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BEST MANAGEMENT PRACTICES FOR OPERATING WIND MACHINES FOR MINIMIZING COLD INJURY IN ONTARIO

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ABSTRACT Cold or frost injury can occur on sensitive perennial crops such as grapevines and tender tree fruits if plant tissue temperatures fall below critical values beyond which there is an irreversible physiological condition causing malfunction or death of plant cells. One method for protecting these crops is to use wind machines, which are tall, fixed-in-place engine-driven fans that pull warm air down from high above ground during strong temperature inversions, raising air temperatures around cold-sensitive crops. Wind machines are relatively new to Ontario, only first used for grapes in Niagara in the late 1990's. Today there are close to 500 in use. They have worked well for growers, but there have been noise complaints from nearby neighbours. A four-year applied research project ended in fall 2009 with the objective to establish best management practices for wind machines and find ways to use them more effectively. After the test wind machine operated 29 times for a total of 141 hours over the research period, the authors learned a great deal about ways to minimize machine operation. This paper summarizes the findings.

Keywords: Wind machine, Cold injury, Temperature inversion, Agricultural noise, Frost protection.

INTRODUCTION The Ontario grape and wine industry has been planting more high quality *vinifera* grapes. Unfortunately, many cultivars are sensitive to cold injury in late spring, early fall and mid winter. The winters of 2003-2005 had sufficiently cold temperatures to result in vine bud and plant injury. Many wind machines were installed as a result, but there was little local knowledge on how best to operate them. As a result, a project addressing *best management practices* was conducted from November 2005 to October 2009 in Niagara.

HOW DO WIND MACHINES WORK Wind machines are tall, fixed-in-place, engine-driven fans that pull warm air down from high above ground during strong temperature inversions, raising air temperatures around cold-sensitive perennial crops such as grapes (Figure 1). They are not the same as wind turbines which are designed to create electricity from wind energy (Fraser *et al*, 2009).

Figure 1. This vineyard and wind machine were studied. The picture was taken from a tower (note shadow of tower) used to monitor wind speed/direction and the air temperature profile from fruiting level to 20 m above the vineyard.

There are currently four types of machines, but all work similarly. Fan blades angle 6^{o} down from vertical and during operation, wind machines pull warm air from at least 15 m above the field then blow it down and out, pushing away and replacing cold air near target crops (Figure 2). This breaks up microscale air boundary layers over plant surfaces, improving sensible heat transfer from the air to the plants. Wind machines transfer heat by forced convection. While the blades spin, the head of the fan rotates around the tower's vertical axis. Air circulates north, east, south, west then back where it started 4.5-6.5 minutes earlier, depending on machine type. The area protected covers 3-5 ha depending on topography, field layout, strength of temperature inversion, time of year and drift due to slight winds. If the machine completes this circuit too slowly, cold air can resettle or drift in from cooler areas upstream or upwind of the machine, resulting in crop injury.

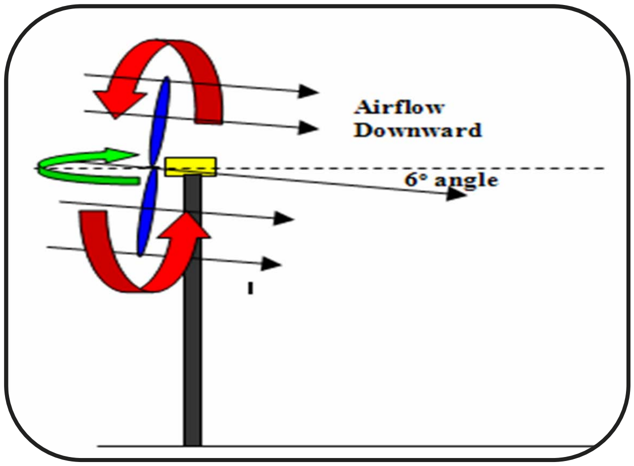

Figure 2. Wind machines pull warm air down from high above crop, blowing it downward and outward, pushing away cold air and replacing it with warmer air near target crops.

TEMPERATURE INVERSIONS Temperature inversions are *strong* if air temperatures 20 m above the field are at least 3°C warmer than at vine level 0.625 m. Strong night-time radiative temperature inversions were confirmed during periods when wind machines might be used below and above the Niagara Escarpment when skies were clear and starlit, with minimal wind movement.

Inversions are affected by even slight atmospheric winds. Wind speeds less than about 7 km/h are necessary for inversions to form and greater than 7 km/h to break up (Figure 3).

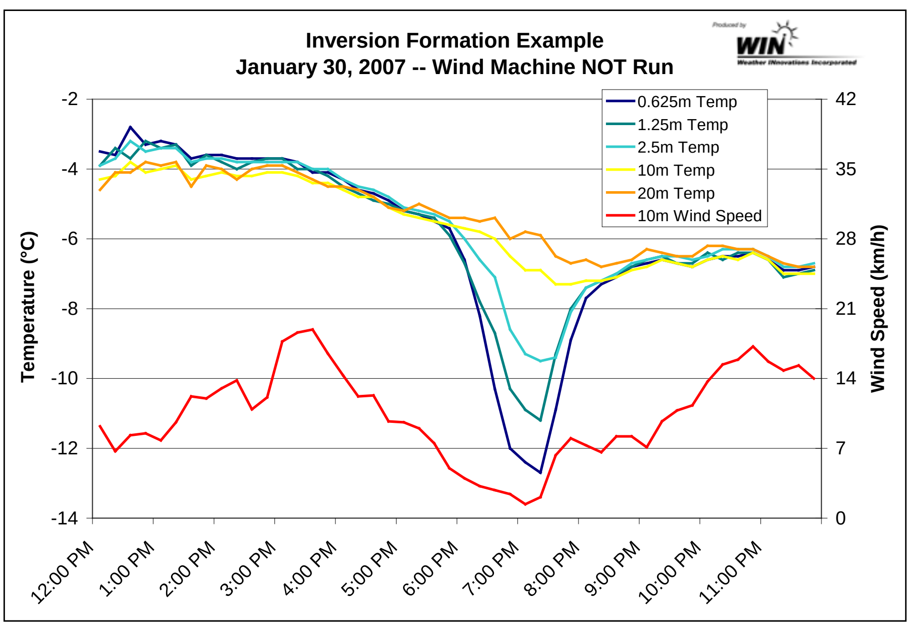

Figure 3. This strong temperature inversion below Escarpment near Virgil of about 7°C between 20 m above and 0.625 m above ground, started forming as winds dropped below 7 km/h at 5:30 pm. The inversion ended when wind speed rose above 7 km/h at 8:00 pm.

A date was chosen when the machine was <u>not</u> operated so the true impact of atmospheric wind would demonstrate its affect.

Temperature inversions just before wind machines were turned on during this project generally ranged from 5-7^{o}C, but inversions as great as 10^{o}C were observed. Inversions can develop, dissipate, and redevelop all in the same night as winds rise or fall. Wind machines can raise air temperatures around plants by about half the temperature inversion difference.

Vineyard air temperatures are often very different from local or regional forecasts. Forecasts don't predict temperatures close to the ground where grape buds are located and they don't account for low areas where temperatures are often colder. Temperatures can drop abruptly, many degrees in an hour, often at sunset or sunrise, so predicting exactly if and when a wind machine might need to be operated can be difficult.

HOW WIND MACHINES AFFECT AIR TEMPERATURES IN A VINEYARD
The effect on ground air temperatures is almost instantaneous after a wind machine is turned on, but air temperatures will vary slightly throughout the area. See Table 1. Note the strong temperature inversion of 4.8°C just before the wind machine started (6.2–1.4 = 4.8°C), while air temperatures high above the vineyard remained almost constant, indicating what might be considered 'an ocean of warm air' above.

Table 1. Air temperatures measured in real-time over 35 minutes at several vine level locations (0.625 m above ground) compared to 20 m above the vineyard before and after a wind machine started during a potential spring frost 18 May 2009. The vineyard was located below the Niagara Escarpment southeast of Virgil.

Time of Day (a.m.)	**Wind Machine Status**	**20 m <u>above</u> vineyard**	**150 m South of WM (0.625 m level)**	**75 m South of WM (0.625 m level)**	**115 m North of WM (0.625 m level)**
2:20	Off	6.1°C	1.6°C	1.7°C	1.5°C
2:25	Started	6.2°C	1.4°C	1.7°C	1.4°C
2:30	On	6.1°C	1.2°C	1.5°C	1.5°C
2:35	On	5.8°C	1.0°C	1.0°C	1.7°C
2:40	On	5.8°C	0.9°C	1.0°C	2.0°C
2:45	On	6.1°C	0.9°C	1.3°C	2.2°C
2:50	On	6.0°C	0.8°C	1.2°C	2.5°C
2:55	On	6.2°C	0.8°C	1.2°C	2.7°C

The machine was set to start at 1.5^{o}C using a sensor 15 m away at 0.5 m above ground. The differential was set at 2^{o}C so the machine would turn off if the air temperature rose to 3.5^{o}C (1.5^{o} + 2^{o} = 3.5^{o}C). The smaller the differential, the less time the machine operates after temperatures rise. There was a slight SW wind of 4-5 km/h pushing air NE. The vineyard site was almost level. Even though wind machines blow air outward, mixing it in all directions, their area of influence is not circular. It can be distorted by land slope and wind direction. Cold air flows down slope like 'cold molasses'. In Niagara, below the Escarpment, there is a natural airflow from the base of the Escarpment to Lake Ontario which naturally skews a wind machine's area of influence into an elliptical shape.

Even though winds are usually calm to light when wind machines operate, wind direction appears to skew the area of influence. If both land slope and wind direction are in the same direction, areas of influence will be elliptical in shape in that direction. If land slope and wind direction are in opposite directions or at right angles to each other, this alters the shape of the area of influence. Most times when wind machines are used in Niagara, winds are from SW creating the area of influence shape as in Figure 4.

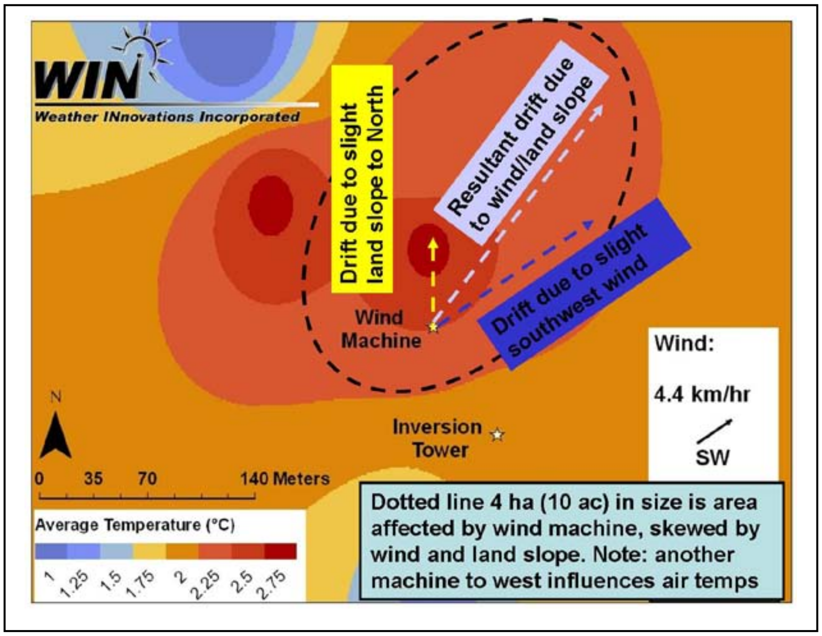

Figure 4. This 18 May 2009 spring frost event vineyard map shows the area influenced by a wind machine is skewed by the effect of the slope of land and wind direction and speed, even though winds are generally calm to light when machines operate. The dotted line represents 4 ha of vineyard.

WIND MACHINE USE DURING RESEARCH TESTING PERIOD During the four year research project, the test site wind machine operated 29 times for a total 141 hours, which is less than originally anticipated, with the range 22 to 48. It is likely that during the very cold winters of 2003, 2004 and 2005 (before this project commenced) wind machines would have operated for longer periods. With experience, growers operate machines more precisely with fewer hours.

DEW POINT TEMPERATURE One tool for understanding when to turn on a wind machine is to understand *dew point temperature* (Evans, 2009) at which condensation of water vapour in air first condenses from a gas to a liquid. If there is a large difference between outside air temperature and the dew point, the air is 'dry'. If there is a small difference, the air is more ‘humid’. At 100% relative humidity, the dew point and outside air temperature are the same.

During a radiative freeze, often after sunset, infrared radiation is constantly exchanged between any object, like grape vines and the atmosphere. If skies are cloudy, water vapour in the air absorbs and re-emits the infrared radiation back to the earth’s surface. If overnight skies are clear, and winds calm, more infrared radiation is emitted from the vines than back from the atmosphere. So, vine surfaces become cooler than the air around them. ***When water condenses on a surface (eg. grape bud) it releases lots of heat (latent heat of condensation) and this is helpful in protecting your crop from cold injury.*** This heat is often more than enough to sufficiently replace heat lost through radiation to the dark night time sky, and averting further temperature decreases, at least temporarily. During radiative freezes, exposed plant tissues can be 1 to 2^{o}C colder than the surrounding ambient air and so will reach the dew point before the air surrounding them. So, water condenses on these tissues, releasing heat and keeping the tissues at, or very near, the dew point temperature.

If dew point is only a few degrees above critical crop damaging temperatures, there is little likelihood of damage to that crop. The dew point basically establishes the minimum expected air temperature for the night period. This is because once you reach dew point, air temperatures drop slowly as more water is condensed and releases heat to the air and anything else that air is in contact with, such as a grape bud.

If dew point is at, or a few degrees below critical crop damaging temperatures, some intervention may be needed using wind machines, or adding heat to make up the difference between dew point and critical temperatures. You might want to turn on wind machines sooner to reduce the 1 to 2^{o}C cooler temperatures of plant surfaces compared to air around it. This might allow you to outlast the rate of temperature drop during the night until the sun rises. Fortunately, most radiation frosts in spring and fall have fairly high dew points near critical temperatures, so heat released through condensation may be all that’s needed. Wind (either natural, or caused by wind machines) mixes the colder air mass near the crop caused by radiation cooling with the warmer air mass high above the crop. It evens out the air temperature profile so air is warmer near the crop, even as the crop continues to radiate heat to the night time sky.

MEASURING BUD HARDINESS AND BUD SURVIVAL Grapes transition from a cold tender to cold hardy state beginning in fall, responding to seasonal changes in temperature, day length and moisture content of plant tissues (Zabadal *et al*, 2007). There are three critical times Ontario growers need to protect crops against cold injury: late spring frosts (early growing season); early fall frosts (just before harvest); and mid winter cold (dormant season)

A system for differential thermal analysis was constructed to assess cold hardiness of grapevine buds based on one developed and used at Washington State University. This unit incorporated a sample chamber with a programmable freezer and a data acquisition system. When water freezes, heat is released in an exothermic reaction. By using sensitive thermoelectric modules, one is able to identify these heat loss or freezing episodes during a controlled freezing test. Low temperature exotherms (LTE) indicate the freezing of intracellular water (within cells), typically resulting in bud death (Figure 5).

The data was analysed and recorded as LTE_{50}, the temperature at which 50% of the buds are killed.

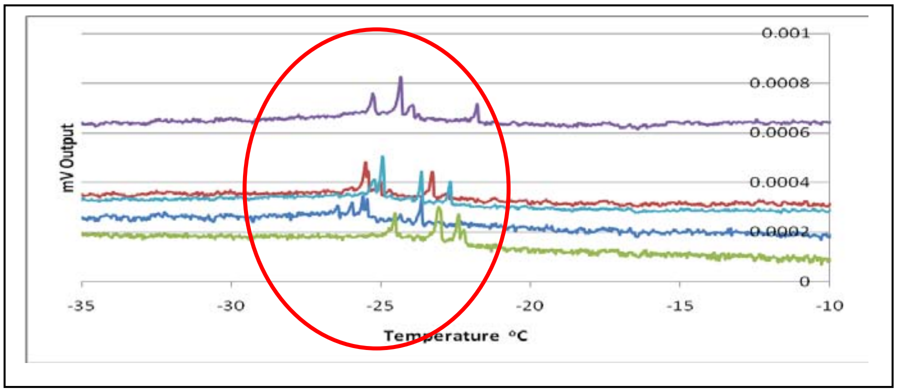

Figure 5. Low Temperature Exotherms (LTE) from Chardonnay sample from 4 Dec 2008. Spikes indicate a bud killing event. The above data resulted in a LTE_{50} of -23.1^{o}C.

NOISE FROM WIND MACHINES Many neighbours do not like wind machine noise (Fraser *et al,* 2006). Wind machines need large engines operating at high RPM and long pitched blades to blow air a long distance, so it is difficult to design machines that are quieter. Sound comes from the engine and from the blades as they rotate. Slower blade speed reduces noise, but reduces airflow, meaning more machines are needed to cover the same area. Depending on machine type, it takes 4.5 to 6.5 minutes for a wind machine to make a full 360^{o} sweep around the tower, so sound oscillates in intensity in a sinusoidal fashion. Some find this irritating, since it makes them wait in anticipation for the sound to grow louder (Figure 6).

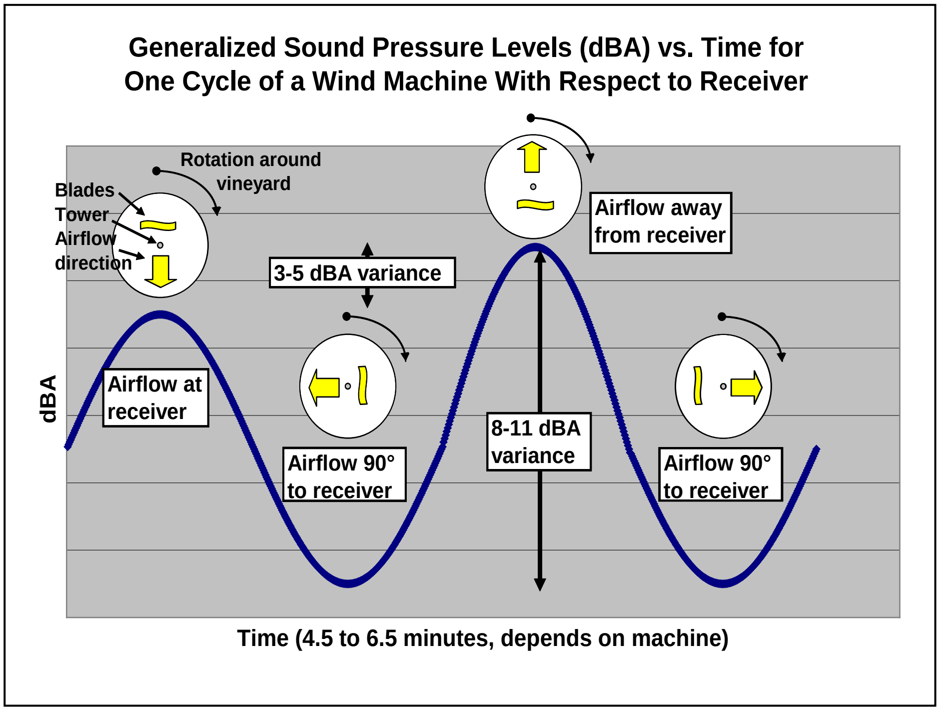

Figure 6. Neighbours hear wind machine sound as varying sinusoidally as blades sweep around the field. Sound is greatest when blades blow air *away* from neighbours, next greatest when blowing *at* them. If air is blown perpendicular, the sound is greatly reduced.

Conditions *outside* a house complicate and affect sound movement from wind machines:

- natural quiet of a cold, rural spring, fall or winter night
- absence of normal wind sound
- lack of grape vegetation, grass on ground or leaves in woodlots to muffle sounds
- bouncing of sound waves off the warmer temperature inversion layer high above ground
- hard, non-absorbing ground surfaces in winter for sound waves to travel across
- source of sound being very high above ground
- simultaneous operation of multiple machines
- low relative humidity of the cold air

Conditions *inside* homes that complicate and allow external sound waves to penetrate, or be amplified include; large rooms, large windows, hard floors and light construction. Wind machine sound is generally quieter and less offensive in small carpeted rooms with heavy thick walls and in areas of the house on the opposite side to the wind machine(s) or in basements. The sound is sometimes partially masked inside a house if there is 'white noise' present such as a radio, television, or ventilation fan operating.
Wind machine blades produce low frequency infrasound waves that travel long distances and may penetrate, or excite, building components of residential structures. Low frequency sound is like the low bass music sounds you might hear in your home when someone next door is playing their stereo, even though you cannot hear the rest of the music.

WIND MACHINES AND NORMAL FARM PRACTICE Farmers are protected from nuisance noise complaints by neighbours provided they are following *normal farm practice*. Normal farm practice can only be determined by the *Normal Farm Practices Protection Board (FFPPA),* a quasi-judicial administrative board appointed by the Ontario Government, but comprised of non-government members.

The *FFPPA, 1998* defines normal farm practice as one which:

- Is conducted in a manner consistent with proper and acceptable customs/standards, as established and followed by similar agricultural operations under similar circumstances

- uses innovative technology consistent with proper advanced farm management practice

BEST MANAGEMENT PRACTICES Based on our research, here is a list of best management practices for operation of wind machines to use them more effectively and minimize nuisance noise for neighbours.

Crop hardiness

- Plants should be managed so they are as healthy as possible going into winter

- The most up-to-date plant hardiness information and critical temperatures should be taken into account when decisions are made to operate a wind machine

Placement

- Wind machines should be located to take into account the expected skewing effects on their areas of influence by topography and wind direction

- Wind machines should be located to take into account the location of adjacent wind machines and features which might provide additional cold injury protection (roads, warm buildings, streams, woodlots)

- Growers should consider planting crops that are more sensitive to cold injury as far as practical from neighbours' houses, so wind machines can be located further from homes

Monitoring

- Growers should use the best local weather available

- Growers should continually monitor for strong temperature inversions, greater than 3^{o}C, on or near their farm, so they know if operating machine(s) might provide some plant protection from cold injury. This includes a tower at least 10 m high to monitor temperatures high above the crop

- Growers should set start-up temperatures for their wind machines based on sensors located within 15 m of each machine, and below the fruiting wire height

- Growers should monitor and automate start up/operation/shut down of wind machines, using a combination of real-time remote temperature/wind speed/wind machine operation sensing devices and monitoring via cell phones/computers/pagers, etc.

- Growers should set start-up temperatures as close as practical to expected critical air temperatures; Spring frost: 2 to 3°C; Fall frost: 1 to 2°C; Winter: Variable based on latest bud hardiness data from local freezing trials

- Growers should set the differential (wind machine stop) temperature 2°C - 3°C higher on their wind machines than for their start-up temperatures

Wind

- Growers should not operate wind machines if wind speeds are much higher than 7 km/h as there is unlikely to be a strong temperature inversion or 'heat' above the field anyway

- Growers should not operate wind machines if wind speeds are 13 km/h, or higher, as this can damage their long, thin blades

- Growers should never operate wind machines if wind speeds are 21 km/h, or higher, as this can seriously damage their wind machines

Maintenance

- Growers should maintain machines in good condition with checkups annually by; changing gearbox oil (at tower base and top); lubricating drive lines and inspecting seals; checking tension of all bolts on tower; inspecting blades and attaching hardware; performing regular engine maintenance; and keeping booster cables handy for quick use

Noise

- Wind machines should be located as far as practical from neighbouring homes within agricultural areas, but not closer than 125 m unless best management practices are used

- For neighbours living within 125 m of a machine, growers should; discuss the need for wind machines and how and why they operate; consider creating an early warning system about possible machine use; give them a 24-hour cell phone number to call; use a 'Last On, First Off' principle for machine(s)

- Growers should be more diligent in operating wind machines on farms where they do not live, as they are not always there to hear if and how their machines are operating

- All wind machine engines should have mufflers

On-going learning

- Growers should train and educate all employees who will operate wind machines on the latest best management practices to minimize machine operation

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