Development of probability estimates of grape diseases infestation and extent of infestation for each major grape disease

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Nova Scotia Federation of Agriculture would like to recognize the collaborative relationships that exist among Agriculture and Agri-Food Canada and the Nova Scotia Departments of Agriculture and Environment.

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Summary

Grape diseases, which represent a major constraint on Eastern Canada grape production (Carisse, 2009) are likely to be affected by temperature and rainfall changes resulting from global climate warming. There is no evaluation of the potential impact of climate change on grape diseases in Eastern Canada. Consequently, this study undertook a quantitative analysis of the relationship between weather and seasonal disease risk for the key diseases affecting grapes. From these analyses, probability estimates of grape diseases infestation were developed (risk indexes). The purpose was to ascertain likely changes in regional disease development and consequent losses and disease control requirements arising from climate change, to allow the Nova Scotia grape industry to carry out future planning.

Fungal pathogens such as those affecting grapes must go through a series of steps (or processes) in order to complete their life cycle. Typical grape pathogen life cycle encompasses two reproduction cycles; the sexual reproduction cycle which aim at surviving during the winter months and at maintaining genetic diversity. The asexual or vegetative cycle, aim at increasing the pathogen population so that enough individuals will be able to initiate the sexual cycle. In practice, diseases (symptoms) are mostly caused by the secondary cycles provided that initial inoculum is present to initiate epidemics. Almost all steps (infection, sporulation, dispersal) involved in secondary cycles occur in a timeframe of few hours (Carisse et al., 2000). Consequently, most disease prediction models use hourly data to estimate probability of disease.

The challenge here was that only daily data were available to make disease risk predictions. In addition, only temperature (Tmax and Tmin) and precipitation data were available. This restricted the type of models that could be used. Because, downy mildew (*Plasmopara viticola*) epidemics are mostly driven by the occurrence and frequency of rain, it was decided to develop downy mildew risk indexes based on number of days favorable to disease development. For powdery mildew (*Erisyphe necator*) the most important variable is temperature, which affects the rate at which epidemics will develop and consequently yield losses. The powdery mildew risk indexes were thus developed using degree-days. Unfortunately, it was not possible to develop risk indexes for Botrytis bunch rot (*Botrytis cinerea*) because the most important variable affecting disease development is relative humidity which was not available (Carisse et al., 2018).

Nevertheless, for both downy and powdery mildew, risk indexes were developed following three steps. First, a 13-years data set on downy and powdery mildew severity, hourly microclimate within or near the grape canopy, and yield losses at harvest was used to develop seasonal disease risk indexes. Second, the same data set was used to calculate the risk indexes using a daily data (Tmax, Tmin and rain), and to estimate the reliability of daily data-based indexes (correlations between the indexes and yield losses). Finally, the daily data-based indexes were calculated using the projection data (2015-2025) for the 22 locations in Nova Scotia.

Summary of the results for downy mildew. Downy mildew risk indexes were first calculated using hourly weather data monitored within or near the grape canopy. The best downy mildew risk index was calculated as the number of days favorable to both zoospore dispersal and primary infection in May and the number of days favorable to primary and secondary infections in June. The correlation coefficient between this index and yield losses was 0.93, 0.89, and 0.86 for the grape variety Chancellor, Vidal, and Seyval, respectively. However, when the indexes were calculated using daily data correlation coefficients were lower. Nevertheless, the most reliable index was calculated as the number of days favorable to spore dispersal in May and June with correlation coefficient between this index and yield losses of 0.69, 0.73, and 0.80 for the grape variety Chancellor, Vidal, and Seyval, respectively. This index was used to estimate the risk of downy mildew in Nova Scotia at 22 sites with the projection data from 2015-2025. Both spatial and temporal variations in predicted yield losses caused by downy mildew were present.

Summary of the results for powdery mildew. Regardless of how degree-days were calculated (from hourly or daily data) there was a low correlation between degree-days accumulated since April 1st and incidence of diseased leaves. However, the correlation between degree-days cumulated since April 1st and yield losses were much higher. For degree-days calculated from April 1st to end of August (Day 244) from hourly data, correlation coefficients were 0.87, 0.90, and 0.87 for grape variety with high, moderate or low susceptibility to powdery mildew. Similar trend were observed when degree-days were calculated using daily data. For degree-days calculated using daily data, higher correlation coefficients were obtained when degree-days were accumulatedfrom April 1st to the end of June (Day 183). This could be explained by the high level of susceptibility of inflorescence and berries during this period. This index was thus used to

estimate the risk of powdery mildew in Nova Scotia at 22 sites with the projection data from 2015-2025. Both spatial and temporal variations in predicted yield losses caused by powdery mildew were present.

Introduction

In Canada, grapes (*Vitis* spp.) are mostly produced in Ontario (7,596 ha; 60% of national acreage) and in British Columbia (4,122 ha; 33% of the national acreage). Grapes are also produced in Quebec (575 ha; 5% of the national acreage) and Nova Scotia (356 ha; 3% of the national acreage)*. Most of the fresh market grape varieties belong to *Vitis lubrusca* which originated from North America. To produce winter hardy and phylloxera resistant rootstocks, several crosses were made with *Vitis riparia*, while *Vitis vinifera* is used to make wine and is often denoted as "European grape". The first wines, made by European settlers in North America, were made with *Vitis labrusca* and *V. riparia*. Unfortunately, the resulting wines were not of great quality compare to the wines made in Europe at that time. To improve wine quality, several grapes growers tried to grow *V. vinifera* without much success mostly because of their poor winter hardiness. In Canada, the first vineyards were planted in the mid 1800's in Ontario and British Columbia. Both *Vitis lubrusca and V. vinifera* varieties were planted but winter survival was still a challenge. In 1980's, advances in viticulture practices and shift in consumer demand for dry table wines favor the expansion of the grape and wine industry in Canada. The wine industry is much more recent in Quebec and in Nova Scotia. Winter survival and the number of days without frost are major challenges for these regions. Because, the current market demands are for European-style wines, it is expected that growers will be tempted to plant *V. vinifera* varieties which are not winter hardy and for most of them more susceptible to diseases. In this context, it is crucial to study the impact of climate change on the major grape diseases.

*Statistics Canada. Table 001-0009 - Area, production and farm gate value of fresh and processed fruits, by province, annual CANSIM (database) (accessed 2016-01-29

In almost all grape production areas, including eastern Canada, disease management is a concern for grape growers. The risk and potential yield losses associated with grape diseases, is influenced by the susceptibility of the grape cultivar, the prevailing weather conditions, and the size of the

pathogen population (disease triangle). Grape diseases are caused by fungi, fungus-like organisms (oomycetes), bacteria, phytoplasma, and virus. More than 50 grape diseases are described in the « Compendium of Grape Diseases » published by the American Society of Phytopathology (Pearson and Goheen, 1988). The most important diseases, based on prevalence and potential impacts on yield losses (quantity and quality) are downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and Botrytis bunch rot (Botrytis cinerea). For some cultivars, anthracnose (*Elsinoe ampelina*) and black rot (*Guignardia bidwellii*) may be important diseases (Carisse and Morissette-Thomas, 2013). Under optimal disease development conditions (high inoculum + susceptible cultivar + favorable weather), these diseases may cause up to 100% yield losses (Carisse, 2009). In most commercial vineyards, however, these diseases caused reduced yield (Kg/ha), reduced vine vigor and winter survival, and affect organoleptic quality of grapes (Calonnec et al., 2004; Gadoury et al., 2001; Pool et al., 1984).

In Eastern Canada, management of the major grape diseases (downy mildew (DM), powdery mildew (PM) and Botrytis bunch rot (BBR) will required from 6 to 15 fungicides applications (Bervejillo et al., 1998; carisse, 2009; Carisse 2015; Carisse et al., 2009). This represents a significant production cost, potential residues on berries, impact on vine flavors, and marketing issues (consumers demand). In addition, the expected demand for wines made with *Vitis vinifera* varieties, which are generally more susceptible to grape diseases, will create pressures to keep these high-value grapes free from diseases.

Background

Importance of grape downy mildew (Plasmopara viticola).

Downy mildew is one of the most important grape diseases worldwide. It is caused by the fungus-like organism *Plasmopara viticola*, which was first observed in 1834 in the northeastern USA, its center of origin (Gessler *et al*. 2011). Because of the importance of grapes and of downy mildew, many scientific and technical reports are available on *P. viticola* genetic and ecology, and on downy mildew epidemiology and management (Gessler *et al*. 2011). In their review, Gessler *et al.* (2011) mentioned that since 1910, more than 3,000 reports had been published on grape downy mildew.

Epidemiology grape downy mildew.

Grape downy mildew is a polycyclic disease with two distinct phases, the primary infections caused by zoospores produced in oospores (sexual structure) and the secondary infections caused by sporangia (asexual structure) (Figure 1). *Plasmopara viticola* overwinters as oospores within infected leaves fallen on the vineyard floor or within the surface layer of the soil. In the fall, oospore production is favored by dry conditions and occurs under a wide range of temperatures during leaf senescence (Rouzet and Jacquin, 2003). Oospores mature during the late winter and early spring, and mature oospores germinate during the spring period, causing the primary infections. The temperature influences the moment when primary infections begin. The germination of oospores starts when the soil temperature reaches 12°C and the soil is wet; an accumulation of 160 degree-days (base temperature of 8°C) is necessary to break oospore dormancy (Rouzet and Jacquin, 2003). Once dormancy has been broken, germination is influenced by temperature, rain, and humidity (Caffi et al. 2009; Hill 2000; Rossi et al. 2007a, 2007b, 2008). Oospore germination is favored by temperatures above 11°C (Park et al., 1997) and inhibited by temperatures above 30°C (Blouin, 2007). In Eastern Canada, the period of oospore germination corresponds to May to June. However, the germination of oospores may occur over a period of 2 to 3 months (Gobbin et al. 2003, 2005). Under favorable conditions, up to 50 zoospores per oospore could be produced and rain-splashed to new shoots positioned near the ground (Rossi and Caffi 2012; Viret and Siegfried 1996). Vines trained as Low Head system with fruiting buds located at 30 to 40 cm from the ground are highly susceptible to infection by splashed zoospores.

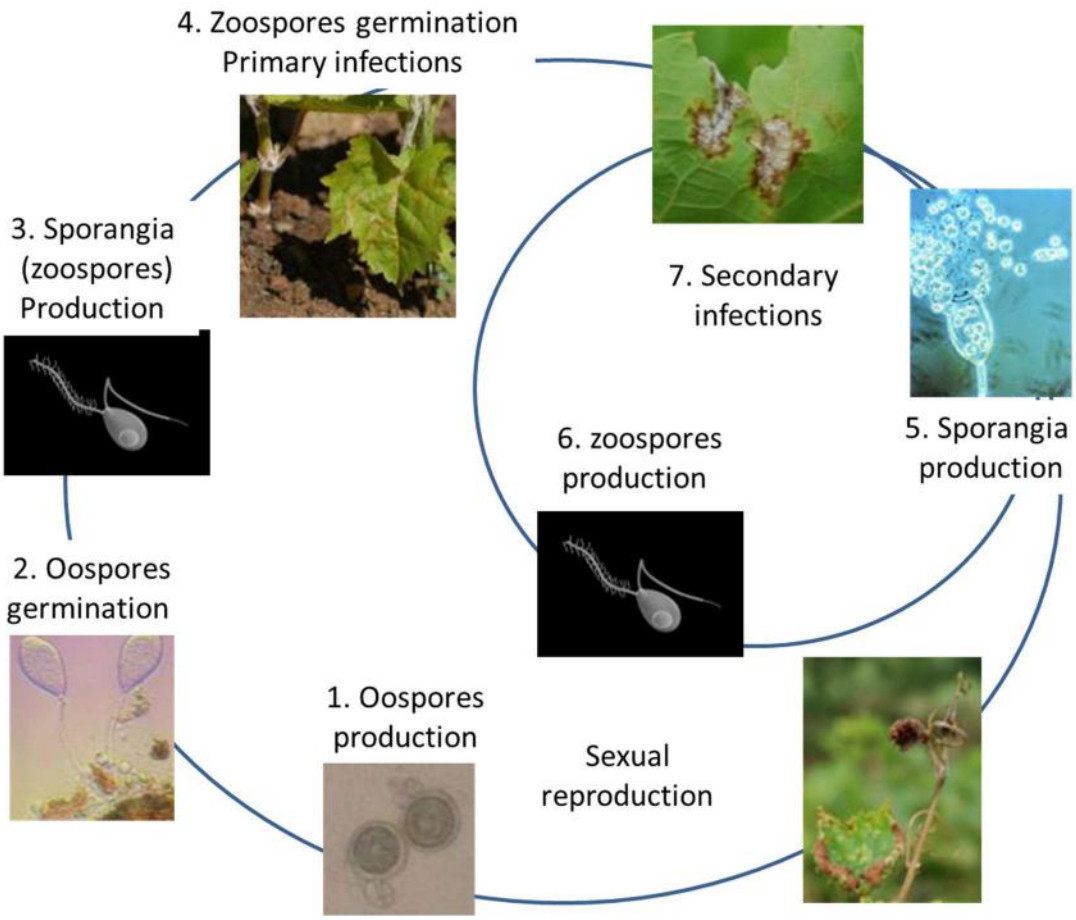

Figure 1. Schematic representation of simplified *Plasmopara viticola* (downy mildew) life cycle

In the presence of tissues wetness, zoospores infect the vines (above ground parts). The severity of infection will depend on duration of tissue wetness, temperature, and ontogenic resistance conditions (Kennelly et al., 2005; Lalancette et al., 1987; Riemann et al. 2002). The incubation period (time between infection and symptoms appearance) varies from 4 to 9 days depending on air temperature, relative humidity, and vine susceptibility (Kennelly et al., 2007; Orlandini et al., 2008; Rosa et al., 1995). Initially, lesions appear as oil spots (Figure 2A) and eventually become reddish brown. New spores (sporangia) are produced on the underside of leaf lesions (Figure 2B), on infected tendrils (Figure 2C), and on berries. These sporangia are responsible for the secondary infections. Most downy mildew damages are due to infections of inflorescences (flower rot) (Figure 2 D-E) and by infections of bunches before the nouaison growth stage (Figure 2F). Berries become less susceptible once the veraison stage has been reached (Kennelly et al.,

2005). Consequently, from a yield perspective, early infections are much more damaging than late ones (after nouaison) (Jermini et al., 2010). However, late infections may reduce vine vigor (Davidou and Crachereau 2011), which is particularly important for northern viticulture, because the vines must be vigorous enough in the fall to survive during the winter months.

Management of downy mildew.

Because of the polycyclic nature of the disease and the importance of oospores as initial inoculum, the management of grape downy mildew generally relies on fungicide applications early in the season to control primary infections and prevent infections of inflorescences, flowers, and young berries (Carisse, 2015).

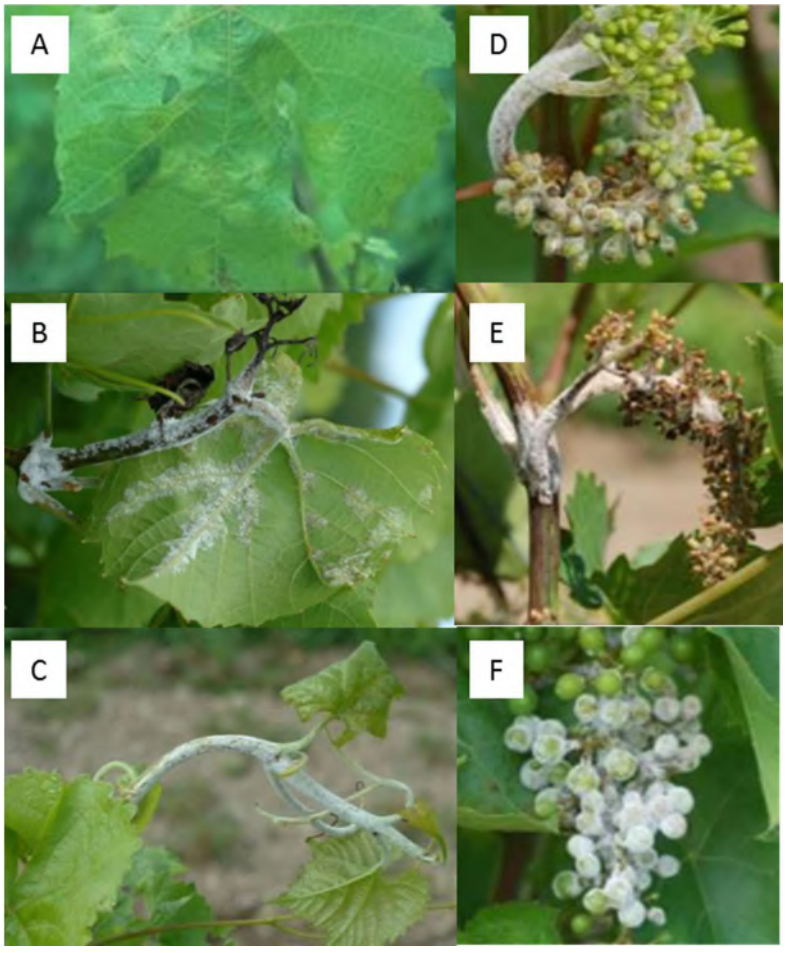

Figure 2. Symptoms of grape downy mildew (*Plasmopara viticola*). Oil spot (A), sporangia produced on the underside of a leaf (B), infected new growth (C), Infected inflorescence (D), flower rot (E), and infected berries (F).

Downy mildew prediction models.

Downy mildew epidemics begin with a limited amount of oospores (initial inoculum) (Carisse, 2015) and disease progress is caused by exponential rate of fungal multiplication through several secondary infection cycles (Lafon and Clerjeau, 1988; Lalancette et al., 1988a,b; Blaise et al., 1999; Orlandini et al., 1993) (Figure 1). The relationship between temperature and moisture (including wetness and rain) and downy mildew development (*P. viticola* reproduction) served as the basis for most prediction systems. Grape downy mildew prediction models have been proposed for identifying the periods of high risk (i.e. conditions are favorable for disease development) and for scheduling fungicide applications (Madden et al., 2000; Rossi et al., 2008). Some of these models are based on the simulation of primary infection development such as the POM (Tran Manh Sung et al., 1990), EPI (Stryzik, 1983), SIMPO (Hill, 1990, 2000), DMCAST (Park et al., 1997) and UCSC (Rossi et al., 2008) models. While other models predict the development of secondary infections through the simulation of one or more stages of *P. viticola* biological cycle (Figure 1) (Blaise et al., 1999; Ellis et al., 1994; Lalancette et al., 1988ab; Madden et al.2000; Magnien et al., 1991; Magarey et al., 1991, Orlandini et al., 1993).

Because oospores play an essential role in the initiation and development of downy mildew epidemics, several downy mildew models are based on the relationship between weather and oospore maturation, release, and infection. In France, Stryzik (1983) developed the EPI model which is based on the influence of winter meteorological conditions on oospore development. The assumption underlying the model is that downy mildew, in a given vine-growing area, is the result of ecological adaptation of *P. viticola* to the meteorological conditions in this specific area. Hence, the model is based on the differences between actual meteorological data and a 30-year climatic series. Tran Manh Sung et al. (1990) proposed the POM model which uses daily rainfall starting in September to calculate DOM which correspond to the date when most oospores are mature, and indirectly the risk of primary infections (early occurring DOM = high risk of severe downy mildew epidemics). Hill (2000) developed a model named SIMPO, which is used to estimate periods of rapid oospore germination from daily mean temperature, mean relative humidity and precipitations. The model output is a daily index corresponding to the number of days needed for oospore germination. The DMCAST model is an adaptation of the POM model,

and is used to predict occurrence of primary infections when nearly 3% of oospores are ready to germinate (Park et al., 1997). These models have been validated under several environmental conditions resulting in variable downy mildew prediction accuracy (Caffi et al., 2007; Rossi et al., 2008). As a result, several crop advisors and growers still use the simple and widely known "3–10" empiric rule (Rossi et al., 2000). This rule is based on the concurrent occurrence of (1) air temperature equal to or greater than 10 °C; (2) vine shoots are at least 10cm in length; (3) a minimum of 10mm of rainfall in 24–48h (Baldacci, 1947).

Importance of grape powdery mildew (Erisyphe necator).

Grape powdery mildew, caused by *Erisyphe necator* (Schw.) Burr., (synonym *Uncinula necator*) is an obligate parasite affecting only plants in the genus *Vitis.* For more than 150 years, grape powdery mildew has been a major challenge for grape production. Hence, researches on powdery mildew were conducted since the 1850s when major epidemics occurred in Europe. At that time, sulfur sprays were proposed as a mean to control powdery mildew and then the disease was considered as a minor disease (Viala, 1893). However, rapidly it was founded that only low levels of powdery mildew on berries is needed to taint and spoil wine. Consequently, it was concluded that more research was needed to develop better management programs. In the context of northern grape production, moderate to severe powdery mildew epidemics cause reduced yield (lower berry weight), delayed berry maturity, and altered wine composition and sensory characters (Calonnec et al., 2004; Gadoury et al., 2001; Pool et al., 1984).

Epidemiology of grape powdery mildew.

Powdery mildew is a polycyclic disease with two distinct phases, the primary infections caused by ascospores (sexual spores) and the secondary infections caused by conidia (asexual spores) (Figure 3). The epidemiology of grape powdery mildew is well documented (Gadoury and Pearson, 1988; Gadoury and Pearson, 1990a, 1990b; Gadoury et al., 1997; Gadoury et al., 2001; Jailloux et al., 1998; Jailloux et al. 1999; Willocquet and Clerjeau, 1998; Willocquet et al., 1998; Willocquet et al., 1996). The pathogen overwinters as cleistothecia and ascospores are probably the sole source of primary inoculum in Eastern Canada. In areas with warmer winters, *E. necator* can survive as mycelium in buds (Pearson and Gadoury, 1987; Pearson and Gartel, 1985; Rügner

et al., 2002). In these areas, powdery mildew on flag shoots may be observed in the following spring; to our knowledge, these symptoms have never been reported in Eastern Canada. Dehiscence of the cleistothecia commonly starts at bud break and continues until the beginning of flowering (Gadoury and Pearson, 1990a). Ascospores are released from cleistothecia in response to rain (greater than 2.5 mm) when the temperatures are between 6 and 24°C. Once released, ascospores which fall on young leaves cause the primary infections. Free water or high relative humidity is required for ascospores germination. Ascospore infection will not take place at temperatures below 5°C and above 31°C. At optimal temperature (20 to 25°C), 4 h of leaf wetness is required for infection. As a result of primary infections, lesions will develop on infected leaves within 6 to 30 days depending on the temperature. Potentially large amounts of conidia are produced on these lesions and are disseminated primarily by wind (Carisse et al., 2009a,b; Willocquet and Clerjeau, 1998; Willocquet et al., 1998). As oppose to ascospores, conidia do not need few water for germination which is influenced by temperature, relative humidity and light intensity. Optimal temperature for germination of conidia is 25°C (Bulit and Lafon, 1978; Delp, 1954). Most conidia germinate at relative humidity of 40 to 100% (Bulit and Lafon, 1978). Consequently, relative humidity is generally not a limiting factor for germination of conidia (Carroll and Wilcox, 2003). At temperatures of 23 to 30°C secondary infection cycles can be completed within 5 to 7 days (Chellemi and Marois, 1991). At the end of the growing season, cleistothecia are produced on infected leaves and berries (Figure 3 and 4).

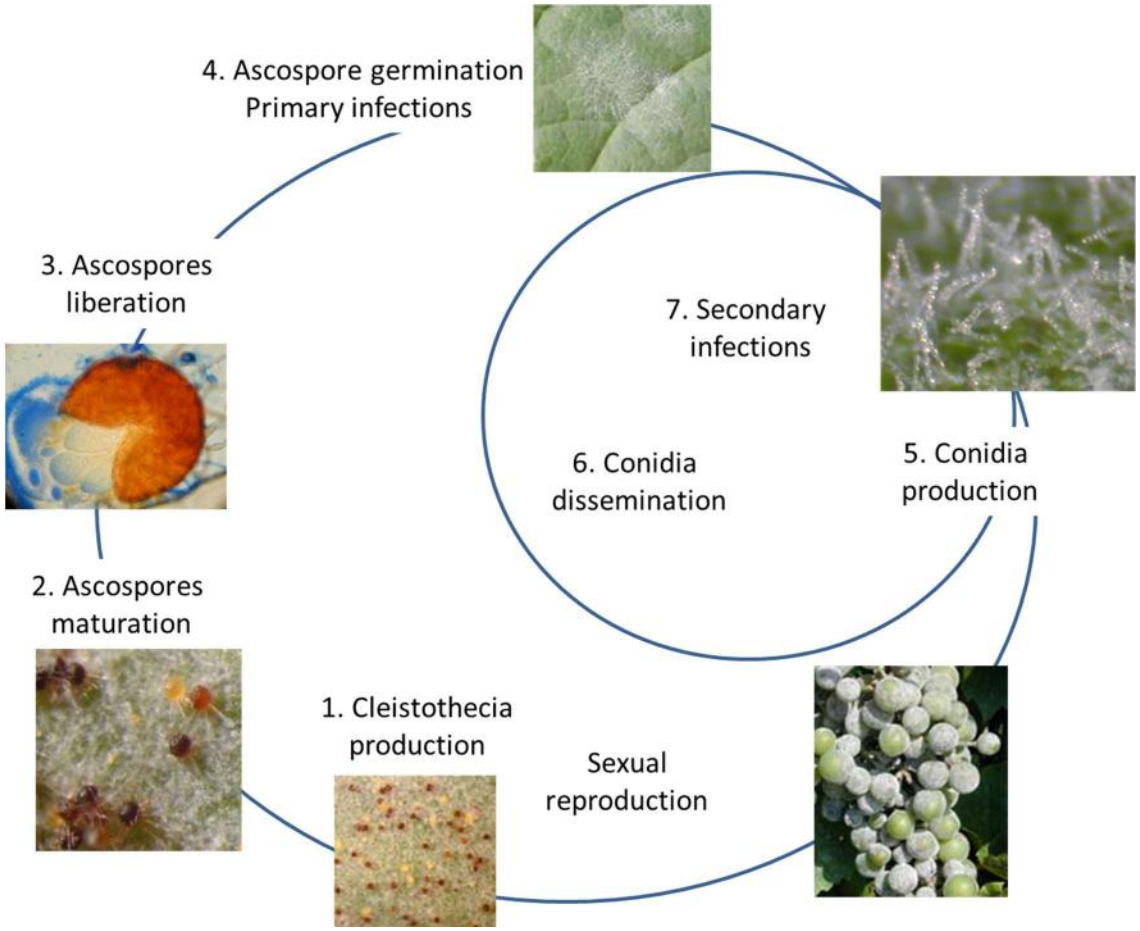

Figure 3. Schematic representation of simplified powdery mildew *(Erisyphe necator*) life cycle

Erisyphe necator can infect all aerial parts on the vine including leaves, stems, inflorescence and berries (Figure 4). The symptoms vary throughout the season as both the vines and *E. necator* advance to different stages of development. In early spring, all growing tissues are highly susceptible to infection. First lesions are small, initially discoloured, followed by the appearance of a thin white powdery layer (Figure 4A). Although all growing parts of the vine can be infected, susceptibility of some organs changes over time. The flowers and berries are highly susceptible to infection from flower formation until the berries reach about 8° Brix (Campbell et al., 2007; Gadoury et al., 2003). However, shoots, petioles and other cluster parts are susceptible all season. Old infections appear as reddish brown areas on dormant canes (Figure 4B). When powdery mildew infection occurs early in the season, it may cause reduced berry size and

reduced sugar content. Under severe epidemics, berry may crack rendering them unsuitable for wine making (Figure 4E). The tolerance level for powdery mildew at harvest is quite low; infection levels as low as 3% can taint the wine and give off-flavors.

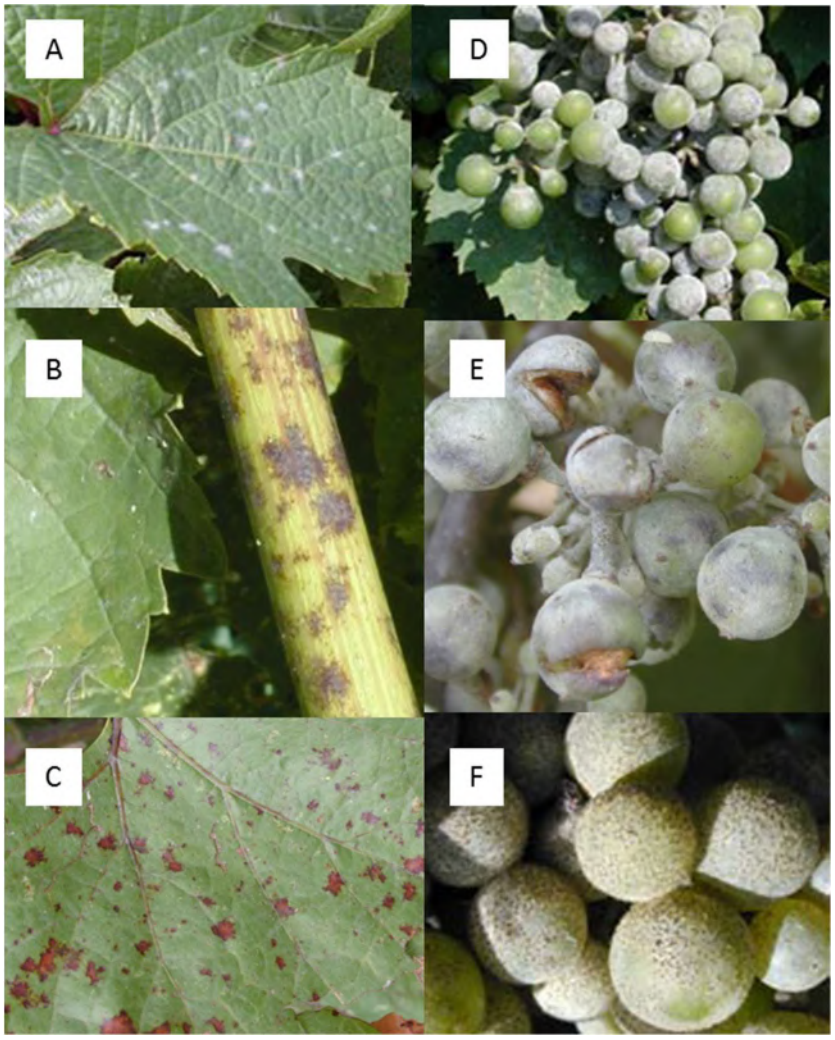

Figure 4. Symptoms of powdery mildew. Small lesions on a leaf (A), lesions on cane (B), old lesions on leaves (C), infected cluster (D), cracked berries (E), and cleistothecia on berries (F).

Management of grape powdery mildew.

Despite the progress in developing alternative strategies (English-Loeb 1999), growers mainly use synthetic fungicides to manage the powdery mildew (Gubler, 2000). In absence of

recommendations adapted to conditions and cultivars in Eastern Canada, growers tend to apply fungicides either on a 7 to 10 day schedule or use a calendar-based fungicide spray program. This practice, however, may promote the development of fungicide resistance in populations of *E. necator* (Gubler et al., 1996; Northover and Homeyer, 2001; Wong and Wilcox, 2002).

Powdery mildew prediction models.

Numerous warning or forecasting programs were developed for the management of grape powdery mildew using fungicide applications. The Gubler-Thomas system developed at UC-Davis, CA uses leaf wetness and temperature early in the spring to predict periods of ascospore infection and temperature during the summer to predict periods of secondary infection (Thomas, 1994). The New York program is based on the assumption that the number and intensity of rain events during the two months following budbreak influences the severity of powdery mildew on berries (Gadoury et al., 1997). This model is used to estimate the number of primary infections between budbreak and flowering. The criteria for ascospores infection being that primary infection will occur in response to a rain event of more than 2.5 mm when temperature is above 10 ^{o}C (Gadoury et al., 1997). Carisse et al. (2009) developed a degree-day model that forecast the onset of seasonal airborne inoculum production and proven to be helpful to time initiation of a fixed-interval fungicide spray program.

Models development:

Almost all prediction or forecasting models developed for both downy and powdery mildew required microclimate within the canopy data, including tissue wetness and/or relative humidity. In addition, the most reliable models were developed using hourly meteorological data. For example downy mildew primary and secondary infections and powdery mildew primary infections are predicted from the duration of tissue wetness in hours and mean temperature during the wetness period in ^{o}C (Figure 5).

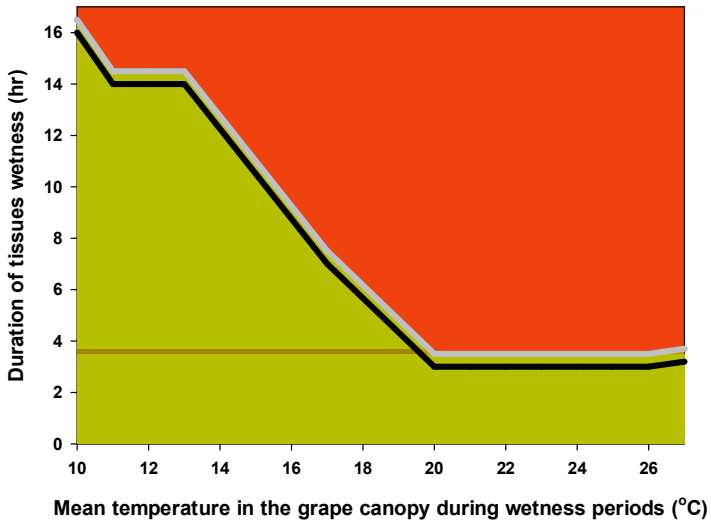

Figure 5. Risk of grape downy mildew (*Plasmopara viticola*) based on the duration of tissue wetness in hours and the mean temperature during the wetness period (°C). The area in green indicates a low risk while area in red indicates a high risk of downy mildew infection (adapted from Crespy, 2007).

The challenge here was thus to modify existing or develop new disease risk indexes using limited meteorological data: regional daily maximum temperature (°C), regional daily minimum temperature (°C), and regional daily amount of rain (mm). Initially, all downy and powdery mildew models available in the scientific and technology transfer literature were assessed for their potential to be used to develop the new disease risk indexes. Unfortunately none of the published prediction models were considered as useful for this purpose. Considering that only regional daily temperature and rain data were available, it was decided to develop simple disease risk index.

The risk indexes were developed following three steps. First, a 13 years data set on both downy and powdery mildew severity/incidence, hourly microclimate within or near the grape canopy, and yield losses at harvest was used to develop seasonal disease risk indexes (Annexe I). Secondly, the same data set was used to evaluate the reliability of risk indexes calculated using daily data (Tmax, Tmin and rain), and to estimate the reliability of daily data-based indexes

(correlations between the indexes and yield losses). Finally, the daily data-based indexes were calculated using the projection data (2015-2025) for the 22 locations in Nova Scotia.

Description of the data used to develop the risk indexes.

Experimental vineyard plots description. Data were collected at the Agriculture and Agri-Food Canada experimental farm located in Frelighsburg, Québec, Canada (lat. 45 degrees 03'12' N; long. 72° 51'42' W) or commercial vineyards (2000-2004 data). Data were collected in three to eight years vineyards plots planted with the grape cultivars: Chancellor, Frontenac, Seyval, and Vidal. For winter protection, the lower parts of the cultivars Chancellor, Seyval, and Vidal were covered during the first week of November with 40 to 60 cm of soil from within rows. The following spring, the soil was moved back to within rows using specialized machineries. These plots were established as part of various fungicide efficacy, epidemiology, and disease management trials. Plots varied in size from 500 m^2 to 1000 m^2. In all plots, the rows were spaced 3·0 m apart, and within rows, the plants were spaced 90 cm apart. For the purpose of this study, we selected plots that were managed for powdery mildew and Botrytis bunch rot to develop the risk indexes for downy mildew and similarly plots managed for downy mildew and Botrytis bunch rot to develop the risk indexes for powdery mildew. Insecticides were applied when required mainly to control flea beetle. Other cultural practices were done in accordance to the standard practices used in the other parts of the vineyard (Anonymous, 2008).

Within the canopy meteorological data. A data logger (CR-10X, Campbell Scientific, Edmonton, Canada) located in the vineyard was used to measure hourly air temperature (°C), relative humidity (%), wind velocity, light intensity and rain intensity (mm). The temperature and relative humidity were monitored at a height of 1.5 m with a vaisala sensor Model HMP45C (Campbell Scientific, Edmonton, Canada) located in a white shelter. Wind speed was monitored with an anemometer located 1.3 m above the ground (model 014A, Met One Instruments Inc., Grants Pass, Oregon, U.S.A.). Light intensity was monitored with a pyranometer (LI-200SA, Li-Cor, Lincoln, NE, U.S.A.). Rain was monitored with a tipping bucket (Geneq, Montréal, Québec, Canada) with the opening at 50 cm above the ground.

Figure 6. Weather station used to monitor hourly data in or near the grape canopy in 2000 to 2012.

Disease assessment. Grape downy and powdery mildew was assessed weekly from bud break (mid-May) until harvest (mid to late September) by looking at two shoots on eight vines per plot, selected randomly at each sampling. At each sampling, the total number of leaves and the percent leaf area diseased were recorded. The percent leaf area diseased was estimated using a scale that was divided into eight classes corresponding to 0%, >0% to 1%, >1% to 5%, >5% to 10%, >10% to 20%, >20% to 40%, >40% to 80%, and >80% to 100% leaf area diseased. For powdery mildew, because severity assessments is not always reliable, the severity data were converted to disease incidence data by simply rating a leaf as diseased if it had one or more lesions. Yield loss was estimated at harvest as the percent bunch area diseased.

Development of the downy mildew risk index: assumptions

Assumptions: Because downy mildew epidemics are initiated by the overwintering inoculum (zoospores from oospores) and considering the polycyclic nature of downy mildew we assumed that: If weather conditions are suitable for primary infections to occur during spring, there is a high probability of yield losses; the number of days favorable to primary infection in the spring-early summer (May and June) is proportional to yield losses at harvest.

Development of the downy mildew risk index: methods

Step 1. From the hourly data, a series of weather variables were calculated such as mean daily temperature during hours of tissues wetness, mean daily temperature during hours of relative humidity >90%, or sum daily temperature during hours of tissues wetness (Table 4). From the hourly data, various risk indexes were calculated. These indexes were:

1. The number of days favorable to zoospore dispersal in May: binary data; day assigned 0=not favorable when MTEMP<10°C and RAIN<10mm; day assigned 1=favorable when MTEMP≥10 °C and RAIN≥10mm (SPODISPM)
2. The number of days favorable to primary infection in May: binary data day assigned =0=not favorable when the meant temperature during the wet periods is < 10 °C; day assigned 1=favorable when the meant temperature during the wet periods is > 10 °C (INFM)
3. The number of days favorable to both zoospore dispersal and primary infection (DISPINF).
4. The number of days favorable to primary and secondary inoculum dispersal (zoospores and sporangia) in June: binary data; day assigned 0=not favorable when MTEMP<10°C and RAIN<10mm; day assigned 1=favorable when MTEMP≥10 °C and RAIN≥10mm(SPODISPJ)
5. The number of days favorable to primary and secondary infection (zoospores and sporangia) in June: binary data day assigned =0=<4 hours of leaf wetness; day assigned 1=favorable when =>4 hours of leaf wetness and the meant temperature during the wet periods is > 10 °C (INFJ).
6. The infection potential during June: June average daily degree-hours (sun of temperature) during wet hours (rain > 2mm) (INFP)
7. Early season risk calculated as: RI= DISPINF x PSINF

These downy mildew risk indexes were calculated for the 13 years of data. To select the most reliable index, the various downy mildew risk indexes were correlated with both observed % leaf area diseased and % bunch area diseased at harvest (Table 1). The correlation analysis was conducted for three grape varieties Chancellor, Vidal, and Seyval Blanc which are considered as having high, moderate, and low susceptibility to downy mildew (ANNEXE I). Based on this correlation analysis, the best downy mildew index was: Early season risk calculated as: DISPINF x PSINF (Table 1). This downy mildew risk index was calculated as the number of days favorable to

both zoospore dispersal and primary infection in May and the number of days favorable to primary and secondary infections in June (Figure 7).

Table 1. Pearson coefficients of correlation between downy mildew risk indexes calculated from hourly data and observed % leaf area diseased (PLAD) and yield losses expressed as % bunch area diseased at harvest (%YLDL) for three grape varieties Chancellor, Vidal, and Seyval.

Variable[a]	SPODISPM	INFM	DISPINF	SPODISPJ	INFJ	INFP	RISK
PLAD Chancellor	**0.83**[b]	**0.44**	**0.87**	0.30	**0.33**	**0.71**	**0.92**
YLDL Chancellor	**0.84**	**0.50**	**0.90**	0.19	0.29	**0.66**	**0.93**
PLAD Vidal	**0.79**	**0.41**	**0.83**	**0.32**	0.28	**0.76**	**0.89**
YLDL Vidal	**0.84**	**0.47**	**0.89**	0.26	0.31	**0.66**	**0.93**
PLAD Seyval	**0.76**	**0.48**	**0.86**	0.26	-0.16	**0.71**	**0.85**
YLDL Seyval	**0.78**	**0.44**	**0.83**	**0.33**	-0.08	**0.68**	**0.86**

[b] *Values in bold are different from 0 with a significance level alpha=0.05*

[a]SPODISPM: The number of days favorable to zoospore dispersal in May

INFM: The number of days favorable to primary infection in May

DISPINF: The number of days favorable to both zoospore dispersal and primary infection (May)

SPODISPJ: The number of days favorable to zoospore and sporangia dispersal in June

INFJ: The number of days favorable to primary and secondary infection in June

INFP: The secondary infection potential during June

RISK: Early season risk calculated as: DISPINF x INFJ

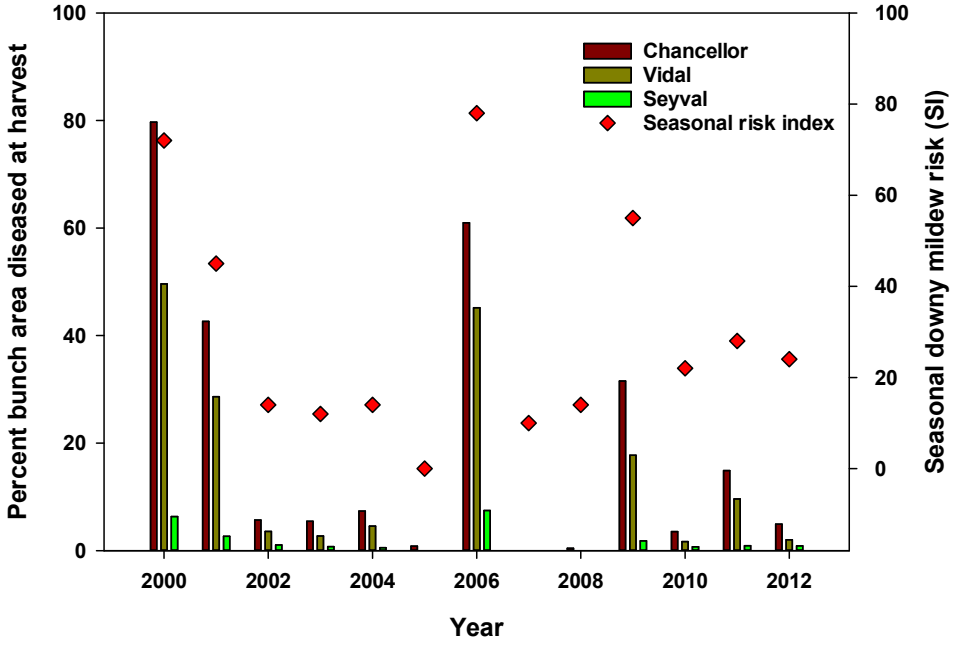

Figure 7. Relationship between observed yield losses (bunch area diseased) and seasonal downy mildew index calculated using hourly data in 2000 to 2013.

Step 2. Based on the results of the correlation analysis between downy mildew indexes, calculated using the hourly data, and percent leaf area diseased and percent bunch area diseased at harvest (Table 1), it was concluded that it would be possible to develop a downy mildew risk index based on the number of days favorable to spore dispersal (calculated from daily temperature and rain) and infection (calculated from daily rain). Hence, a series of variables derived from daily data were used to calculate risk indexes. These indexes were:

1. **SDDDISPERSAL:** seasonal number of days favorable to spore dispersal from April to September: binary data; day assigned 0=not favorable when mean daily temperature <10^{o}C and daily RAIN<10mm; day assigned 1=favorable when mean daily temperature $\geq$10 ^{o}C and daily RAIN$\geq$10mm
2. **SDDINF:** seasonal number of days favorable to infection (rainy days) from April to September; day assigned 0=not favorable when daily RAIN<2mm; day assigned 1=favorable when daily RAIN$\geq$2mm.
3. **SDRAIN:** Total amount of rain from April to September. Sum of the seasonal rainfall in mm
4. **M andJDDDISPERSAL:** number of days favorable to spore dispersal (DDDISPERSAL) in May and June
5. **M andJDDINF:** number of days favorable to infection (rainy days)(DDINF**)** May and June
6. **M andJDRAIN:** Total amount of rain May and June

Based on this correlation analysis (Table 2), the best daily data-based downy mildew risk index was calculated as the number of days favorable to spore dispersal in May and June (M andJDDDISPERSAL) (Table 2).

Table 2. Pearson coefficient of correlation between downy mildew risk indexes calculated from daily data and observed % leaf area diseased (%PLAD) and % bunch area diseased at harvest (%YLDL) for three grape varieties Chancellor, Vidal, and Seyval.

Variable[a]	SDDDISPERSAL	SDDINF	SDRAIN	M andJ DDDISPERSAL	M andJ DDINF	M andJ DRAIN
PLAD Chancellor	**0.36**[b]	0.18	0.18	**0.73**	**0.52**	**0.62**
YLDL Chancellor	0.29	0.13	0.06	**0.69**	**0.50**	**0.52**
PLAD Vidal	**0.34**	0.12	0.19	**0.72**	**0.43**	**0.59**
YLDL Vidal	**0.33**	0.13	0.11	**0.73**	**0.51**	**0.59**
PLAD Seyval	**0.35**	0.10	0.12	**0.75**	**0.50**	**0.62**
YLDL Seyval	**0.41**	0.15	0.22	**0.80**	**0.55**	**0.70**

[b] *Values in bold are different from 0 with a significance level alpha=0.05*

[a]SDDDISPERSAL: number of days favorable to spore dispersal from April to September
SDDINF: number of days favorable to infection (rainy days) from April to September
SDRAIN: total amount of rain from April to September
M andJ DDDISPERSAL: number of days favorable to spore dispersal (DDDISPERSAL) in May and June
M andJ DDINF: number of rainy days ($\geq$2mm) in May and June
M andJ DRAIN: total amount of rain May and June

Summary of the results from step 1 and step 2. When downy mildew risk indexes were calculated using hourly weather data monitored within or near the grape canopy (Figure 6), most correlation coefficients between indexes and downy mildew severity (PLAD) and yield losses (YLDL) at harvest were high (Table 1). The best downy mildew risk index was calculated as the number of days favorable to both zoospore dispersal and primary infection in May and the number of days favorable to primary and secondary infection in June (Figure 7). The correlation coefficient between this index and yield losses was 0.93, 0.89, and 0.86 for the grape variety Chancellor, Vidal, and Seyval, respectively (Table 1, Figure 7). However, when the indexes were calculated using daily data, correlation coefficients were lower (Table 2). Nevertheless, the most reliable index was calculated as the number of days favorable to spore dispersal in May and June (M andJDDDISPERSAL) (Figure 8).

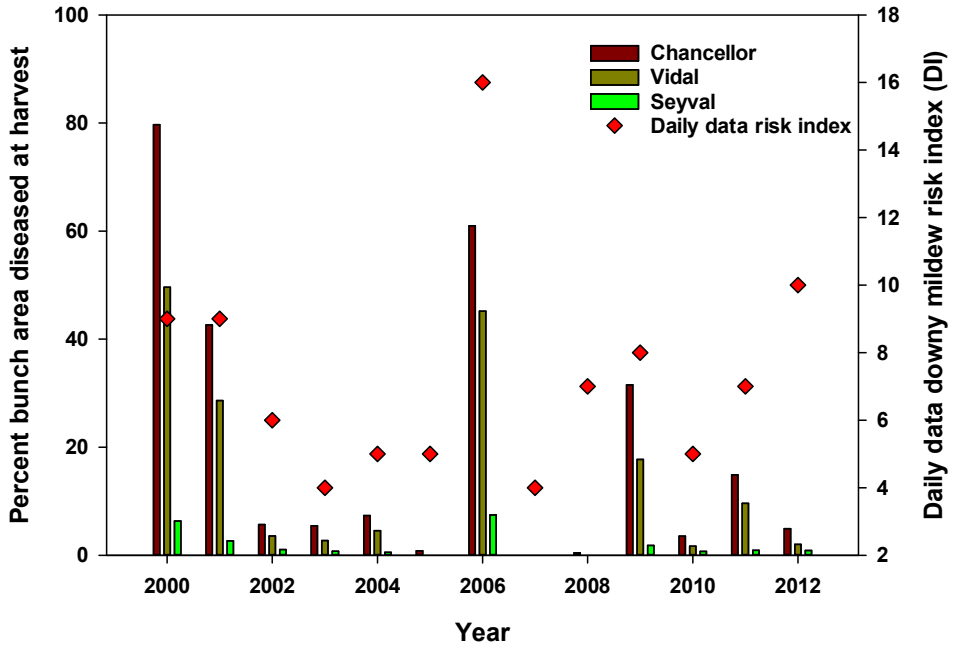

Figure 8. Relationship between observed yield losses (bunch area diseased) and downy mildew risk index calculated as the number of days favorable to spore dispersal in May and June calculated using daily data in 2000 to 2013.

For the 13 years of data, there was a linear relationship downy mildew indexes and both downy mildew severity (PLAD) and yield losses at harvest (YLDL) expressed as PLAD or YLDL = β_1 x (β_2 x index). Regardless of the grape variety, the coefficient of determination (R^2) was higher when the downy mildew index was calculated using the hourly data. The R^2 varied from 0.80 to 0.89 and from 0.49 to 0.66 for the indexes calculated using the hourly and daily data, respectively (Tables 3 and Figures 9). Because only daily maximum temperature, daily minimum temperature, and daily rainfall were available in the projection meteorological data sets (2015-2025), downy risk index was calculated based on the number of days favorable to spore dispersal in May and June (Figure 10).

Table 3. Regression parameters and coefficients of determination of the linear regression between disease severity or yield losses caused by downy mildew and disease risk index calculated using hourly and daily weather data, for three grape cultivars.

	Hourly data index (early season risk calculated as RI= DISPINF x PSINF)			Daily data index (DI=nb of days favorable to spore dispersal in May and June)		
Parameters	Intercept (β_1)	Slope (β_2)	R^2	Intercept (β_1)	Slope (β_2)	R^2
PLAD Chancellor	-11.539 (4.320)	0.945 (0.113)	0.86	-25.045 (12.445)	5.707 (1.564)	0.55
YLDL Chancellor	-9.602 (4.058)	0.987 (0.106)	0.89	-20.718 (13.649)	5.551 (1.715)	0.49
PLAD Vidal	-6.038 (3.630)	0.634 (0.094)	0.80	-15.454 (8.924)	3.879 (1.121)	0.52
YLDL Vidal	-7.120 (2.681)	0.664 (0.070)	0.89	-16.329 (8.564)	3.974 (1.076)	0.55
PLAD Seyval	-1.026 (0.824)	0.152 (0.021)	0.82	-3.571 (1.993)	0.971 (0.250)	0.58
YLDL Seyval	-0.883 (0.424)	0.089 (0.011)	0.85	-2.573 (1.024)	0.596 (0.129)	0.66

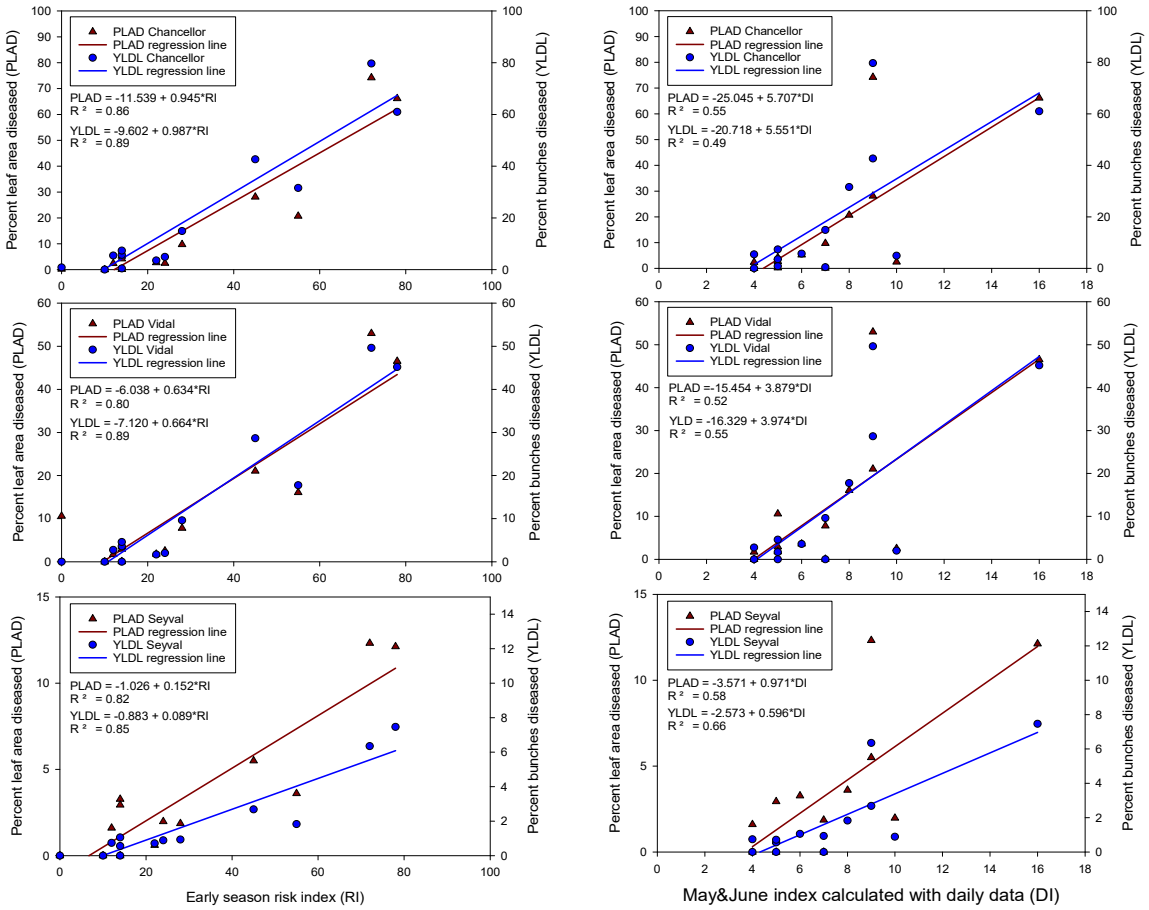

Figure 9. Relationship between downy mildew (*Plasmopara viticola*) early season risk index (right) (calculated from hourly within canopy data) or daily index (left) (calculated from daily data) and percent leaf area diseased and percent bunch area diseased at harvest for the grape varieties Chancellor (top), Vidal (middle), and Seyval (bottom).

Downy mildew model outputs from projection data:

Step 3. Downy mildew severity (% leaf area diseased) and of yield losses (% bunch area diseased) was predicted from the number of days favorable to spore dispersal from April to September (DI) (Table 3). Predicted yield losses for 2015 to 2025 at 22 sites in Nova Scotia are presented in (Figure 10). The standard error associated with the parameter estimates are provided in table 3.

For the grape variety Chancellor (high susceptibility):
PLAD =-25.045 + 5.707xDI
YLDL =-20.718 + 5.551xDI

For the grape variety Vidal (moderate susceptibility)
PLAD =-15.454 + 3.879xDI
YLDL = -16.329 + 3.974xDI

For the grape variety Seyval (low susceptibility)
PLAD = -3.571 + 0.971xDI
YLDL = -2.573 + 0.596xDI

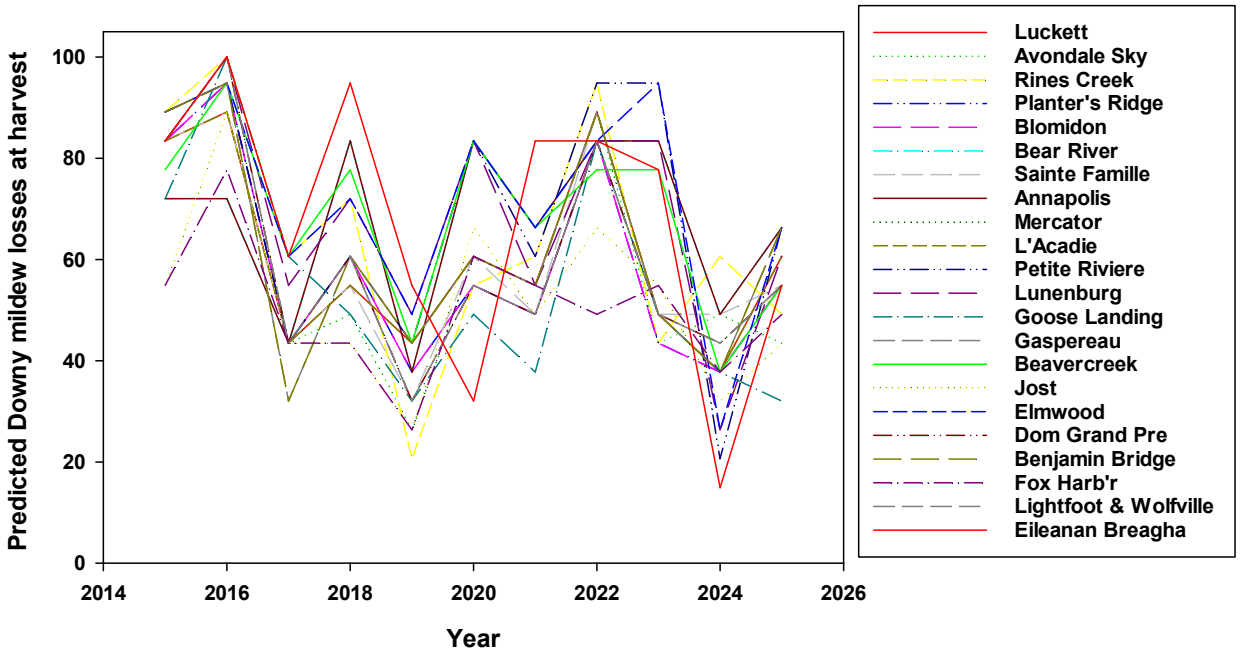

Figure 10. Predicted yield losses caused by downy mildew estimated using daily regional projection data.

Table 4. Summary of weather variables used to develop the downy mildew risk indexes.

Variables	Description
MONTH	Month
DOY	day of year
MTEMP	mean daily temperature (C)
MRH	mean daily relative humidity (%)
RAIN	daily amount of rain (mm)
MTEMP30	mean daily temperature below 31C (C)
MTWET	Mean daily temperature during hours of tissues wetness (C)
MTRH90	Mean daily temperature during hours of relative humidity >90% (C)
STWET	Sum daily temperature during hours of tissues wetness (C)
SPODISP	Spore dispersal: zoospores (in May) or both zoospores andsporangia (in June) are dispersed and available for infection;binary data; day assigned 0=not favorable when MTEMP<10oC and RAIN<10mm; day assigned 1=favorable when MTEMP>10 oC and RAIN>10mm
PINF	The number of days favorable to primary infection in May: binary data day assigned =0=not favorable when the meant temperature during the wet periods is < 10 oC; day assigned 1=favorable when the meant temperature during the wet periods is > 10 oC (PINF)
DISPINF	The number of days favorable to both zoospore dispersal and primary infection (DISPINF).
INFP	conditions for secondar infections based on STWET on rainy days (>2mm)
SPODISP in May	number of days favorable to initial inoculum dispersal in May
PINF	number of days favorable to initial infection (zoospores) in May
SDDDISPERSAL	number of days favorable to spore dispersal from April to September
SDDINF	number of days favorable to infection (rainy days) April to September
SDRAIN	Total amount of rain April to September
M andJDDDISPERSAL	number of days favorable to spore dispersal in May and June
M andJDDINF	number of days favorable to infection (rainy days) May and June
M andJDRAIN	Total amount of rain May and June

Development of the powdery mildew risk index: assumptions

Assumptions: Because powdery mildew epidemics are initiated by the overwintering inoculum (ascospores from cleistothecia) and considering the polycyclic nature of powdery mildew we assumed that: weather conditions for primary infections are not limiting (Carisse, 2009) and progress of powdery mildew epidemics is mostly driven by temperature and is well represented by the accumulation of degree-days (base 6°C) during the growing season (Carisse et al., 2009a.b). There is a linear relationship between yield losses caused by powdery mildew and disease severity at harvest; yield losses can be predicted from degree-days or disease severity at harvest.

Development of the powdery mildew risk index: methods

Step 1. From the hourly data, mean daily temperature was calculated excluding hours with temperature above 30.5°C, hours with temperature below 0°C, and hours with rainfall >2 mm. Hours with temperatures above 30.5°C or below 0 were excluded because at these temperatures, sporulation by *E. necator* is inhibited and hence including these hours may cause overestimation of disease progress (Delp, 1954). Similarly, because free water on tissues surface inhibits infection by conidia, rainy hours were not included in the degree-day calculations. From the mean daily temperature, 6°C, which is the minimum temperature for conidia production and infection, was subtracted to obtain base 6°C degree-days (Bulit and Lafon, 1978; Carisse et al., 2009a,b; Carroll and Wilcox. 2003; Delp, 1954).

Step 1. Degree-days were calculated for the 13 data sets and cumulative degree-days were calculated by summing daily degree-days from April 1st. The cumulative degree-days were calculated from April 1st to day 183, 213, 244, and 260, days corresponding to the end of June, end of July, end of August, and mid-September (harvest), respectively. To select the most appropriate powdery mildew index, these cumulative degree-day values were correlated with incidence of powdery mildew and with yield losses at harvest.

Table 5. Pearson coefficients of correlation between powdery mildew risk indexes calculated from hourly data and observed incidence of diseased leaves (INC) and yield losses expressed as % bunch area diseased at harvest (%YLDL) for three grape varieties Chancellor, Vidal, and Frontenac.

	AccumulatedDegree-days until :			
Variable[a]	Day 183	Day 213	Day 244	Day 260
INC Chancellor	**0.37**	**0.32**	**0.32**	0.29
YLDL Chancellor	**0.79**	**0.77**	**0.87**	**0.84**
INC Vidal	**0.36**	0.31	**0.36**	**0.34**
YLDL Vidal	**0.89**	**0.86**	**0.90**	**0.84**
INC Frontenac	**0.33**	0.27	**0.33**	0.30
YLDL Frontenac	**0.84**	**0.78**	**0.87**	**0.84**

[b] *Values in bold are different from 0 with a significance level alpha=0.05*

[a] Degree-days were calculated from hourly data in T Base 6°C excluding hours with temperature above 30.5°C, hours with temperature below 0 °C, and hours with rainfall >2 mm.

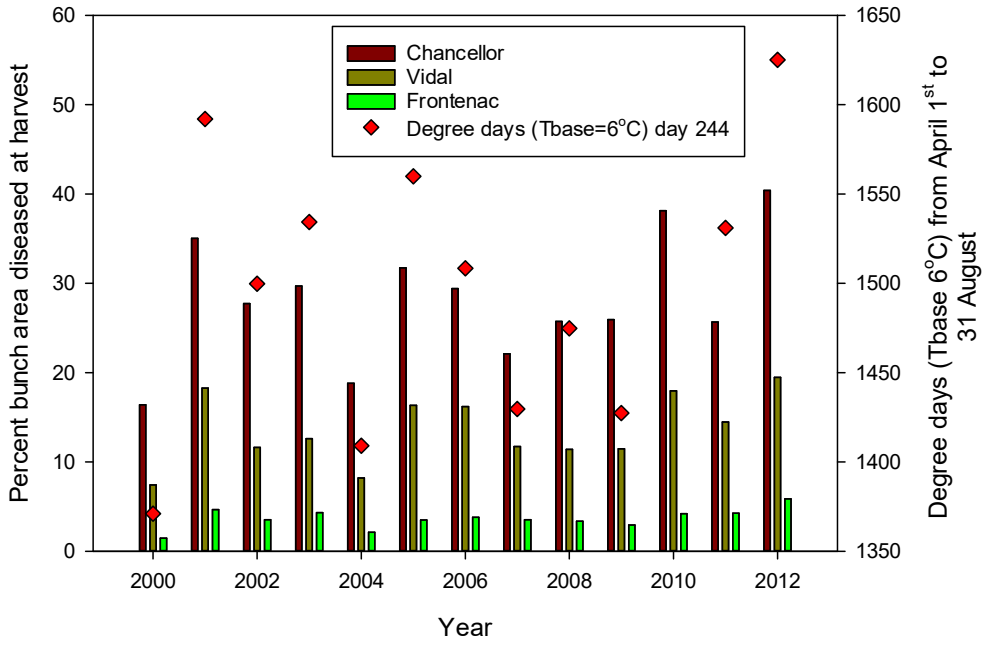

Figure 11. Relationship between observed yield losses (bunch area diseased) and accumulated degree-days (Tbase 6°C) from April 1 to 31 August (Day 244) calculated using hourly data in 2000 to 2013.

Step 2. Based on the results of the correlation analysis between powdery mildew indexes (Degree-days) calculated using the hourly data and percent bunch area diseased at harvest (Table 5), it was concluded that it would be possible to develop a powdery mildew risk index based on degree-days (Tbase =6°C) accumulated from April 1st until end of August (Day 244). Hence, degree-days were calculated using daily data from the same 13 data sets. In this case, rainy days were excluded from the degree-days calculation. Daily mean temperature was calculated as DT=((Tmax + Tmin)/2), 6°C, which is the minimum temperature for conidia production and infection, was subtracted to obtain base 6°C degree-days. Cumulative degree-days from April 1st to day 183, 213, 244, and 260, days corresponding to the end of June, end of July, end of August, and mid-September (harvest), respectively, were correlated with incidence of powdery mildew and with yield losses at harvest.

Table 6. Pearson coefficients of correlation between powdery mildew risk indexes (degree-days) calculated from daily data and observed incidence of diseased leaves (INC) and yield losses expressed as % bunch area diseased at harvest (%YLDL) for three grape varieties Chancellor, Vidal, and Frontenac.

	AccumulatedDegree-days until :			
Variable[a]	Day 183	Day 213	Day 244	Day 260
INC Chancellor	**0.35**	0.29	0.23	0.16
YLDL Chancellor	**0.72**	**0.65**	**0.67**	**0.63**
INC Vidal	**0.33**	0.26	0.23	0.21
YLDL Vidal	**0.77**	**0.71**	**0.66**	**0.60**
INC Frontenac	0.30	0.23	0.20	0.18
YLDL Frontenac	**0.79**	**0.63**	**0.58**	**0.54**

[b] *Values in bold are different from 0 with a significance level alpha=0.05*

[a] Degree-days were calculated from hourly data in T Base 6°C excluding hours with temperature above 30.5°C, hours with temperature below 0 °C, and hours with rainfall >2 mm.

Summary of the results from step 1 and step 2. Regardless of how degree-days were calculated (from hourly or daily data) there was a low correlation between degree accumulated since April 1st and incidence of diseased leaves (Table 5 and 6). However, the correlation between degree-days accumulated since April 1st and yield losses were much higher. For degree-days calculated from hourly data correlation coefficients ranged from 0.79 to 0.87, 0.84 to 0.90, and 0.78 to 0.87 for grape variety with high, moderate or low susceptibility to powdery mildew. Similar trend was observed when degree-days were calculated using daily data (Table 6). For degree-days calculated using daily data, higher correlation coefficients were obtained when degree-days were accumulated from April 1st to the end of June (day 183). This could be explain by the high level of susceptibility of inflorescence and berried during this period (Campbell et al., 2007; Gadoury et al., 2003).

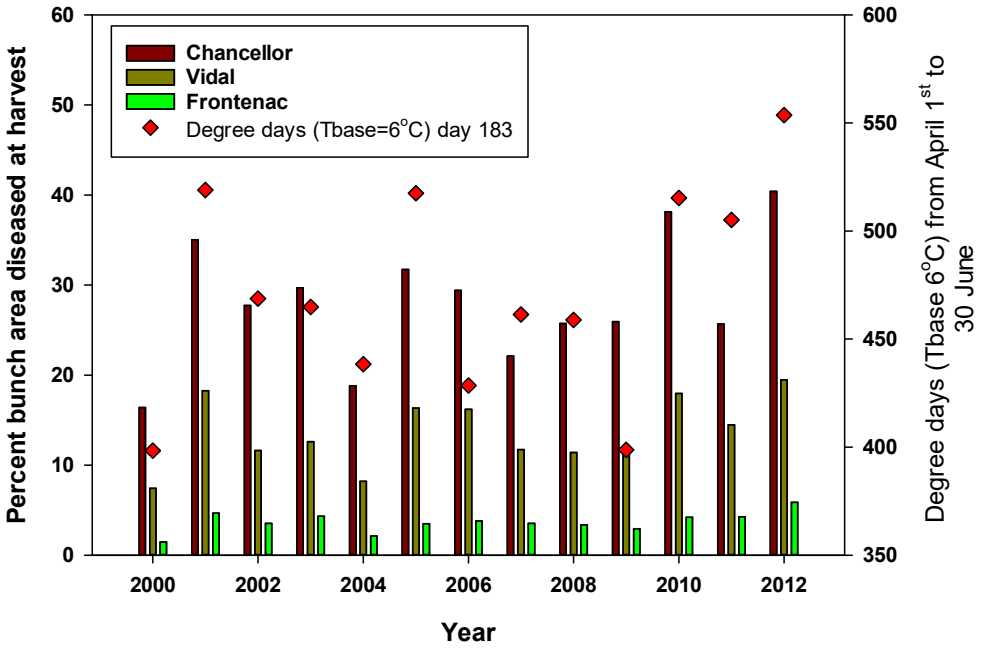

Figure 12. Relationship between observed yield losses (bunch area diseased) and accumulated degree-days (Tbase 6°C) from April 1 to 30 June (Day 183) calculated using daily data in 2000 to 2013.

For the 13 years of data, there was a linear relationship powdery mildew indexes and yield losses at harvest (YLDL) expressed as YLDL = β_1 x (β_2 x index). Regardless of the grape variety, the coefficient of determination (R^2) was higher when the powdery mildew index was calculated using the hourly data. The R^2 varied from 0.80 to 0.91 and from 0.62 to 0.66 for the indexes calculated using the hourly and daily data respectively (Table 7 and Figure 13). Because only daily maximum temperature, daily minimum temperature, and daily rainfall were available in the projection meteorological data sets (2015-2025), powdery mildew risk index was calculated based on the degree-days (Tbase=6°C) accumulated from April 1st to end of June (Day 183) (Figure 14).

Table 7. Regression coefficients and coefficient of determination of the regression between yield losses caused by powdery mildew and disease risk index (degree-days) calculated using hourly and daily weather data, for three grape cultivars.

	Hourly data index (degree-days (Tbase=6°C) accumulated from April 1st to end of August (Day 244)			Daily data index (degree-days (Tbase=6°C) accumulated from April 1st to end of June (Day 183)		
	Intercept (β_1)	Slope (β_2)	R^2	Intercept (β_1)	Slope (β_2)	R^2
YLDL Chancellor	-99.312 (12.259)	0.085 (0.008)	0.91	-25.709 (12812)	0.114 (0.027)	0.62
YLDL Vidal	-54.526 (7.669)	0.045 (0.050)	0.88	-16.294 (6.718)	0.064 (0.142)	0.65
YLDL Frontenac	-15.320 (2.825)	0.013 (0.002)	0.80	-5.146 (1.912)	0.019 (0.004)	0.66

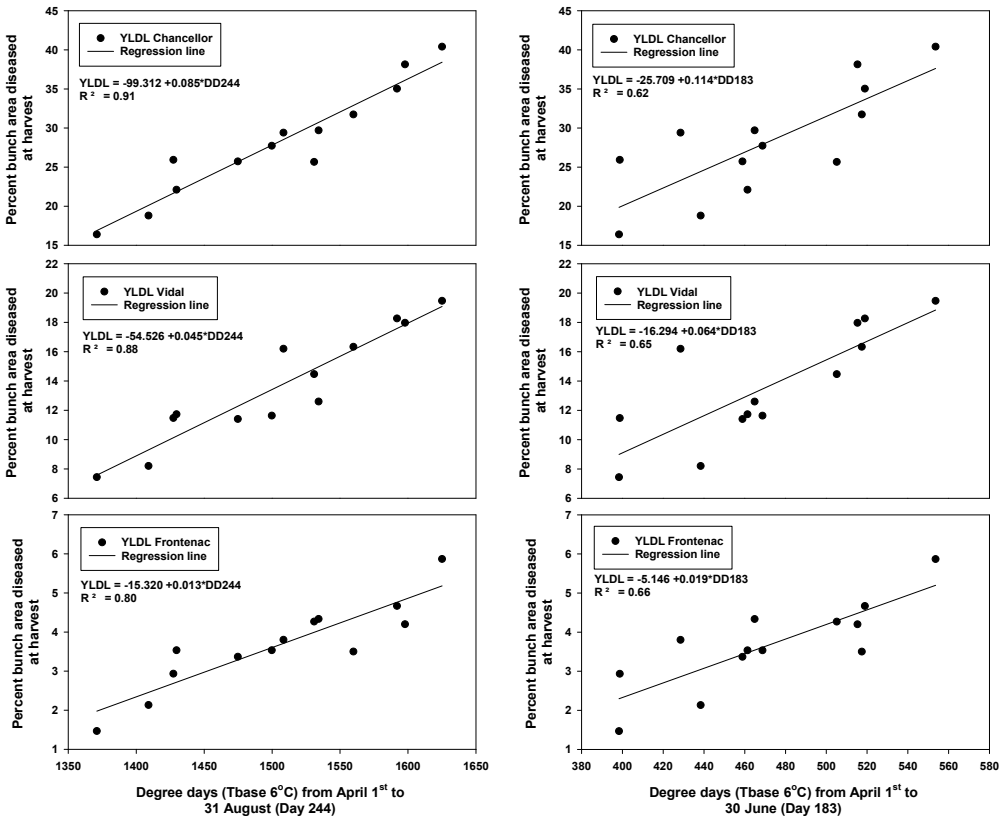

Figure 13. Relationship between powdery mildew (Erisyphe necator) risk index calculated as the degree-days (Tbase=6°C) accumulated from April 1st to end of August (Day 244) (calculated from hourly within canopy data) (right) or daily index calculated as degree-days (Tbase=6°C) accumulated from April 1st to end of June (Day 183) (left) and percent bunch area diseased at harvest for the grape varieties Chancellor (top), Vidal (middle), and Frontenac (bottom).

Powdery mildew model outputs from projection data:

Step 3. Yield losses (% bunch area diseased) caused by powdery mildew was predicted from the degree-days (Tbase=6°C) accumulated from April 1st to end of June (Day 183) (Table 7). Predicted yield losses for 2015 to 2025 at 22 sites in Nova Scotia are presented in (Figure 14). The standard error associated with the parameter estimates are provided in table 7.

For the grape variety Chancellor (high susceptibility):
YLDL =-25.709 + 0.114xDD183

For the grape variety Vidal (moderate susceptibility)
YLDL = -16.294 + 0.064xDD183

For the grape variety Frontenac (low susceptibility)
YLDL = -5.146 + 0.019xDD183

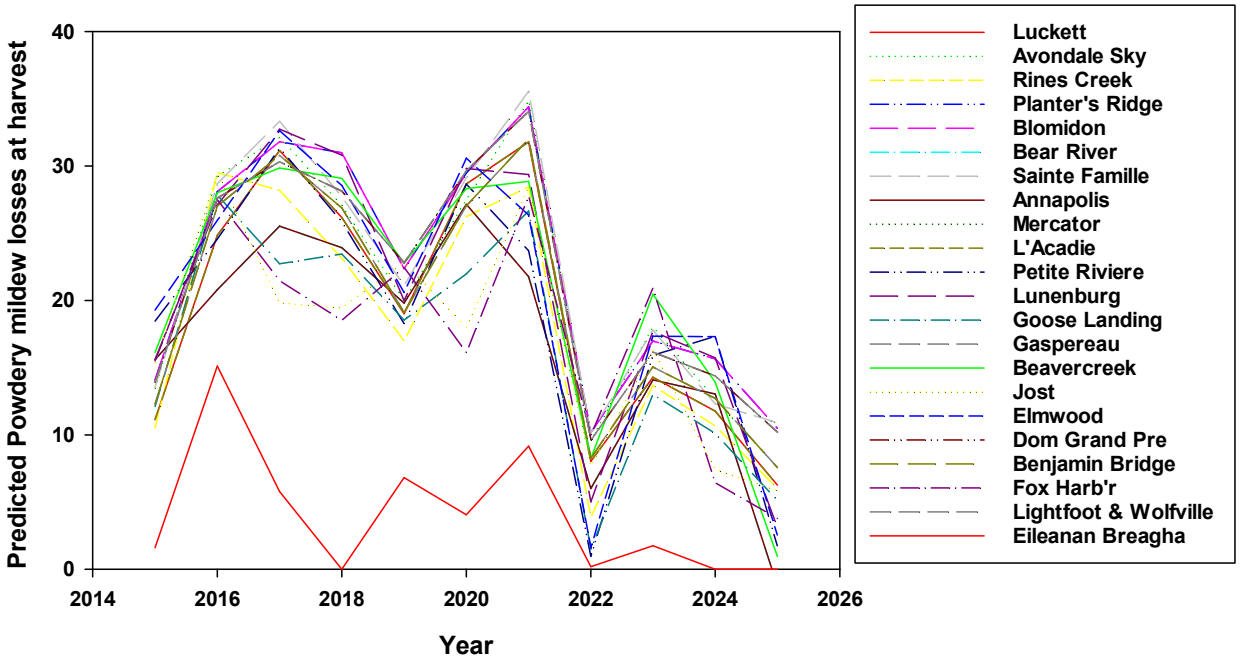

Figure 14. Predicted yield losses caused by powdery mildew estimated using daily regional projection data.

Model application:

In this study, 13 years of data on downy and powdery mildew disease severity or incidence and yield losses at harvest and on meteorological data collected within or near the grape canopy every hour was available to develop and validate the disease risk indexes. For both downy and powdery mildew weather-based indexes were more reliable when derived from hourly data than when derived from daily data. Nevertheless, the disease risk indexes derived from daily data

provided acceptable prediction of potential yield losses and can be used to predict yield losses and needs for downy mildew management such as fungicide applications.

It is important to understand that to complete their life cycle, fungi including *Plasmopara viticola* or *Erisyphe necator* must go through several processes such as spore dispersal, spore germination, spore penetration, fungal colonisation, spore production,… The time scale of these processes is in hours. Therefore, most infection or sporulation models are based on the duration, in hours, of tissues wetness or of relative humidity at a given threshold, and on the mean temperature during these periods (Carisse et al., 2000). This explains why overall disease risk indexes calculated using hourly data are more reliable to predict disease development or yield losses. In addition, some of these processes occur on or within grape tissues. Hence, micrometeorological data monitored within the grape canopy are generally more reliable variables that meterological data collected outside the vineyard.

Next steps or where to go from here:

In this study, only limited projection data were available (daily maximum temperature, daily minimum temperature, and daily rainfall) from 2015 to 2025. Consequently, all available or possible disease prediction models or risk indexes could not be used. Nevertheless, new downy and powdery mildew risk indexes were developed and were validated using 13 years of observations. Overall, the disease indexes based on daily temperature and rainfall explained approximately 60% (49% to 66%) of the variation in yield losses (Table 3 and 7). In most studies on the impact of climate change on crop diseases including grape diseases do not include model validation against real observations. If the projection data are refined, it is expected that more reliable grape disease predictions can be made. Nevertheless, within the time frame of the projection data provided (2015-2025) they were no temporal trends that could be derived from this analysis. However, there was large variations among years and some variations among locations. Longer time series in projection data are needed to determine the future trend in grape disease development and yield losses. For example, Caffarra et al (2012) studied the impact of climate change from 2000 to 2080 on grape powdery mildew and depending on the climate

change scenario used, reported a tendency for decreasing number of infection cycles and concluded that climate change might decrease the severity of powdery mildew. In a similar study, Salinari et al. (2006) predicted increase in downy mildew as a consequence of more favourable temperatures during the months of May and June (Italy). There simulations suggest that more attention should be paid in the management of early downy mildew infections and that one or two more fungicide applications might be needed early in the season. Regardless of the simulation, it is expected that the pathogen populations will adapt to climate change and more knowledge on how grape pathogens will adapt will be necessary to improve predictions.

It was clear from this study that using weather data collected in or near the vineyards has great values in terms of reliability of disease predictions. For downy mildew, the simple disease risk index calculated using hourly data monitored within the grape canopy explained 85 to 89% of the variations in yield losses. However, when risk index were calculated using regional daily data, only 49% to 66% the variations in yield losses was explained. Similarly, for powdery mildew, 80% to 91% of the variations in yield losses was explained when the risk index was calculated using hourly data compared to 62% to 66% using daily regional data. If we assumed that in general, the use of prediction models allow for a reduction in fungicide application of 20-30% this represents a considerable cost to grape growers, impact on environment and on consumers interest.

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Annexe I

Description of the files

File name	Content
1- Weather data Frelighsburg 2000-2012.xlsx	Raw hourly weather data
2-DOWNY MILDEW HOURLY_DAILY RISK (March-2018).xlsx	Seasonal indexes calculates from hourly and daily data, observations (data) on disease severity and yield losses for all 3 grape varieties for 2000-2012
3-Grape powdery mildew model development.xlsx	Degree-days calculated from hourly data and disease incidence for 2000-2012
4-Powdery mildew yield losses 2000-2012 (HS-MS-LS).xlsx	Degree-days calculated from hourly and daily data and correlation analysis with disease incidence and yield losses for 2000-2012
5-Correlation DM_indexes.xlsx	Correlation analysis between downy mildew indexes calculated from hourly and daily data and disease severity and yield losses for 2000-2012
6-Projection data 2015-2025 (DM-PM predictions).xlsx	Calculations of the downy and powdery mildew indexes from the projection data
7-Summary DM and PM predictions 2015-2025.xlsx	Predicted yield losses from downy and powdery mildew for 2015-2025 at 22 sites in NS

Note: files with the extension .JNB contains the figures 7 to 14 made with SigmaPlot