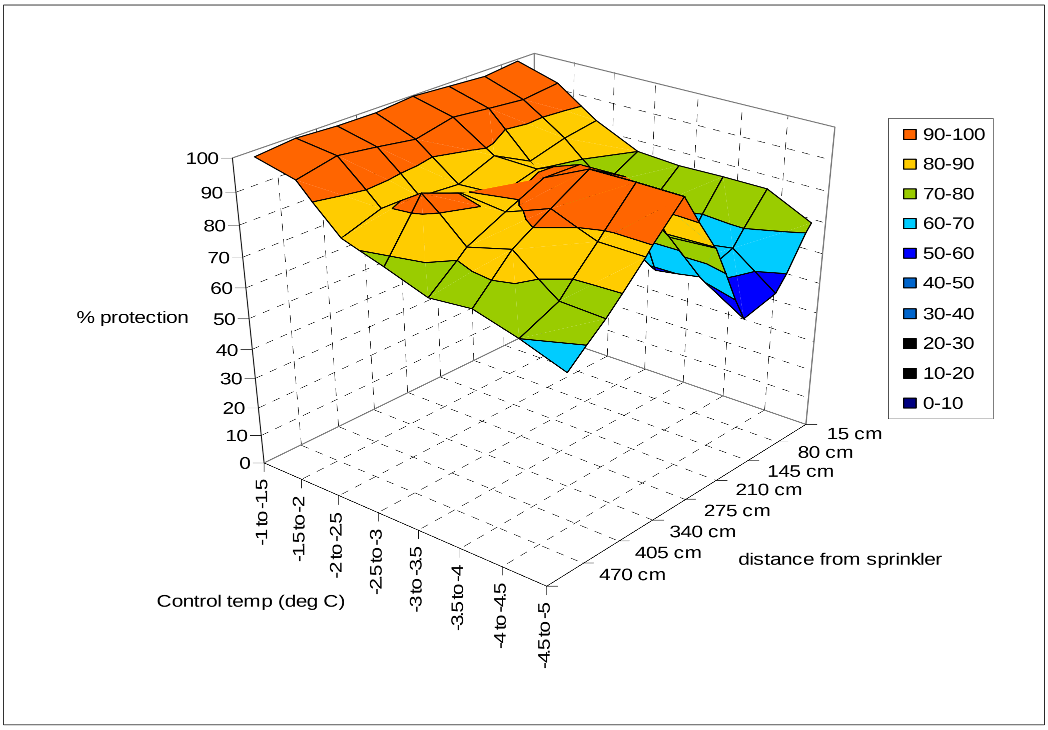


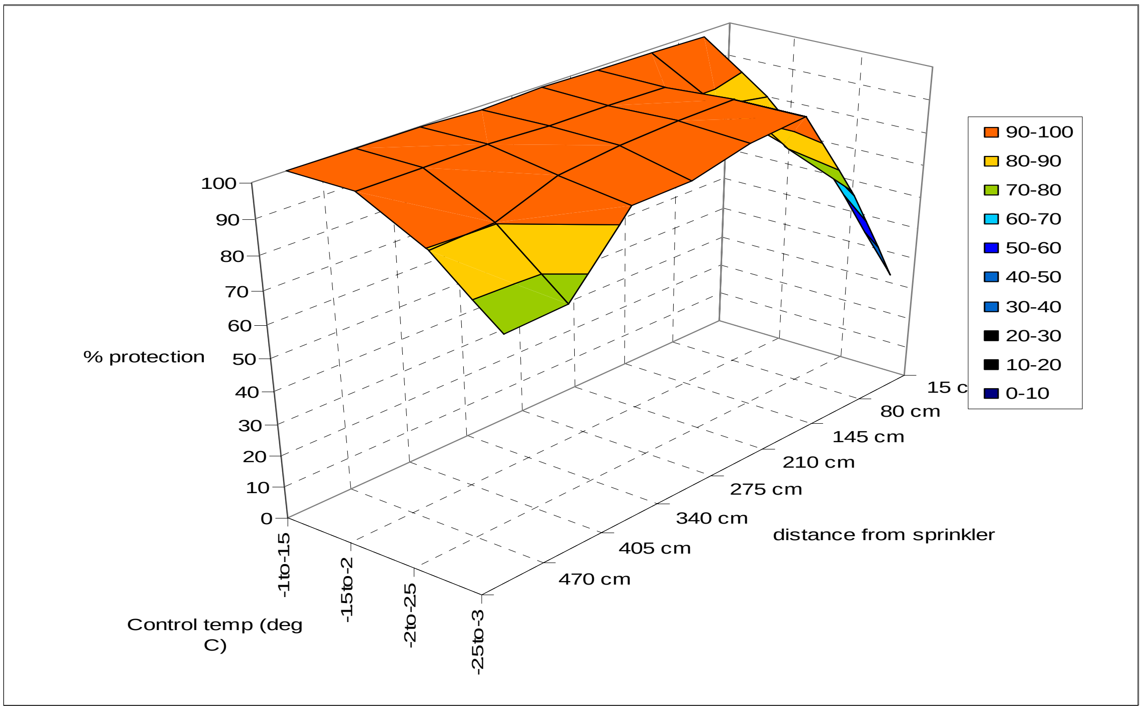
Figure 19. Mean level of protection (%) provided by NaanDan Flipper with black 25 l/hr nozzles spaced at 7.2m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text)

6.3.4 Targeted, 25 l/hr 250 kPa at 7.2 m, new sway (2006,7)

The targeted NaanDan Flipper with black 25 l/hr nozzles spaced at 7.2 m and operating at 250 kPa were sited in block 8, and data recorded on data logger 3.

Table 13. Values of mean level of protection (%) provided by NaanDan Flipper with black 25 l/hr nozzles spaced at 7.2 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	98	98	99	99	98	100	100	100
-1.5 to -2	85	88	99	99	99	100	100	100
-2 to -2.5	66	81	100	100	99	97	90	90
-2.5 to -3	38	72	100	98	94	94	74	73
-3 to -3.5								
-3.5 to -4								
-4 to -4.5				No data for this sprinkler at low temperatures				
-4.5 to -5								
-5 to -5.5								
-5.5 to -6								



(Missing data at low temperatures)

Figure 20. Mean level of protection (%) provided by NaanDan Flipper with black 25 l/hr nozzles spaced at 7.2m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text)

6.3.5 Targeted, 35 l/hr 250 kPa at 7.2 m (2004,5)

The targeted NaanDan Flipper with violet 35 l/hr nozzles spaced at 7.2 m and operating at 250 kPa were sited in block 11, and data recorded on data logger 4.

Table 14. Values of mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 7.2 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	100	100	100	100	100	100	100	100
-1.5 to -2	99	100	100	99	100	99	98	99
-2 to -2.5	94	95	93	94	96	92	94	98
-2.5 to -3	93	92	94	98	100	94	100	95
-3 to -3.5	86	89	89	92	100	95	92	86
-3.5 to -4	80	90	84	100	100	99	100	84
-4 to -4.5	75	75	90	96	100	97	100	75
-4.5 to -5	62	70	65	77	100	88	100	63

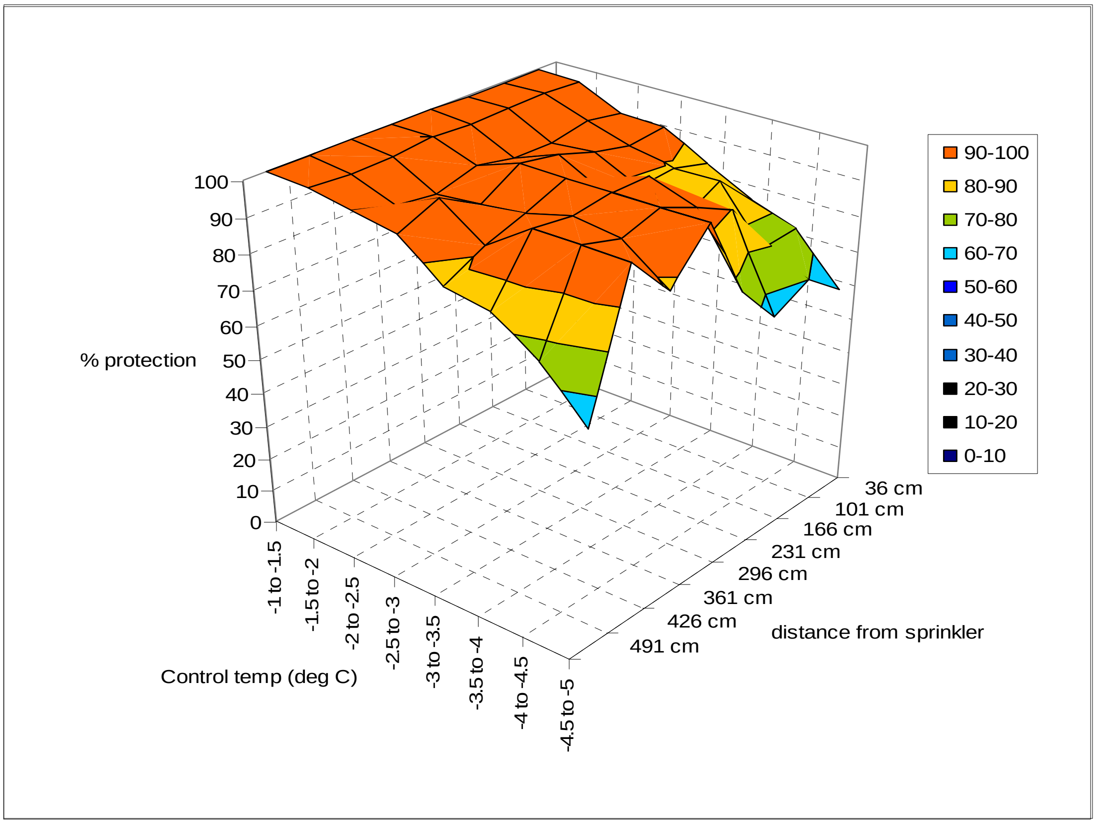


Figure 21. Mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 7.2m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.3.6 Targeted, 35 l/hr 300 kPa at 7.2 m (2004,5)

The targeted NaanDan Flipper with violet 35 l/hr nozzles spaced at 7.2 m and operating at 300 kPa were sited in block 2, and data recorded on data logger 2.

Table 15. Values of mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 7.2m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	99	100	100	100	100	100	100	99
-1.5 to -2	98	99	100	100	100	98	98	98
-2 to -2.5	93	95	97	96	96	89	95	89
-2.5 to -3	93	98	97	96	93	82	97	86
-3 to -3.5	94	91	91	97	93	78	91	75
-3.5 to -4	97	99	99	98	93	74	86	86
-4 to -4.5	92	96	99	100	82	63	88	57
-4.5 to -5	85	85	86	87	75	66	87	57

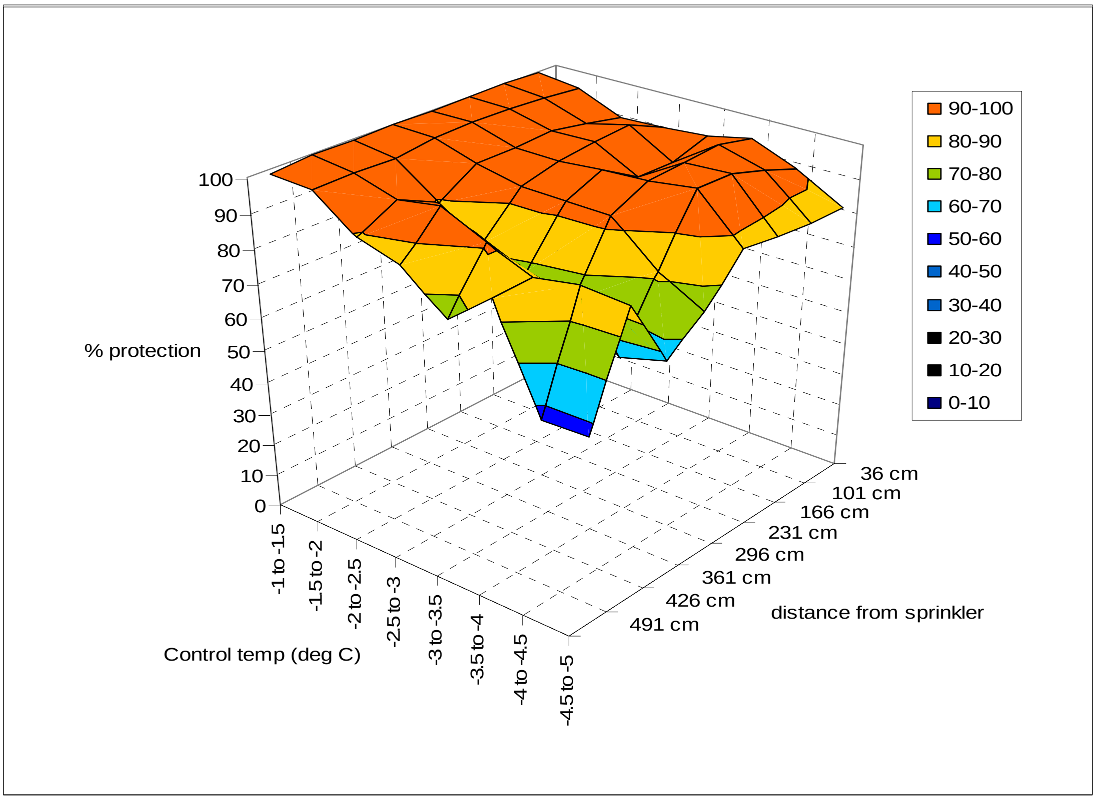


Figure 22. Mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 7.2m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.3.7 Targeted, 43 l/hr 300 kPa at 7.2 m (2006,7)

The targeted NaanDan Flipper with brown 43 l/hr nozzles spaced at 7.2 m and operating at 300 kPa were sited in block 4, and data recorded on data logger 1.

Table 16. Values of mean level of protection (%) provided by NaanDan Flipper with brown 43 l/hr nozzles spaced at 7.2 m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	98	98	99	99	99	99	98	98
-1.5 to -2	98	98	99	99	100	99	98	99
-2 to -2.5	96	94	97	96	98	95	91	94
-2.5 to -3	90	85	94	91	99	92	86	85
-3 to -3.5	64	69	92	83	100	93	85	73
-3.5 to -4	59	66	89	80	100	92	84	65
-4 to -4.5	48	59	82	72	100	90	81	61
-4.5 to -5	38	44	71	59	100	78	61	41
-5 to -5.5	39	44	72	57	98	74	55	42
-5.5 to -6	41	45	79	55	100	71	51	44

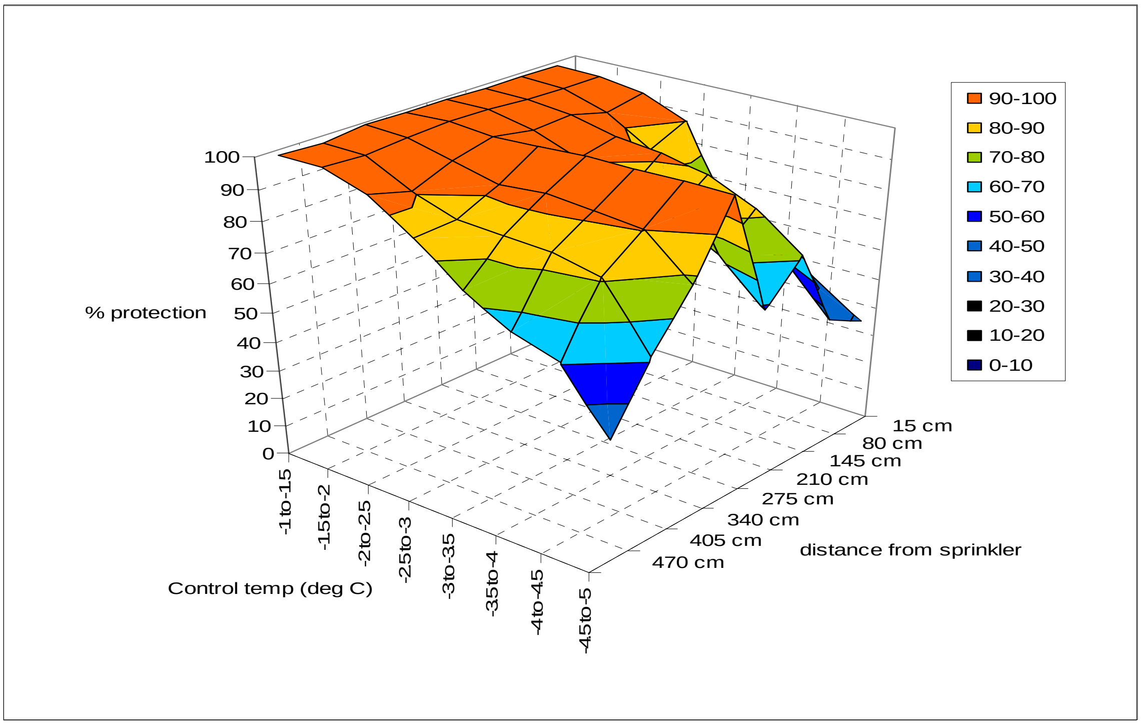


Figure 23. Mean level of protection (%) provided by NaanDan Flipper with brown 43 l/hr nozzles spaced at 7.2m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.3.8 Targeted, 35 l/hr 250 kPa at 9 m (2004,5)

The targeted NaanDan Flipper with violet 35 l/hr nozzles spaced at 9 m and operating at 250 kPa were sited in block 10, and data recorded on data logger 5.

Table 17. Values of mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 9 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	100	100	99	99	100	100	100	100
-1.5 to -2	100	100	99	98	99	99	98	100
-2 to -2.5	97	95	92	93	88	91	95	91
-2.5 to -3	96	91	88	86	82	88	95	90
-3 to -3.5	94	84	87	86	77	83	92	81
-3.5 to -4	90	79	72	73	71	82	87	77
-4 to -4.5	76	70	65	60	63	69	73	69
-4.5 to -5	84	66	74	68	55	61	70	62

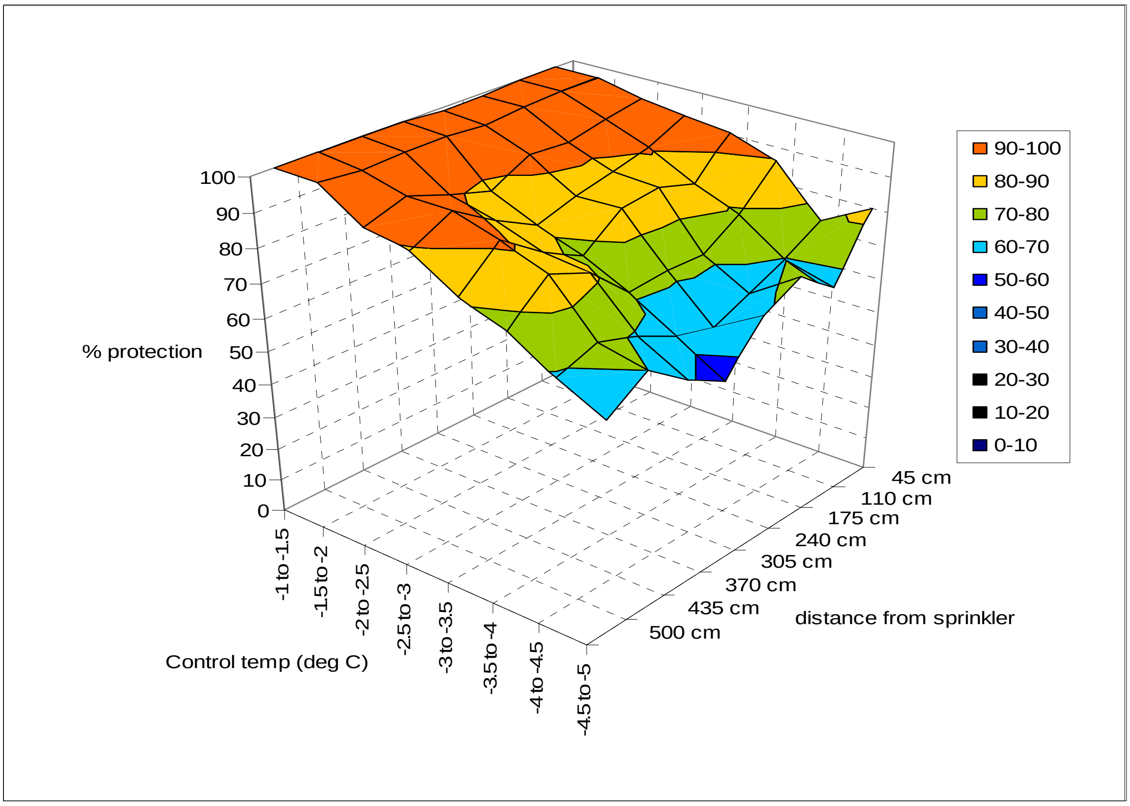


Figure 24. Mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 9m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.3.9 Targeted, 35 l/hr 300 kPa at 9 m (2004,5)

The targeted NaanDan Flipper with violet 35 l/hr nozzles spaced at 9m and operating at 300 kPa were sited in block 1, and data recorded on data logger 1.

Table 18. Values of mean level of protection (%) provided by NaanDan Flipper with violet 35 l/hr nozzles spaced at 9m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text). Data in red are interpolated due to defective sensor.

Control temp (ºC)	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	100	100	100	99	99	97	100	100
-1.5 to -2	97	96	95	96	90	90	95	98
-2 to -2.5	90	89	87	88	83	73	85	91
-2.5 to -3	81	77	73	73	66	64	75	84
-3 to -3.5	66	66	68	62	57	57	63	72
-3.5 to -4	63	57	57	58	56	60	63	66
-4 to -4.5	57	54	54	53	51	47	54	61
-4.5 to -5	57	51	50	54	46	45	51	56

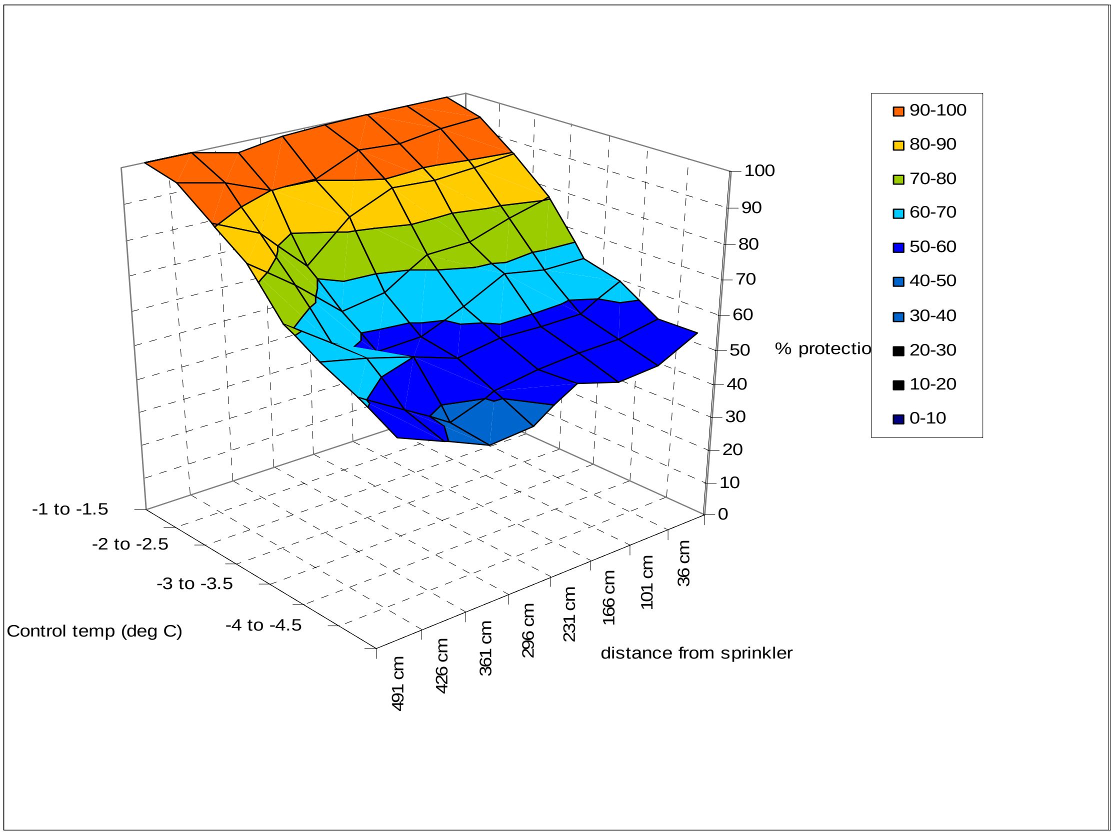


Figure 25. Mean level of protection (%) provided NaanDan Flipper with violet 35 l/hr nozzles spaced at 9m grid and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.3.10 Targeted, 43 l/hr 300 kPa at 9 m (2006,7)

The targeted NaanDan Flipper with brown 43 l/hr nozzles spaced at 9m and operating at 300 kPa were sited in block 5, and data recorded on data logger 2.

Table 19. Values of mean level of protection (%) provided by NaanDan Flipper with brown 43 l/hr nozzles spaced at 9m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp(°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	100	99	99	98	100	100	100	100
-1.5 to -2	95	98	99	95	100	99	100	100
-2 to -2.5	92	98	95	99	100	100	100	100
-2.5 to -3	86	96	94	98	100	100	99	99
-3 to -3.5	71	83	80	94	100	100	93	92
-3.5 to -4	72	71	73	90	99	99	85	86
-4 to -4.5	66	62	67	83	99	99	71	82
-4.5 to -5	50	45	48	63	96	90	58	60
-5 to -5.5	48	48	51	65	96	84	58	56
-5.5 to -6	48	48	53	73	100	86	60	59

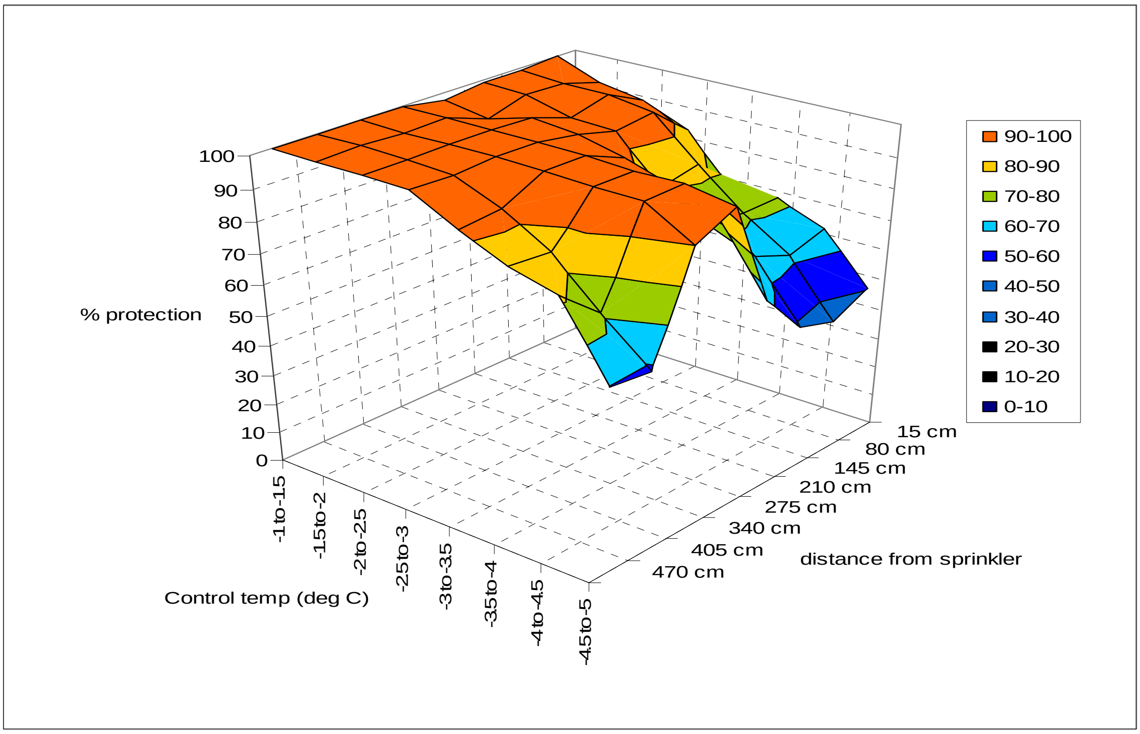


Figure 26. Mean level of protection (%) provided NaanDan Flipper with brown 43 l/hr nozzles spaced at 9m grid and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

7 DISCUSSION

To assist with comparison between different sprinkler types and configurations, estimates of the effective application depth and water use for each configuration is provided in Table 20. These data will be used below in discussing the merits and performance of each configuration.

Table 20 Configuration of sprinklers and their resultant water use and effective application depth.

Sprinkler	Pressure (kPa)	Spacing (m)	Flow rate (l/hr)	Cover/sprinkler m^2 (incl inter-row)	Rate, l/hr/m^2 (incl inter-row)	Est. rate (mm/hr)
SMamkad yellow	250	13.2 x 9	450	118.8	3.8	3.8
SMamkad yellow	300	13.2 x 9	490	118.8	4.1	4.1
SMamkad yellow	350	13.2 x 9	529	118.8	4.5	4.5
501-U t'hammer	250	4.4 x 9	178	26.4	6.7	6.7
501-U t'hammer	300	4.4 x 9	196	26.4	7.4	7.4
501-U t'hammer	300, 50%	4.4 x 9	98 (nom.)	26.4	3.7	3.7
Flipper, black , new	250	2.2 x 6	33 (est.)	13.2	2.5	10
Flipper, violet	300	2.2 x 6	43	13.2	3.3	13.2
Flipper, black	250	2.2 x 7.2	39	15.8	2.5	9.8
Flipper, black, new	250	2.2 x 7.2	39	15.8	2.5	9.8
Flipper, violet	250	2.2 x 7.2	39	15.8	2.5	9.8
Flipper, violet	300	2.2 x 7.2	43	15.8	2.7	10.8
Flipper, brown	300	2.2 x 7.2	53	15.8	3.4	13.6
Flipper, violet	250	2.2 x 9	39	19.8	2.0	7.8
Flipper, violet	300	2.2 x 9	43	19.8	2.2	8.6
Flipper, brown	300	2.2 x 9	53	19.8	2.7	10.8

Assumes one quarter of the row spacing is covered

In general, the expectation is that full cover sprinklers provide a more consistent protection pattern than targeted sprinklers because the overlap patterns provide several, typically 3 or 4 different directions from which water droplets are delivered to a particular bud or shoot. Further, many of these will approach from the side, from which there will generally be less obstruction from other shoots, cordons and support structures. Targeted sprinklers deliver water droplets from along the row so the opportunity for interception is higher and hence a more variable response is expected and was observed. Further, obstruction would be expected to increase over time as the ice burden on the intercepting components increases their size. Nevertheless, occlusion does occur with full cover sprinklers but our contention is that the frequency and spatial extent of the occlusions are smaller with full cover than with targeted sprinklers.

Given the above, a question that arises is, how are water savings best achieved? Although we discuss in §6 management practices that can limit the time for which the sprinklers are operated, at installation time is it better to choose targeted sprinklers or pulsed full-cover sprinklers to achieve reduced water use over full cover sprinklers? For the sprinklers tested here, we think the best approach depends on the likelihood of severe frosts:

Risk of a frost < -3ºC	Water savings required: Low	Water savings required: High
Low	Targeted	Targeted
High	Pulsed full cover	Targeted

Performance is not the only factor. Targeted systems employ considerably more sprinklers than full cover, and nozzle sizes are smaller. Consequently, maintenance (clearing nozzles blocked by insect entry etc) is generally higher, and more are likely to be damaged by pruning, leaf plucking and harvesting. On the other hand, targeted sprinklers keep the inter-row area dry and make navigating the vineyard easier whether by vehicle or on foot.

In preparing this report, we faced a slight quandary. The trial has been run beyond the usual frost protection season to provide data for severe frosts that fortunately occur only occasionally during the normal protection periods, and all these data are aggregated to provide a resultant graph of the extent of protection for a range of sprinkler configurations. In 2006 there was a particularly severe frost event (during dormancy) which means those configurations tested during the 2006/7 seasons were disadvantaged when compared with those during the 2004/5 seasons. These were all valid data and should be recorded; on the other hand the differences make direct comparisons invalid. We elected, according to sound experimental method, to report all data but draw attention to the care that will be required when comparing sprinkler configurations from different seasons.

As mentioned earlier, this report combines data from all trials to date and supercedes, to some extent, the 2004 report. In that report, a fairly rigid decision on protection was made; if a sprinkler fell below 80% protection at any sensor position, it was deemed to have failed, and this cut-off was used to state the extent of protection, e.g. to -3 ºC. In hindsight, this may have been a little harsh on targeted sprinklers since some isolated points of failure are expected and may not have a large impact on overall crop yield. Although the trial provided a large number of data points collected over time, there are just 8 sensors along a transect from each sprinkler. Had there been the luxury of a large number of sensors along each transect, a statistical method, as used for the temporal data, would be most appropriate. Instead we have elected to consider a sprinkler to be protecting the crop if:

1. At least seven of the eight sensors provide a mean level of protection greater than 80% AND
2. All sensors provide a mean level of protection greater than 60%.

However, this judgement is only applied to this discussion and thereby to the report summary. We encourage growers and designers to consider the results carefully and make their own judgement about the extent of protection.

7.1 Full Cover Ball Drive

These tests were conducted on the NaanDan Super Mamkad sprinklers with yellow 445 nozzles and tested at 250, 300 and 350 kPa on a 13.2 by 9 m rectangular grid. All configurations provide good protection down to -3.5 ºC, but protection rapidly decreased thereafter at 250 kPa. At 300 and 350 kPa, there were few instances where the protected exposed temperature fell below the protection level of -1 ºC, and 350 kPa pressure provided a little more protection at lower temperatures (
Figure 10 and **Figure 23**) than 300 kPa. Reference to Appendix C shows the orientation of the data logging booms with respect to the sprinkler patterns, and places the results in Sections **6.1.2** and **6.1.2** in context (the measurements are along a row between the sprinklers). Application from at least two and in some instances four sprinklers, means that water is applied to the vines from several directions, reducing the likelihood of interception by ice-laden spurs, branches or support wires, and this is supported by the quite uniform frost protection down to relatively low temperatures. Good protection (>80%) is obtained for temperatures down to about -3.5 ºC at 250 kPa, -4 ºC at 300 kPa and -5 at 350 kPa for an application depth of around 4 mm/hr, but since they are full cover sprinklers, the water use is also quite high at around 4 l/hr/m^2.

There is a lack of protection at 145 cm at 250 kPa and 53 cm at 300 kPa, and to some extent at 508 cm, and both are attributed to some shading. The 145 and 53 cm sensors in particular, were occluded from two sprinklers due to the angle of the sensor and partially due to the data logger box. The 340 cm sensor at 350 kPa is similarly partially occluded, causing poor protection at lower temperatures. These effects are typical of real conditions in vineyards where some buds get inadequate water and damage to those buds occurs. It is rather surprising that the small increase in water pressure and flow rate dramatically improves the performance of the Super Mamkad on a 13.2 by 9 m grid at low temperatures (below -4 ºC), but since the manufacturer's distribution pattern data is only available for one pressure, investigation into the likely reasons for this would require our own sprinkler tests. Nevertheless, performance of both configurations is sufficiently good that further investigation of the reasons for this is barely warranted.

In this configuration, the Super Mamkad sprinklers provided protection of approximately 0.9 ºC/mm/hr at 250 kPa, 1 ºC/mm/hr at 300 kPa, and 1.1 ºC/mm/hr at 350 kPa. Note that these water efficiency figures indicate that as the pressure increases, more effective use is made of the water, or put another way; each cubic metre of water provides more protection.

7.2 Full Cover, Turbohammer

This configuration uses NaanDan Turbohammer sprinklers on a 4.4 by 9 m rectangular grid.with green 160 l/hr nozzle and provides good frost protection (>80%) down to -3.5ºC at 250 kPa and -4.5 ºC at 300kPa. Despite the application rate for this sprinkler being approximately 50% higher than for the Super Mamkad at the same 300 kPa, the protection is little better. Nevertheless, as would be expected for an application depth of around 6 mm/hr and water arriving from several sprinklers, protection is good along the monitored portion of the row, but fails below -4.5 ºC (**Figure 26**) at 300 kPa, and below -3.5ºC at 250 kPa. Note (Appendix C) that there is no sprinkler at the logger end of the monitoring boom at 300 kPa so the configuration is skewed, although this is not apparent from the level of protection (**Figure 26**).

The Turbohammer sprinklers, with a rotation rate of approximately 15 seconds (the ball drive is approximately 30 seconds) should be an excellent contender for pulsing, which has proved successful in other trials (John et. al., 1987). As might have been expected, the 2-minutes-on/2-minutes-off timing provides good performance, protecting down to almost -3ºC, and showing the viability of pulsing at this rate, and providing water use efficiency similar to the ball drive sprinkler. It must be recognised that short cycle times lead to lower sprinkler efficiency due to additional time operating at reduced (transitional) line pressure and also create possible hydraulic issues. Unfortunately, longer cycle times that are easier to manage hydraulically and which in principle, should provide better efficiency from proportionately less transition time, led to diminished performance due to excessive off time, instead only providing protection down to a mean level of -2 ºC for 3-minutes-on/3-minutes-off. This is in accord with general recommendations on pulsing; 1 to 2 minutes is appropriate for the sprinkler-off part of the cycle. This contention is supported by time-temperature plots that show several instances of 1 ºC fall during the 3 minute off period, and quite slow recovery. Consequently, if pulsing is to be used, we recommend 2-minutes-on/2-minutes-off for the Turbohammer sprinklers.

In summary, the Turbohammer sprinklers provided protection of approximately 0.8 ºC/mm/hr at 300 kPa, and 0.7 ºC/mm/hr when pulsed. It is apparent that a strategy of pulsing until the temperature falls below -2.5 ºC would have resulted in considerable savings in water, especially for milder frosts. An even better strategy would be to have a flow controller that every 2-minutes, begins a 2-minute off cycle. The off-cycle would then be interrupted early if the mean of several protected temperature sensors is below, say, -0.5 ºC. In this manner the system would hover around the mean application rate that is just sufficient to protect the block, and thereby maximise water savings. This forms a likely future research direction.

7.3 Targeted sprinklers, 6 m spacing

These tests were conducted at 6m spacing, using targeted NaanDan Flipper sprinklers with black 25 l/hr nozzles operating at 250 kPa with a new type of sway and violet 35 l/hr nozzles operating at 300 kPa with conventional sway. The performance of these sprinklers as reported here was limited by a particularly severe frost event on the night of 23August 2006, and these data were incorporated in the statistical results. The poor performance of the 25 l/hr sprinkler for example was at odds with other results (eg. 7.2 m spacing using 2004/5 data); it barely protected to -2.5 ºC, yet was at the manufacturer's recommended span for that nozzle size. The 35 l/hr nozzle was operated at a higher pressure and provided slightly better protection, but also to approximately -2.5 ºC. It too was limited in protection by quite strong air movement on the night of 23/24 August 2006. This produced quite a strong correlation between protection failure and wind speeds in excess of 1.5 m/s (some evaporative cooling) and moving across the rows where some distortion of sprinkler distribution pattern could have be expected. In summary, we consider it safe to assume that protection using these configurations at 6m spacing provide a similar level of performance as 7.2m spacing which, from the results alone, would seem to have performed better.

It can be instructive to compare the frost protection performance with the sprinkler distribution pattern; a correlation would normally be expected. Unfortunately, much of the manufacturer's distribution data appear somewhat suspect. Figure 27 for example, shows the overlapped distribution for 6m sprinkler spacing, using data from the NaanDan specification. It shows a very non-uniform pattern with a very low application rate in the centre. Further, the application depths indicated in the data were incorrect, so an uncalibrated scale is shown in the figure. These obvious errors led us to conduct our own series of tests, and the results were distinctly different (Figure 28) and provided much greater uniformity. Prior to conducting these new tests, we had attributed some poor protection at lower temperatures to poor distribution uniformity. Instead, the lack of protection at some locations along the row is due predominantly to occlusions - interception of water by vine, shoots, and wires, which can all increase significantly in size with ice formation.

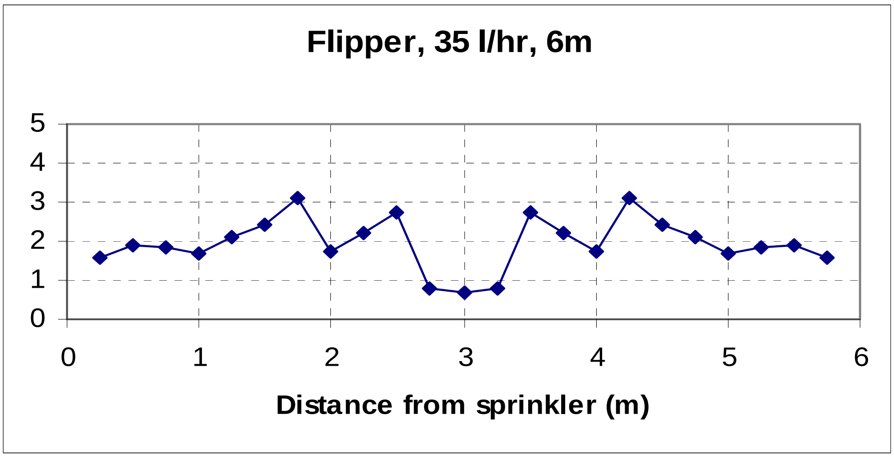


Figure 27 Overlap pattern of 35 l/hr Flipper operating at 250 kPa and spaced at 6 m, using distribution data from the NaanDan specifications.

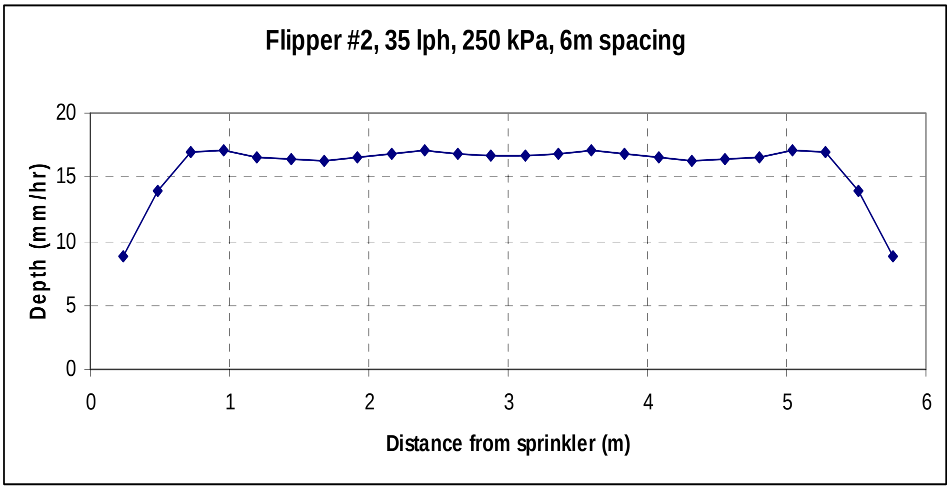


Figure 28 Overlap pattern of 35 l/hr Flipper operating at 250 kPa and spaced at 6 m, measured at Lincoln Ventures Ltd. The application rate is for the centre 400 mm of the distribution pattern.

At first consideration, one could expect the non-uniformity in protection to be revealed by the shape of the distribution pattern, but caution is required in this simplistic approach. It could, under frost damage conditions predict damage severity, but factors such as distortion of the effective distribution pattern by occlusion, air movement, and the extent to which particular shoots are exposed to the clear sky (ie their radiation balance), etc all combine to make such prediction unreliable. Nevertheless, it forms a useful indication.

7.4 Targeted sprinklers, 7.2 m spacing.

Targeted NaanDan Flipper sprinklers with black 25 l/hr nozzles operating at 250 kPa with 7.2 m spacing provided good protection down to -2.5 ºC. Below -2.5 ºC, performance was constrained by non-uniformity, and exhibited a protection distribution not unlike the sprinkler distribution pattern (Figure 29).

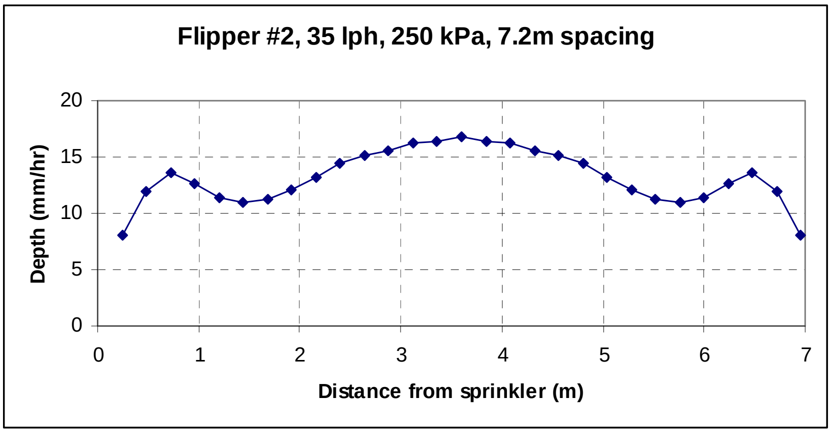


Figure 29 Overlap pattern of 25 l/hr Flipper operating at 250 kPa and spaced at 7.2 m, measured at Lincoln Ventures Ltd. The application rate is for the centre 400 mm of the distribution pattern.

The key differences in interception with full cover sprinklers are that water arrives from typically four sprinklers rather than two and the droplet trajectory of the full-cover sprinkler is more horizontal rather than from above with flipper-type sprinklers.

Assuming an application width of 1.1 m, the black 25 l/hr Flipper spaced at 7.2 m provides protection of approximately 0.8 ºC/mm/hr water at 250 kPa. This configuration provided a high volumetric protection efficiency of 1.4 ºC /l/hr/m^2.

This configuration (black 25 l/hr nozzles operating at 250 kPa with 7.2 m spacing) was also evaluated with a new sway design, apparently intended to 'fill the hole' next to the sprinkler. It also created another peak at around 1.5m (Figure 30). Although our 15cm sensor was partially occluded, the new sway does seem better for this configuration, as shown by the protection uniformity along the row down to -3 ºC (there was no data for this sprinkler at lower temperatures).

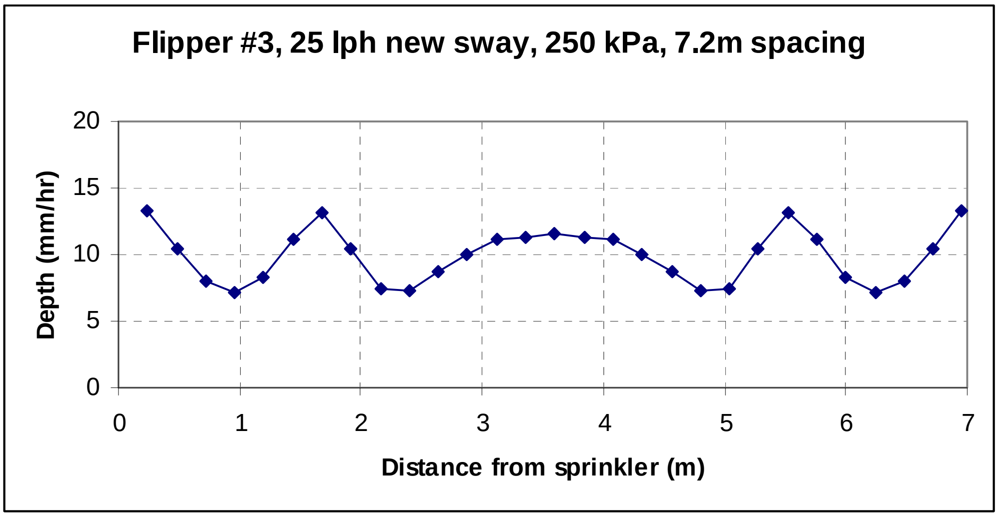


Figure 30 Overlap pattern of 25 l/hr Flipper operating at 250 kPa and spaced at 7.2 m, measured at Lincoln Ventures Ltd. The application rate is for the centre 400 mm of the distribution pattern.

The violet 35 l/hr nozzles, when operated at 250 kPa, performed very well with good protection down to -4 ºC. At the recommended 300 kPa for this nozzle, there was more protection near the sprinkler than at 250 kPa, but the same overall result; good protection down to -4 ºC. The latter result clearly shows an occluded sensor at 360 cm.

One trial was also conducted using a brown 43 l/hr nozzle, operating at 300 kPa with the 7.2 m spacing. Superficially, this only provided good protection down to -3 ºC, but this result included the severe 2006 frost event – performance without this event provided good protection down to -4 ºC.

7.5 Targeted sprinklers, 9 m spacing.

Targeted NaanDan Flipper sprinklers with violet 35 l/hr nozzles operating at 250 kPa and 300 kPa at 9 m spacing provide an interesting comparison with the full cover sprinklers. Here the 300 kPa configuration only gave adequate protection down to -2.5 ºC, but at 250 kPa faired somewhat better, protecting to -3.5 ºC. We attribute the better performance at low pressure to a larger droplet size, a characteristic we have observed in previous trials. Since the effect was apparent along the whole span of the sprinkler throw, it appears not to be a trajectory factor but rather due to the size of the droplet alone.

Using an application width of 1.1 m, the 35 l/hr Flipper spaced at 9m provided protection of approximately 0.7 ºC/mm/hr and 1.3 ºC /l/hr/m^2 at 250 kPa and 0.5 ºC/mm and 0.9 ºC /l/hr/m^2 at 300 kPa.

Refer now to the 43 l/hr sprinkler, also operated at 300 kPa. It provided good protection down to -3.5 ºC. If data from the severe frost of 23/24 August 2006 were **not** used for the analysis, the configuration demonstrated a creditable performance down to -4.5 ºC, with very good flatness, although it does fail our benchmark for good protection at -3.5 ºC, recovering thereafter until -4.5 ºC.

Table 21. Values of mean level of protection (%) provided by NaanDan Flipper with 43 l/hr nozzles spaced at 9m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text), ***but excludes data from severe frost 23/24 August 2006****.*

Control temperature	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	99	99	99	100	99	100	99	100
-1.5 to -2	99	99	100	100	100	99	99	99
-2 to -2.5	97	96	98	97	98	96	93	96
-2.5 to -3	91	88	94	91	99	93	87	87
-3 to -3.5	68	71	93	80	100	92	89	78
-3.5 to -4	61	87	100	84	100	100	98	87
-4 to -4.5	67	100	100	89	100	100	100	99
-4.5 to -5	0	0	0	0	0	0	0	0

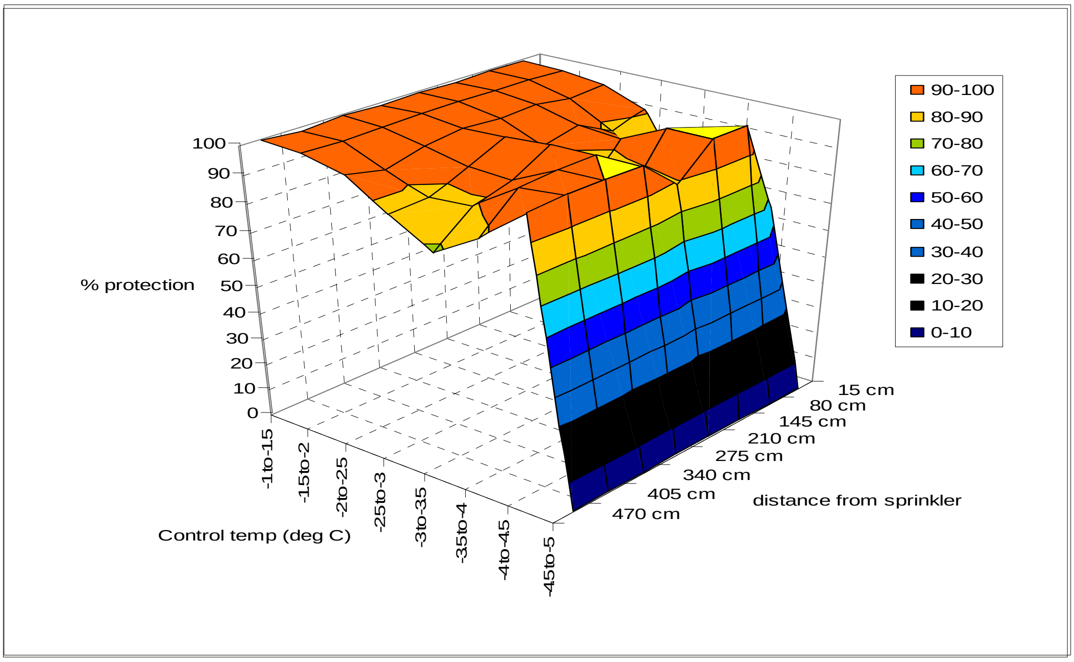


Figure 31. Mean level of protection (%) provided NaanDan Flipper with 43 l/hr nozzles spaced at 9m grid and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text), ***but excludes data from severe frost 23/24 August 2006****.*

The results raise the question, when taking into account that the quantity of water used (l/hr/m^2) is similar to the Super Mamkad configurations that provide quite uniform protection down to at least -4.5 ºC.

8 ADDITIONAL FINDINGS

As the trials and discussions with growers proceeded, several questions were raised which required definitive answers. Some issues lacked solid New Zealand data on which to base an investigation, so additional trials were conducted. These additional issues and key findings are listed in Table 22, and results and detailed explanations follow.

Table 22 Additional issues and key findings

Issue	**Summary information**
Measuring frost conditions	Base startup decisions on exposed sensors not air temperature, and be aware of the difference.
Typical frost temperatures	Air (screen) temperature is warmer than buds or vine tissue.
Damage thresholds	For published thresholds, note variety, assume they are bud/tissue temperature, not air temperatures
Start-up and shut-down temperatures	Do not start sprinklers too early. Wait until exposed temperature at cordon height in coldest part of vineyard is minus 0.5 °C (equivalent to air temperature of + 0.5 °C to + 2 °C)
Targeted systems	Generally uses less water but is also less robust and more susceptible to loss of protection due to wind distorting distribution.
Freezing in laterals	Stationary water in a lateral typically takes an hour to freeze at a temperature of -3 °C. If an issue, insulate, bury or raise laterals. Avoid raising start-up temperature.

8.1 Measuring frost conditions

Whether the need is to select an appropriate frost protection system or to manage an existing system, it is important for vineyard managers to record temperatures inside the vineyard during frost events. The widespread availability of economical, simple to use data loggers enable compilation and storage of temperature records throughout the orchard. Historical records are useful for building frost profiles for managing a frost protection system, and in the event that a frost protection system fails, will provide information on the prevailing conditions that led to failure.

A crucial aspect of vineyard measurements is measurement accuracy. This is not so much an issue of temperature sensor accuracy, but rather one of sensor placement and shielding. A sensor within a radiation shield provides a measure of air temperature, but is a blunt indicator of likely damage or of when to begin frost protection. Instead, we recommend a sensor that is exposed to the sky and which hence indicates a temperature closer to that of a bud or shoot. Note that this exposed sensor will indicate a temperature lower than air temperature under common radiative frost conditions, but under these conditions, bud or vine tissue temperature is similarly lower than air temperature.

Figure 32 Typical radiation shield for easurement of air temperature. Unlike the state of this shield, it should be kept clean to ensure best alignment with air temperature.

Figure 33 Typical exposed sensor to represent bud or tissue temperature.

A short trial was conducted to test how representative a small exposed sensor was of vine tissue temperature. A 2 mm diameter bead thermistor was inserted into a short soft tissue vine shoot, and a black exposed sensor 5 mm diameter was secured to the vine approximately 50 mm away. Temperature readings from the two sensors were measured at 10 minute intervals during a light Canterbury frost in late August 2006. The exposed temperatures were measured at 10 minute intervals, and the nearby air temperature was also measured but represented hourly mean value at 1m. Figure 34 demonstrates the close alignment between the two measurements, indicating that an exposed sensor provides a good measure of actual vine temperature. After allowance is made for the higher temperature at 1m compared with 0.5 m elevation (typically 0.3 °C), the air temperature is between 1 and two degrees warmer than the exposed or tissue temperatures, but more importantly, the difference is not constant. Hence air temperature alone is a poor indicator of when to start frost protection.

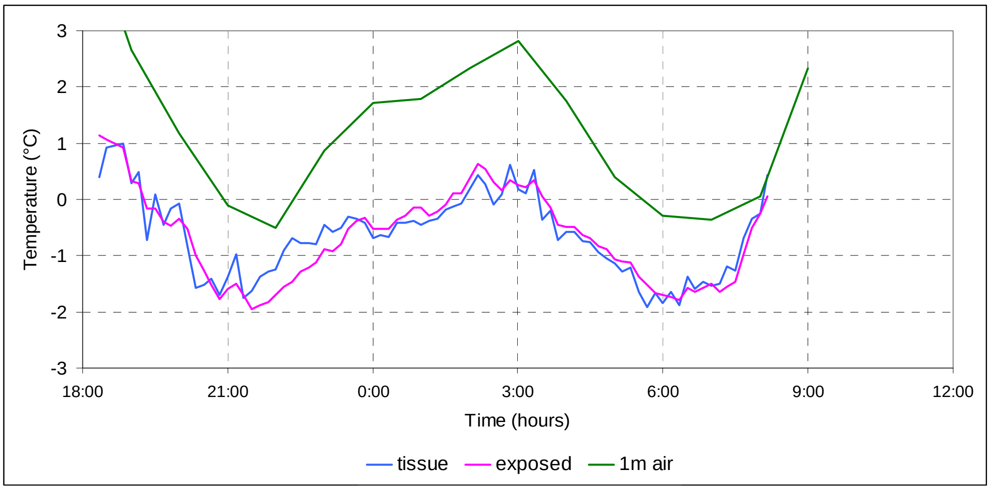


Figure 34 Comparison between a 5 mm exposed temperature sensor and actual vine tissue temperature measured by a small bead thermistor inserted into the short shoot. The instrumented section of vine was approximately 0.5m above ground level

We attribute the discrepancy between the two temperatures during the warming period between 9 p.m. and midnight to some cloud cover and the different response of the two sensors to air temperature driven changes rather than radiation driven changes (to which the responses are very similar). Hence the trial highlights the rapid response of near-surface tissue temperature to air temperature changes, and hence the desirability of exposed sensors to have a relatively short air-temperature thermal lag of approximately one minute (the exposed sensor used for this trial was 2 minutes). Note that the sampling period for a data logger should be no more than half the sensor time constant, although the samples may then be averaged to provide less frequent values for storage.

Measurements should also be made at known elevations. Exposed temperature sensors are most appropriately positioned at cordon height to indicate the actual temperature experienced by bursting buds and shoots. It is also important to measure at several locations in the vineyard; a minimal installation should include measurements within the coldest zone, an average zone, and a control zone which is a nearby position outside the immediate influence of the frost protection system to provide measurements of the prevailing conditions. Air temperature at 1.2 m provides a ready comparison with other sites since that is a standard height for meteorological measurements.

8.2 Typical frost temperatures

Although frosts differ in severity and nature, the common radiation frost is typified by steadily decreasing temperature from before sunset, and terminated by a rapid increase after sunrise. Figure 35 shows both air temperature (labeled 1.2 m air) and the exposed temperature (labeled 1.1 m bud), both decreasing steadily through the night.

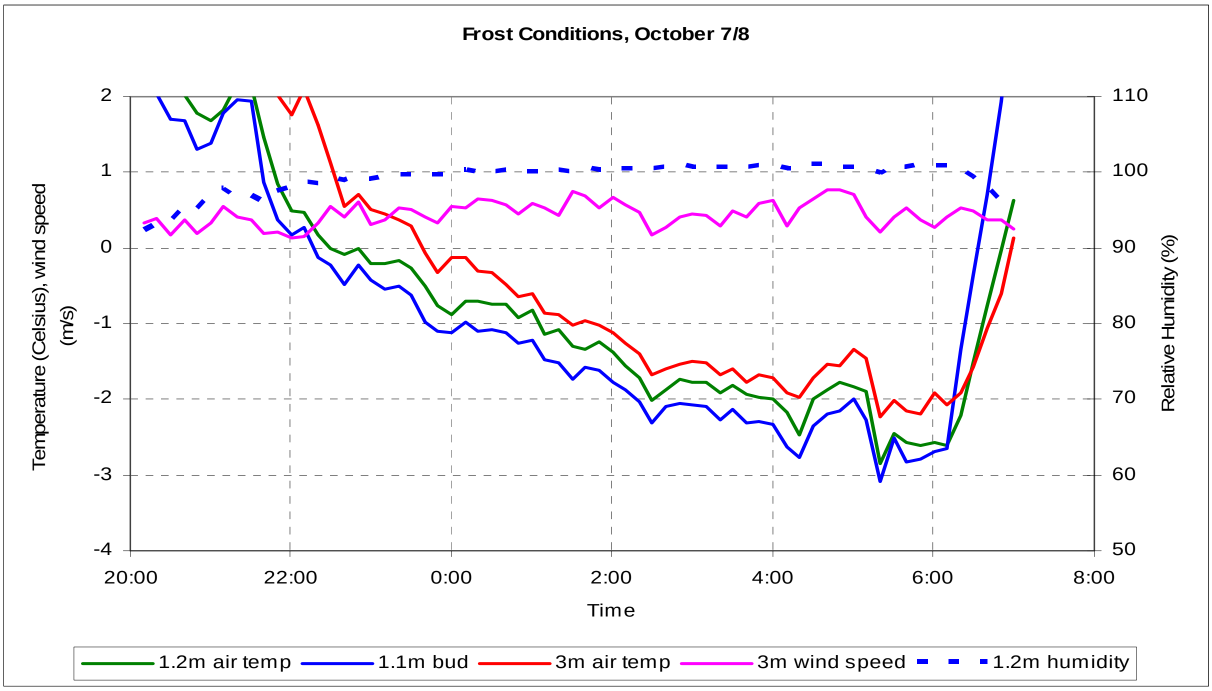


Figure 35 Typical Conditions during a spring frost.

During the early part of the night, the humidity increases to around 100%, indicating that the air is unable to hold further water (humidity cannot exceed 100% but small errors in humidity sensors can lead to readings slightly above 100%). There is an inversion, as indicated by the cooler readings at 1.2m than 3m, and a difference between air and exposed temperatures. In this instance the exposed temperatures are just 0.5°C lower than the air temperature but during a radiation frost this may vary from 0 to 2°C. There is also a light wind of around 0.5 m/s. During a radiation frost, the air is cooled by cold surfaces, so the ground surface and vines (1.1m bud) are colder than the air (1.2m screen). After the sun rises, it warms the surfaces more rapidly than the air, so the exposed sensor becomes warmer than the air temperature. The small variations in temperature during the night are primarily due to air movement.

Occasionally, New Zealand experiences advective frosts due to movement of freezing air, although due to the ocean surrounding the country, these are of a local nature, unlike the general movement of large cold air masses as experienced in North America and Europe.

8.3 Damage thresholds

Damage is likely when the vine tissue is below -1 °C, although some damage may occur at up to 0 °C. A **bud or tissue** temperature of -0.5 °C is a practical value for starting frost protection, although it makes no allowance for start up time. Also, buds at earlier stages of growth are less susceptible to damage, and protection may be delayed earlier in the season. However, it is important that care is taken when interpreting tables listing damage thresholds. For example Table 23, which has been abstracted from the internet and is attributed to Hedberg (2000), is stated to indicate **air** temperatures at which damage to vine tissue may occur. But the relatively few trials that have been conducted to determine damage thresholds for common grape varieties have generally been conducted in cool chambers where air and tissue temperatures are the same, that is there is *no radiative cooling*. Hence the temperatures should be considered to be **tissue** temperatures and not air temperatures.

Table 23 A typical table of damage thresholds. Refer to text for cautions about interpretation of the temperature thresholds.

-3.5 °C or less	woolly bud stage (continued periods can kill the primary bud)
-2.0 °C or less	early budburst
-0.6 °C or less	shoots up to 15 cm long
0 °C or less	shoots 15 cm and longer

8.4 Start-up and shut-down temperatures

Due to regional, seasonal and phenological variation, there is a shortage of dependable data that relates vine tissue temperature to damage. However for the most sensitive exposed shoots and florets, a tissue temperature of -1 °C for more than a few minutes is most likely to result in some damage, so that starting frost protection when the temperature of an exposed sensor (representing vine tissue temperature) in the coolest location of the vineyard falls below *minus* 0.5 °C is recommended. This typically is reached when the air or screened temperature is +0.5 to +1 °C. If the frost protection system comprises roving helicopters or wind machines, commencing protection early only has an impact on the running cost, and hence a conservative approach may be an appropriate strategy. However commencing application of water to vines at a higher tissue temperature than –0.5 °C not only wastes water, but also affects how well the system performs. No ice film is produced until vines are below 0 °C, and even then, newly formed ice crystals may be washed off and delay the onset of freezing, risking crop damage (Figure 36). Starting the sprinklers when the bud or tissue temperature as measured by an exposed sensor at the coolest location is -0.5°C (Figure 37) at canopy height ensures that ice formation occurs rapidly, yet is still above the temperature at which damage is likely to occur (-1 °C tissue temperature).

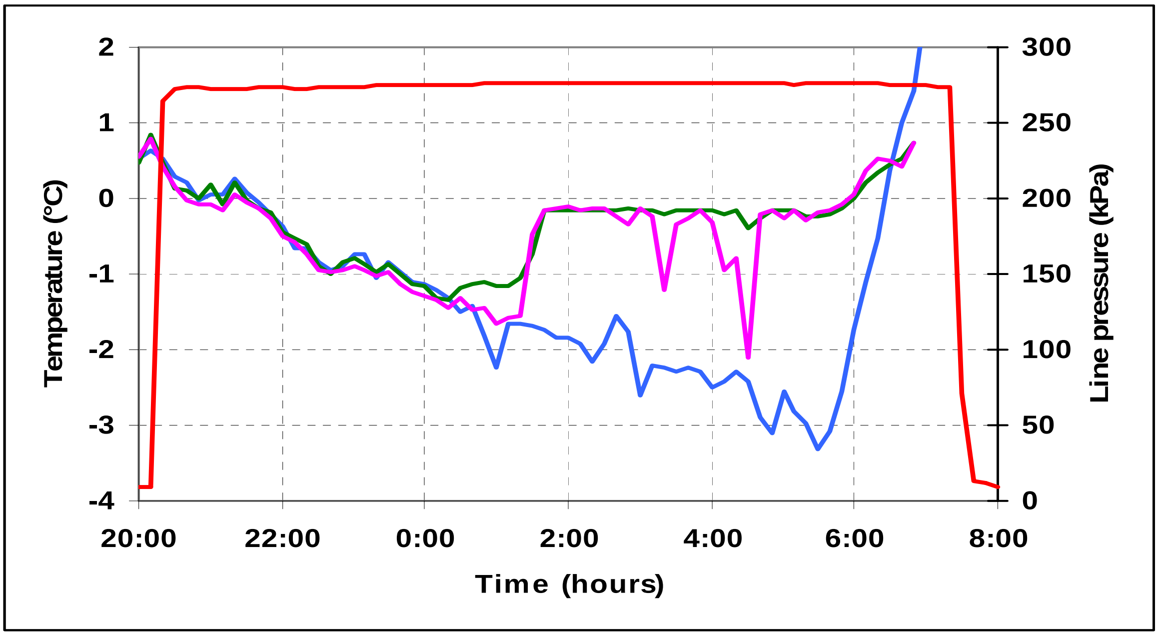


Figure 36 shows the effect of starting the sprinklers (the red trace is the line pressure) shortly after 8pm at a bud or tissue temperature of +0.5 °C. The effect is that the temperatures of both protected and unprotected buds continue to fall. Five hours later, when the tissue temperatures have fallen to -1.5 °C, freezing commences and the protected buds climb to nearly 0 °C while the blue trace of the unprotected sensor, continues to fall.

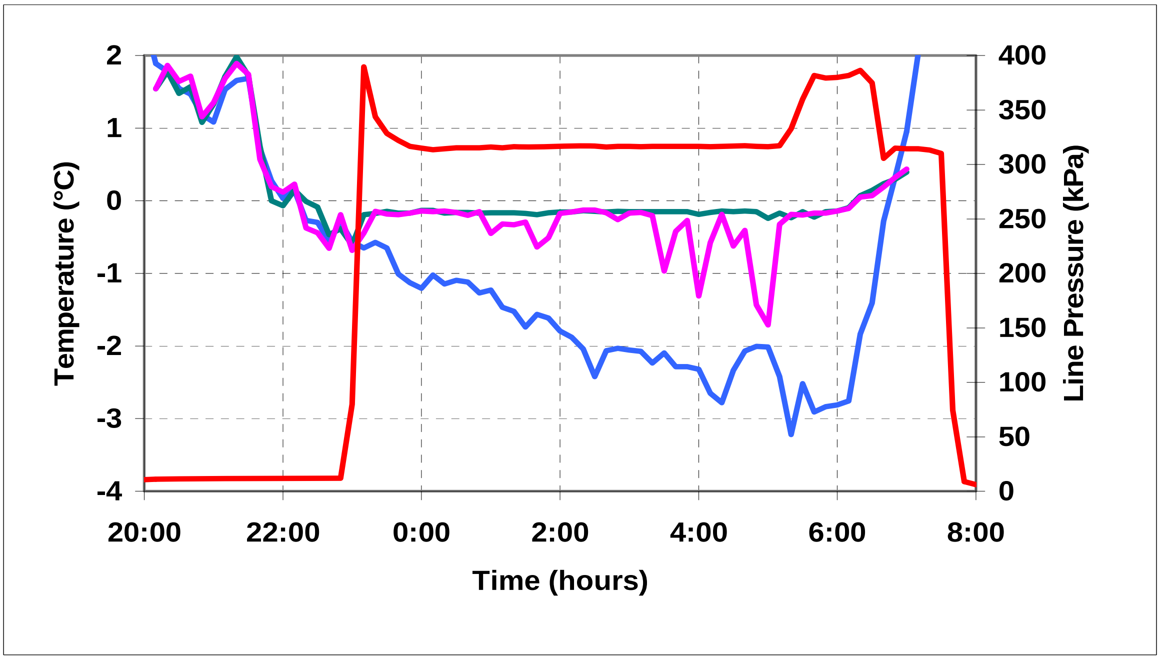


Figure 37 demonstrates the effect of staring frost protection (the red trace is the line pressure) at an appropriate exposed temperature of -0.5 °C. Ice forms almost immediately, as indicated by the exposed temperatures climbing to almost 0 °C, while the blue trace of the unprotected sensor continues to fall.

For most New Zealand frosts, by the time the air temperature has dropped to zero the humidity is near 100% so that the dew point and wet bulb temperature are only slightly below zero, and evaporative cooling is minimal. Applying water when bud or tissue temperature is -0.5 °C, provides an allowance for some evaporative cooling. If the dew point is measured, the startup temperature should be raised by 0.5 °C for every 1 °C the dew point is below -1 °C. Although these conditions are unusual during frost sensitive conditions in New Zealand, they do tend to form 'memorable' occasions during which damage occurs, particularly if the frost protection system is under-designed, constrained due to limited water or some other compromise, or reliant on inversion conditions such as wind machines.

Sprinkler frost protection systems may be switched off in the morning once there is melt water flowing between ice and the vines. It is important to ensure this is also the case in the cooler zones of the vineyard and those shaded from early sun. Figure 40 for example, shows where the exposed temperature in a shaded location did not rise above zero until 10AM. In that case it appears the area received early sun around 8AM, and then intermittent sun until after 10AM. Automatic switch-off could be triggered when the exposed temperature is greater than 0 °C *and* the air temperature is greater than 0 °C and rising, but these conditions have not been trialled so must be evaluated for several events against observations. We hope to perform this trial during the winter of 2008.

8.5 Application rate

Sprinkler frost protection can be very reliable, does not rely on a strong inversion, and can protect against heavy frosts. On the other hand, significant quantities of water may be required. Sprinkler frost protection utilises the large amount of heat released when water freezes, and this is applied directly to the plant tissue. The plant tissue remains at or near 0 °C, even when encased in ice, provided a film of liquid water remains. Most frost protection system designers aim to have an application rate of 1 mm/hr for each °C of protection required, typically amounting to 4mm/hr, but the actual rate is selected according to location and the perceived level of protection required. The chosen level is a judgment call that is affected by capital cost, running cost, estimated frost risk and hence failure rate, and availability of water.

When sufficient water is being applied to vines during frost conditions, transparent ice will form over all surfaces and the ice will have an outer layer of film water as shown in Figure 38. On the other hand, the white appearance of the ice layer in Figure 39, and lack of uniform film water, indicates insufficient water and the likelihood that the temperature is below zero and that tissue damage is occurring. Trapped air bubbles within the ice are indicative of inadequate water at an earlier time.

Figure 38. Clear ice during frost protection, with an outer film of liquid water, indicating adequate application rate.

Figure 39. White ice covering the vines indicates insufficient application rate for the frost conditions, and that vine damage is likely.

8.6 Targeted systems

Targeted sprinklers avoid applying water on the inter-row area, so tend to provide better efficiency, but the performance is constrained by the different action compared with full cover sprinklers. Targeted application may provide inferior cover since sprinkler overlap only occurs down the rows, so there is no contribution from the sides to ensure full coverage without shading effects from leaves, vines or posts. Investigation into methods for providing more uniform coverage and application rate from targeted sprinklers is an area of ongoing research by this team and others.

Pulsing is a technique that enables reduced water use and hence greater frost protection efficiency for light frosts, while retaining the capacity to protect against heavier frosts by reverting to continuous frost protection when the temperature has fallen below the level to which pulsing protects (eg -2 °C). Trials have proved the benefits of pulsing, but the design of the system requires attention to detail. Important aspects include the cycle time - water should not be absent for more than two minutes. Attention to hydraulic design is also important to ensure rapid pressurisation and hence turn-on and turn-off times, and the interaction between pulsing times and sprinkler rotation rate. These aspects are an area of ongoing investigation.

8.7 Freezing in laterals

One issue that sometimes arises is that of water freezing in laterals and risers. Prior to the frost protection system being activated and by the time the exposed temperature at cordon height has fallen to -0.5 °C, the exposed temperature at ground level could be -1 to -2 °C, and if the lateral is at ground level, there is a risk of water inside the lateral freezing. Figure 40 shows the results of a trial measuring the freezing rate of two lateral sizes during a typical radiation (still air) frost. It can be seen that stationary water inside a 13 mm lateral typically takes an hour to freeze (from the onset of ice nucleation) when at -3 °C. To combat this risk, the laterals could be elevated, and the startup tissue or bud temperature of -0.5 °C retained.

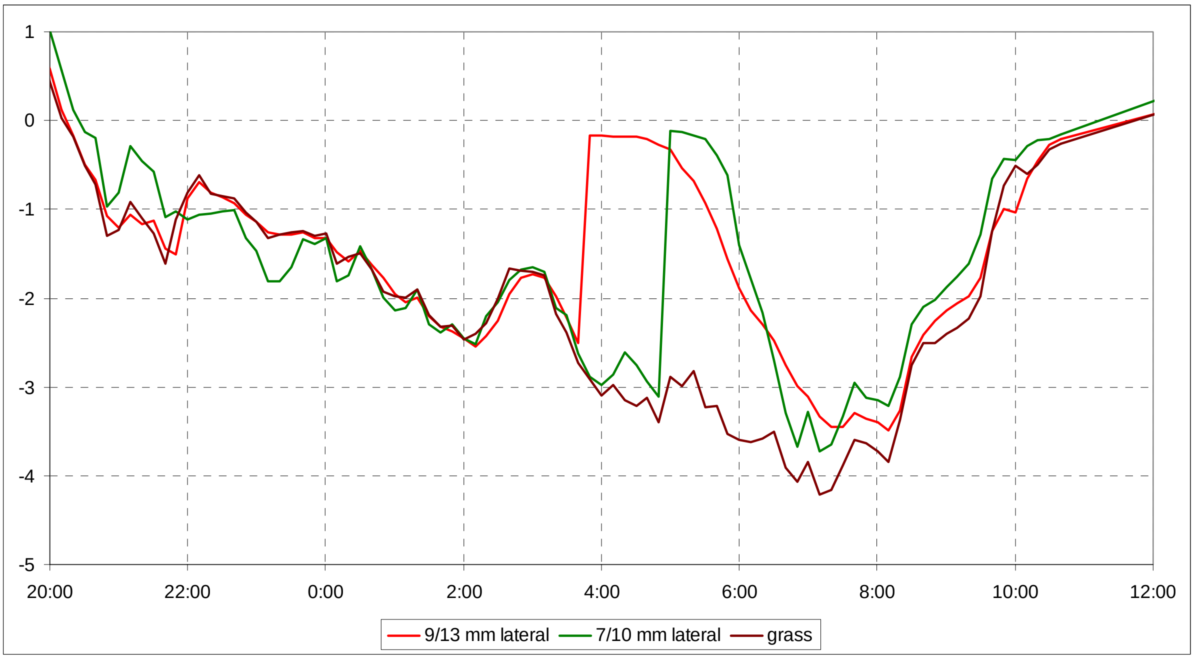


Figure 40 Plot of water temperatures inside ground-level laterals during a typical frost event. The still water is supercooled until less than -2 °C before freezing suddenly occurs and raises the temperature until all the water has frozen.

The next issue is freezing of laterals during normal sprinkler operation. This may occur because there are always stagnation zones in the laterals, whether at the end of a blind lateral, or partway along a lateral fed from each end. Provided the laterals themselves receive a protective application of water, the stagnation zones will not freeze. If that protection cannot be ensured, the ends or stagnation zones should be insulated or elevated, although it must be recognized that for laterals fed from both ends, the stagnation zones will shift due to blocked sprinklers or some other perturbation.

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10 APPENDIX A: INSTRUMENTATION DETAILS

This appendix provides brief notes detailing the instrumentation in the 2005-7 frost monitoring season, which used Campbell CR200 loggers

```
'Hawkes Bay Frost Logger Program Mk1.0

'Logs 8 analogue channels once every 2 minutes when temperature below
3 degrees.
'Assumes Mux Connected to CR200 to expand 5 analogue channels to 8

'Mux Connections
'CR200  Mux
'SE1 -> 1/2 Blue
'SE2 -> 3/4 Purple
'SE3 -> 5/6 Orange
'SE4 -> 7 Brown
'SE5 -> 8 Grey
'AG -> AG Green
'Ex1 -> Ex White
'SW Battery -> S Yellow *
'Battery - -> 0v
'Battery + -> +v

'* Note 10k Pull Down to GND used to overcome FET Capacitance!

'Parameters for 10k thermistor 10k sense and 10k series
'Fit to within 0.02 between +/- 10 degrees

'Serial Connection (standard serial cable)
' 3 -> 2
' 2 -> 3
' 5 -> 5

'Wavecom Connection
'Cable to modem only needs Rx, Tx, and Gnd connecting
'9Pin dtype male -> 15 sub min dtype male
'3 -> 6 red
'2 -> 2 brown
'5 -> 9 yellow

'BATTERY
'Into Battery +/- 7-16V DC use Battery Masta 12V 8 X Alkaline AA
Packs
'12.86 Room Temp into 3mA load
'12.77 in Freezer into 3mA load

'Declare Public Variables (these variables can be seen in the public
table and can be
'written to a user defined data table)

'Wiring
'AN1-AN8 -> t015-t470

'Public
'------

Public mux(5)
Public temp(8)
```

```
Public batt_volt
Public log_temp

'Aliases
'-------

Alias temp(1) = t015
Alias temp(2) = t080
Alias temp(3) = t145
Alias temp(4) = t210
Alias temp(5) = t275
Alias temp(6) = t340
Alias temp(7) = t405
Alias temp(8) = t470

'Declare Dim Variables (these variables can only be seen if written
to a user defined
'data table)

'Dim
'---

Dim x 'mux assignment counter
Dim low_temp 'trigger for frost event output table
Dim init

'Declare Constants (these variables can not be seen in any table,
they are for internal
'program use only)

'Constants
'---------

'thermistor polynomial coefficients
const P0 = -60.4634
const P1 = 319.9599
const P2 = -918.784
const P3 = 1730.379
const P4 = -1692.38
const P5 = 682.3589

'const LOW_TEMP_LIM 25 '*
'const UP_TEMP_LIM 35 '*
const LOW_TEMP_LIM 3
const UP_TEMP_LIM 5

'Define Data Tables, allocate all available memory to this table

'Output Tables
'------------

DataTable (frost_log_bat,1,30)
  DataInterval (0,24,hr)
  'DataInterval (0,10,min) '*
  'Average (1,batt_volt,0)
  Minimum (1,batt_volt,0,0)
EndTable

DataTable (frost_log_temp,low_temp,-1)
  DataInterval (0,2,min)
```

```
  'DataInterval (0,1,min) '*
  Sample (8,temp())
EndTable

'Main Program
'------------

BeginProg                        'start program
  Scan (120,sec)                  'scan every 2 minutes
  'Scan (2, sec) '*

  If (init=0) 'if first pass initialise log_temp
     log_temp=LOW_TEMP_LIM
     init=1
  Endif

   'read first three mux channels 1,3,5
   SWBatt (0)
   ExciteV(Ex1,mV2500)
   'allow 5 time constants for RC network
   Delay(200,mSec)
   VoltSe (mux(),3,1,0.001,0)
   ExciteV(Ex1,mV0)

   'convert mux readings into temperatures and load into temp array
   For x = 1 To 3 Step 1
     temp((x*2)-1) = P0 + P1*(mux(x)) + P2*(mux(x)^2) + P3*(mux(x)^3)
+ P4*(mux(x)^4) + P5*(mux(x)^5) 'scale into physical units (volts ->
degrees)
   Next x

   'repeat above but with mux reading channels 2,4,6 and non muxed
channels 7, 8
   SWBatt (1)
   ExciteV(Ex1,mV2500)
   'allow 5 time constants for RC network
   Delay(200,mSec)
   VoltSe (mux(),5,1,0.001,0)
   ExciteV(Ex1,mV0)
   'switch battery off since capacitance of fet must be discharged
before next pass.
   SWBatt (0)

   'convert mux readings into temperatures and load into temp array
   For x = 1 To 3 Step 1
     temp(x*2) = P0 + P1*(mux(x)) + P2*(mux(x)^2) + P3*(mux(x)^3) +
P4*(mux(x)^4) + P5*(mux(x)^5) 'scale into physical units (volts ->
degrees)
   Next x

   'convert 2 non multiplexed channel readings into temps and load
into temp array
   For x = 4 to 5 Step 1
     temp(x+3) = P0 + P1*(mux(x)) + P2*(mux(x)^2) + P3*(mux(x)^3) +
P4*(mux(x)^4) + P5*(mux(x)^5) 'scale into physical units (volts ->
degrees)
   Next x

   'get battery voltage
   Battery (batt_volt)
```

```
    'set temp logging flag to false
    low_temp = 0
    For x = 1 to 8 Step 1
          If (temp(x) <= log_temp) AND (temp(x) >= -30) Then'dodgy
sensors will read -60 and we dont wont to catch these!
               'set temp logging flag to true
               low_temp = 1
               log_temp = UP_TEMP_LIM
          Endif
    Next x

    If (low_temp<>1)
      log_temp = LOW_TEMP_LIM
    Endif

    CallTable frost_log_temp
    CallTable frost_log_bat
   NextScan
EndProg
```

2. Weather Stations

```
'Hawkes Bay Frost Logger Program Mk1.0

'Logs 8 analogue channels once every 2 minutes when temperature below
3 degrees.
'Assumes Mux Connected to CR200 to expand 5 analogue channels to 8

'Mux Connections
'CR200  Mux
'SE1 -> 1/2 Blue
'SE2 -> 3/4 Purple
'SE3 -> 5/6 Orange
'SE4 -> 7 Brown
'SE5 -> 8 Grey
'AG -> AG Green
'Ex1 -> Ex White
'SW Battery -> S Yellow *
'Battery - -> 0v
'Battery + -> +v

'* Note 10k Pull Down to GND used to overcome FET Capacitance!

'Parameters for 10k thermistor 10k sense and 10k series
'Fit to within 0.02 between +/- 10 degrees

'Serial Connection (standard serial cable)
' 3 -> 2
' 2 -> 3
' 5 -> 5

'Wavecom Connection
'Cable to modem only needs Rx, Tx, and Gnd connecting
'9Pin dtype male -> 15 sub min dtype male
'3 -> 6 red
'2 -> 2 brown
'5 -> 9 yellow
```

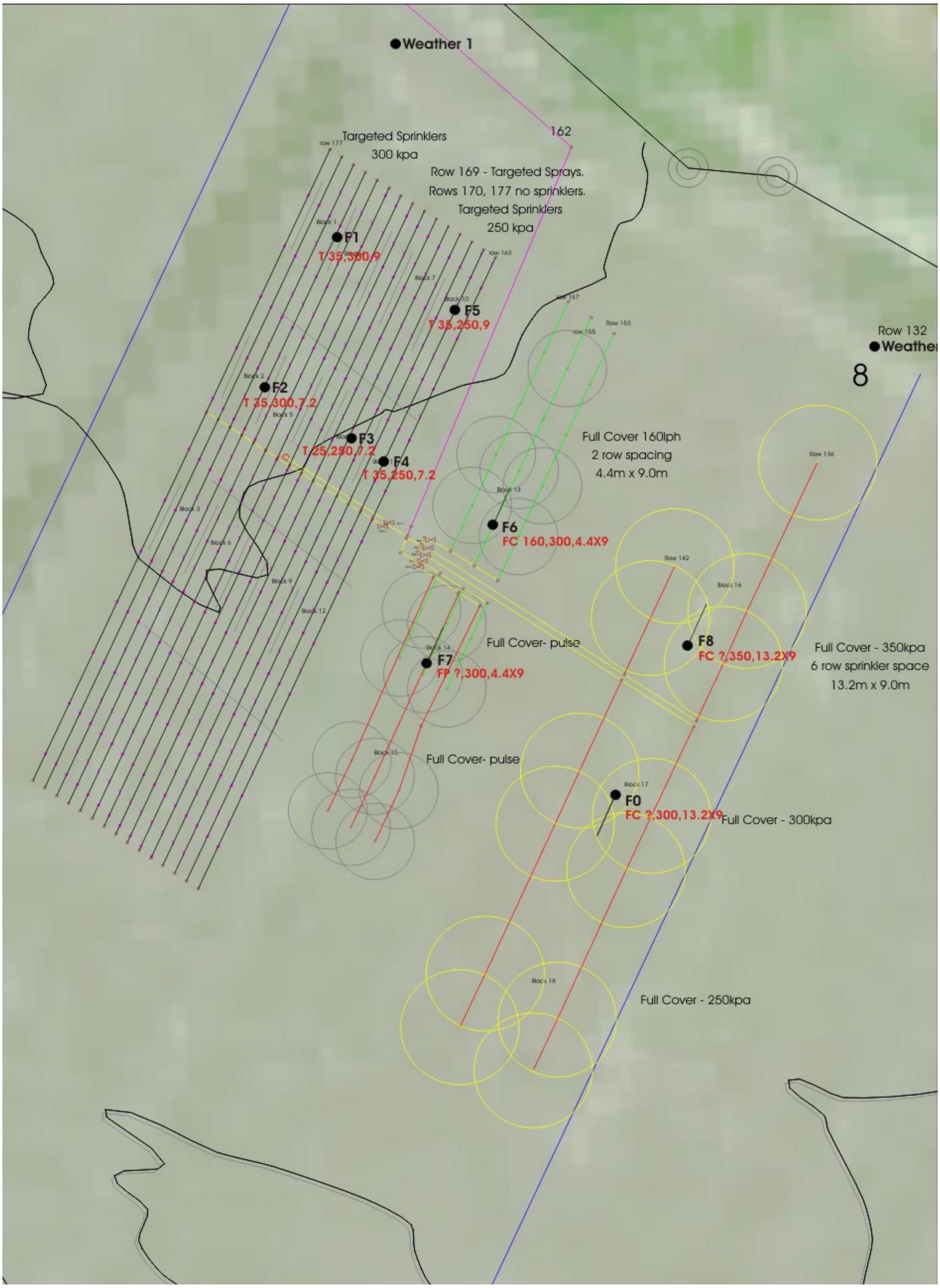
```
'BATTERY
'Into Battery +/- 7-16V DC use Battery Masta 12V 8 X Alkaline AA
Packs
'12.86 Room Temp into 3mA load
'12.77 in Freezer into 3mA load

'Declare Public Variables (these variables can be seen in the public
table and can be
'written to a user defined data table)


'Wiring
'AN1 - 1.2m screen
'AN2 - 1.2m bulb
'AN3 - 0.5m screen
'AN4 - 0.5m bulb
'AN5 - Temp (humitter not currently used)
'AN6 - NC
'AN7 - Wind Dirn
'AN8 - Humidity

'Humitter Connections
'Yellow -> SW 12V
'Brown/Red -> AN8
'Green -> A_GND
'Violet/Blue -> AN5
'White -> NC
'Screen -> GND

'Wind Dirn Connections
'Green -> Ex1
'Yellow -> AN7
'Red -> A_GND

'Wind Speed Connections
'Red -> P_SW
'Black -> A_GND

'Public
'------

Public mux(2)
Public temp(4)
Public batt_volt
Public log_temp
Public wind_dirn
Public rh
Public wind_spd

'Aliases
'-------

Alias temp(1) = t12scr
Alias temp(2) = t12blb
Alias temp(3) = t20scr
Alias temp(4) = t20blb

'Declare Dim Variables (these variables can only be seen if written
to a user defined
```

```
'data table)

'Dim
'---

Dim x 'mux assignment counter
Dim low_temp 'trigger for frost event output table
Dim init

'Declare Constants (these variables can not be seen in any table,
they are for internal
'program use only)

'Constants
'---------

'thermistor polynomial coefficients
const P0 = -60.4634
const P1 = 319.9599
const P2 = -918.784
const P3 = 1730.379
const P4 = -1692.38
const P5 = 682.3589

'const LOW_TEMP_LIM 25 '*
'const UP_TEMP_LIM 35 '*
const LOW_TEMP_LIM 3
const UP_TEMP_LIM 5

'Define Data Tables, allocate all available memory to this table

'Output Tables
'------------

DataTable (frost_log_bat,1,30)
  DataInterval (0,24,hr)
  'DataInterval (0,10,min) '*
  'Average (1,batt_volt,0)
   Minimum (1,batt_volt,0,0)
EndTable

DataTable (frost_log_temp,low_temp,-1)
  DataInterval (0,2,min)
  'DataInterval (0,1,min) '*
  Sample (4,temp())
  Sample (1,wind_spd)
  Sample (1,wind_dirn)
  Sample (1,rh)
EndTable

'Main Program
'------------

BeginProg                      'start program
  Scan (120,sec)                'scan every 2 minutes
  'Scan (2, sec) '*

  If (init=0) 'if first pass initialise log_temp
     log_temp=LOW_TEMP_LIM
     init=1
```

```
  Endif

  'TEMPERATURES (AS PER TEMP LOGGERS!)
 '-----------------------------------------
   'read first two mux channels 1,3
   SWBatt (0)
   ExciteV(Ex1,mV2500)
   'allow 5 time constants for RC network
   Delay(200,mSec)
   VoltSe (mux(),2,1,0.001,0)
   ExciteV(Ex1,mV0)

   'convert mux readings into temperatures and load into temp array
   For x = 1 To 2 Step 1
     temp((x*2)-1) = P0 + P1*(mux(x)) + P2*(mux(x)^2) + P3*(mux(x)^3)
+ P4*(mux(x)^4) + P5*(mux(x)^5) 'scale into physical units (volts ->
degrees)
   Next x

   'repeat above but with mux reading channels 2,4
   SWBatt (1)
   ExciteV(Ex1,mV2500)
   'allow 5 time constants for RC network
   Delay(200,mSec)
   VoltSe (mux(),2,1,0.001,0)

   'WIND SPEED, WIND DIRN HUMIDITY
 '-----------------------------------------
   PulseCount (wind_spd,P_SW,2,1,0.5,0.65) 'f/2 + 0.65 = Vel (m/s) 3
or 6 cup KDR
   'VoltSe (wind_dirn,1,4,0.144,74) 'measure wind direction 0-360 <->
0 - 2500 weather 2
   VoltSe (wind_dirn,1,4,0.144,15) 'measure wind direction 0-360 <->
0 - 2500 weather 1
   VoltSe (rh,1,5,0.1,0) 'measure rh while we've got sw supply on! 0-
1V <-> 0-100%RH

   ExciteV(Ex1,mV0)
   'switch battery off since capacitance of fet must be discharged
before next pass.
   SWBatt (0)

   'convert mux readings into temperatures and load into temp array
   For x = 1 To 2 Step 1
     temp(x*2) = P0 + P1*(mux(x)) + P2*(mux(x)^2) + P3*(mux(x)^3) +
P4*(mux(x)^4) + P5*(mux(x)^5) 'scale into physical units (volts ->
degrees)
   Next x

   'get battery voltage
   Battery (batt_volt)

   'set temp logging flag to false
   low_temp = 0
   For x = 1 to 4 Step 1
         If (temp(x) <= log_temp) AND (temp(x) >= -30) Then'dodgy
sensors will read -60 and we dont wont to catch these!
              'set temp logging flag to true
              low_temp = 1
              log_temp = UP_TEMP_LIM
```

```
          Endif
    Next x

    If (low_temp<>1)
      log_temp = LOW_TEMP_LIM
    Endif

    CallTable frost_log_temp
    CallTable frost_log_bat
   NextScan
EndProg
```

11 APPENDIX B: PLAN OF TRIAL SITE



12 APPENDIX C: SPRINKLER CONFIGURATIONS

Sileni Frost Trial – Block Detail – as at August 06

Overall block area 70m x 100m

From northwest corner (row 175) of block running south then east.

Block 1	Targeted	35 1/hr 300 kpa	9.0 m spacing
Block 2	Targeted	35 1/hr 300 kpa	7.2 m spacing
Block 3	Targeted	35 1/hr 300 kpa	6.0 m spacing
Block 4	Targeted	43 1/hr 300 kpa	9.0 m spacing
Block 5	Targeted	43 1/hr 300 kpa	7.2 m spacing
Block 6	Targeted	43 1/hr 300 kpa	6.0 m spacing
Block 7	Targeted	25 1/hr 250 kpa	9.0 m spacing
Block 8	Targeted	25 1/hr 250 kpa	7.2 m spacing
Block 9	Targeted	25 1/hr 250 kpa	6.0 m spacing
Block 10	Targeted	35 1/hr 250 kpa	9.0 m spacing
Block 11	Targeted	35 1/hr 250 kpa	7.2 m spacing
Block 12	Targeted	351/hr 250 kpa	6.0 m spacing
Block 13	Full Cover	160 1/hr 250 kpa,	4.4 x 9.0 spacing[1]
Block 14	Full Cover Pulsed	160 l/hr, 2 min[2], 300 kpa	4.4 x 9.0 spacing
Block 15	Full Cover Pulsed	160 l/hr, 2min[2], 300 kpa	4.4 x 9.0 spacing
Block 16	Full Cover	350 kpa	13.2 x 9.0 spacing
Block 17	Full Cover	300 kpa	13.2 x 9.0 spacing
Block 18	Full Cover	250 kpa	13.2 x 9.0 spacing

Raw notes from August 7th 06 change-over

As requested by email on the 7 july 06 from Ian Woodhead the following changes have been made to the Seleni frost trial. The two pulse turbo hammer blocks (14,15) at three min on three min off have been replaced with one turbo hammer block (15) at two min on two min off and a super ten block (14) running at the same times.
Logger F7 is already in the turbo hammer block so was left there,
logger F8 was brought across from block 16 to go into the newly created pulsed super tens in block 14.
All the targeted flipper blocks that were requested already existed, given the new sways that were installed as instructed. So loggers were moved from there old positions into the required blocks.
Loggers F1 and F2 were moved across to blocks 4 and 5, The requested 43 l/hr @ 300kpa @ 7.2m and 9.0m, old sway.
Logger F3 was already in position in the correct block (8) bar the new sways and so logger F5 was brought down to block 9 filling the requested 25 l/hr @ 250kpa @ 7.2m and 6.0m, new sway. The left over loggers have been divided up into new positions as follows.
Logger F0 has been brought up from block 18 into block 17, (vice versa, Ian W)
logger F6 has remained inside block 13 but the pressure has been reduced to 250kpa from 300kpa, and logger F4 has been relocated to block three.
Tipper array is now located at Lawn Rd and operated manually. Flipper is new style flipper 35 lph @ 300kpa. All possible data was downloaded before the new changes took place.

[1] Altered from 300kPa on August 7, 2006

[2] Altered from 3min on - 3min off to 2min on – 2min off on August 7 2006

logger 0, block 17
logger 1, block 4, 43 l/hr at 300kpa, 7.2m, old sway
logger 2, block 5, 43 l/hr at 300 kpa, 9m, old sway
logger 3, block 8, new sway, 25 l/hr, 250 kpa, 7.2m (check span)
logger 4, block 3
logger 5, block 9, 25 l/hr at 250kpa, new sway, 9m (check span)
logger 6, block 13, 250 kpa
logger 7, block 15, turbohammer 2min on – 2 min off
logger 8, block 14, super ten pulsed 2min on/off