Development of decision support tools for strawberry production in Quebec

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Preface and contribution of authors

Chapter 2 – I wrote the first draft of the manuscript, which was reviewed by Valérie Gravel and Odile Carisse.

Chapter 3 – Design of the experimental plots and data collection were performed by Odile Carisse and her research team at Agriculture and Agri-Food Canada. I analysed the data under the supervision of Valérie Gravel and Odile Carisse. I wrote the first draft of the manuscript, which was reviewed by Valérie Gravel and Odile Carisse.

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Abstract

Over the last decades, strawberry production in Quebec has evolved in response to consumers' demand for high quality fruits all year round. Growers are gradually adopting new production techniques such as plasticulture, winter row covers or high tunnels. Due to this new complexity of the production, growers need to make numerous short, medium and long-term decisions.

Daily decision-making is often related to weed, insect and disease management. Decision support tools, such as prediction models for diseases, can help growers make their decision, in addition to allow a more efficient use of fungicides. The first objective of this study was to develop a weather-based index to predict the development of strawberry powdery mildew. This disease caused by the ascomycete *Podosphaera aphanis* (Wallr.) is now considered as a major constraint in strawberry production. Several studies show that the development of strawberry powdery mildew is enhanced by new production techniques such as plasticulture systems with day-neutral varieties and the use of high tunnels. Weather data (air temperature, relative humidity and rainfall), disease severity and airborne conidia concentration assessments were used to develop the indices. Their development showed that weather conditions alone are not sufficient to predict disease development. Further studies on strawberry powdery mildew should include additional parameters related to the field (i.e., the phenological stage of the crop or the field disease history).

Complexity of the strawberry production can be overwhelming when growers have to make medium and long-term decisions concerning different aspects of their production. Tools for assessing the impacts of decisions on the environment, on the financial aspect of the production and on society can allow a better consideration of all elements involved in the decision. The second objective of this study was to develop a framework for assessing the sustainability of different cropping systems of strawberry. This framework was developed using a qualitative multi-criteria analysis model which is a hierarchical structure that divides a complex problem into smaller elements easier to assess. As part of the framework, the economic, environmental and social dimensions of sustainability were divided into 11, 11 and 4 basic criteria respectively. For validating the framework, two different scenarios were assessed: an integrated pest management (IPM) strategy and another strategy based on an inappropriate use of pesticides. Assessment results

were consistent with our expectations since the IPM strategy showed a better environmental sustainability compared to the pesticide-based strategy. Ultimately, the assessment framework could be used as a tool for growers and stakeholders to promote sustainable practices within the strawberry industry.

Résumé

Au cours des dernières décennies, la production de fraises (*Fragaria x ananassa*) a évolué au Québec. Les producteurs, qui utilisaient autrefois un seul système de culture, le rang natté, combinent maintenant différentes techniques de production telles que la plasticulture et l'utilisation de bâches ou de grands tunnels. Cette nouvelle complexité de la production amène les producteurs à prendre de multiples décisions sur une base quotidienne, mais aussi des décisions à moyen et long terme portant sur les orientations de leur entreprise.

Plusieurs décisions quotidiennes concernent la gestion des mauvaises herbes, des insectes et des maladies. Des outils d'aide à la décision, tels que des modèles prévisionnels de maladies, peuvent aider les producteurs lors de la prise de décision, tout en permettant une utilisation plus efficace des fongicides. Le premier objectif de ce projet était de développer un indice pour prédire le développement du blanc de la fraise. Cette maladie, causée par l'ascomycète *Podosphaera aphanis* (Wallr.), est apparue au Québec au début des années 2000 et est maintenant présente à travers la province. Elle est particulièrement problématique dans les fraises à jour neutre cultivées en plasticulture ainsi que dans les cultures sous tunnels. Afin de développer un indice de développement de la maladie, des données météorologiques ainsi que des données de sévérité de la maladie et de concentrations de spores ont été utilisées. Toutefois, le développement de l'indice a permis de constater que les données météorologiques ne suffisent pas pour prédire le développement de la maladie : d'autres variables n'ayant pas été mesurées dans le cadre du projet semblent avoir une influence importante. Bien que les indices développés ne soient pas suffisamment précis pour être utilisés par les producteurs, leur développement a permis de faire ressortir la nécessité de considérer d'autres variables liées au champ telles que le stade phénologique de la culture ou l'historique de la maladie lors de futures recherches.

Par ailleurs, la diversité des méthodes de culture peut facilement devenir un casse-tête pour les producteurs de fraise amenés à prendre des décisions à moyen et long terme. Des outils permettant d'évaluer les impacts de ces décisions sur l'environnement, sur l'aspect économique de la production, ainsi que sur la société peuvent permettre aux producteurs de mieux considérer tous les éléments impliqués dans une décision. Le second objectif du projet était de développer un cadre d'évaluation de la durabilité de différents systèmes de culture de la fraise. Le cadre d'évaluation, basé sur un modèle qualitatif multicritère, est composé de 11 critères environnementaux, 11 critères économiques et 4 critères sociaux. Il a été validé en évaluant deux stratégies de phytoprotection opposées. De façon générale, les résultats obtenus lors de la validation correspondent à ce qui était prévu : par exemple, la stratégie reposant sur une gestion intégrée des ennemis des cultures montre une meilleure durabilité environnementale que celle reposant sur une utilisation inappropriée et systématique de pesticides. Un tel outil permettra éventuellement de privilégier des systèmes de culture plus durables, et ce, avant même leur adoption au champ.

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Chapter 1: Introduction

The province of Quebec is the most important strawberry producer in Canada (ISQ and MAPAQ, 2016). In 1990, 937 growers were involved in strawberry production; strawberries covered 2612 hectares; and 9 104 tonnes of strawberries were marketed annually (Urbain and Drouin, 2003). Twenty-five years later, in 2015, fewer growers (524) produced strawberries on a smaller area (1558 ha) for an annual production of 11 612 tonnes (ISQ and MAPAQ, 2016).

Over the last decades, strawberry production has evolved in the province of Quebec. Until the end of the 1980s, short-day varieties were grown with a production system known as "matted row" (Bergeron, 2010). Strawberries were harvested during a 3 to 4-week period in June and July. Since then, growers gradually adopted new production techniques such as plasticulture with day-neutral cultivars, winter row covers and high tunnels (Zerouala, 2008; Urbain, 2005). The combination of these techniques allows for a better distribution of the strawberry production throughout the growing season.

With these new techniques came new challenges, one of them being the emergence of strawberry powdery mildew in the early 2000s (Tellier, 2017). The disease, caused by the ascomycete *Podosphaera aphanis* (Wallr.), is now widespread throughout the province (Tellier, 2017). *P. aphanis* can infect all aerial parts of the strawberry plant, including fruits. Yield losses, albeit variable, can reach up to 30% (Carisse et al., 2013b).

Lately, many efforts have been made to get a better understanding of the influence of weather conditions on germination, growth and sporulation of *P. aphanis* (Amsalem et al., 2006; Miller et al., 2003; Sombardier et al., 2009). However, since *P. aphanis* can develop under a wide range of weather conditions, disease development is difficult to predict (Carisse et al., 2013b). Despite this difficulty, models for predicting powdery mildew of strawberry were developed in several countries (Bardet and Vibert, 2011; Bouchard, 2008; Eccel et al., 2010; Parker et al., 2008). However, either their efficiency remains unknown or they are not available for Quebec growers. Such models could eventually be used as decision support tools for optimizing fungicide applications and thus, improve the environmental sustainability of strawberry production.

Another strategy for reducing the environmental impact of the strawberry production is to act beforehand by promoting more sustainable cropping systems. European researchers have recently developed multi-criteria models for assessing the environmental, economic and social dimensions of sustainability of different crops such as cash crops, vineyards and apple orchards (Aouadi, 2011; Mouron et al., 2010; Pelzer et al., 2012; Sadok et al., 2009). Up to now, there is no model adapted for strawberry production.

The main objective of this work is to develop decision support tools that could contribute to improve the sustainability of the strawberry production in Quebec.

1.1 Objectives

1. Develop a weather-based index for predicting the development of strawberry powdery mildew.

2. Develop a weather and inoculum-based index for predicting the development of strawberry powdery mildew.

3. Develop a framework for assessing the environmental, economic and social dimensions of sustainability of strawberry cropping systems.

1.2 Hypotheses

1. A weather-based index integrating temperature, relative humidity and rainfall can accurately predict the development of strawberry powdery mildew.

2. The combination of the weather-based index and airborne conidia concentration can accurately predict the development of strawberry powdery mildew.

3. A qualitative multi-criteria model is suitable for the development of a framework for assessing the three dimensions of sustainability of strawberry cropping systems.

Chapter 2: Literature review

2.1 Strawberry production

The province of Quebec is the most important strawberry producer in Canada. In 2015, around 1550 hectares were cultivated with strawberries in Quebec, which represents almost half of the total area in the country (ISQ and MAPAQ, 2016). Ontario is the second producer with around a quarter of the total strawberry area in Canada (ISQ and MAPAQ, 2016). Even though Quebec is the most important producer in Canada, strawberries are still imported and come mostly from the United States. In 2015, importations of strawberries in Quebec represented almost 13 million $ (ISQ and MAPAQ, 2016).

The most cultivated strawberry, *Fragaria x ananassa*, is a hybrid of *Fragaria chiloensis* (L.) Duch. and *Fragaria virginiana* (Duch.), two wild species from America (Hancock, 1999). The strawberry plant is a perennial plant that belongs to the Rosaceae family. It has a compressed stem (also called crown) from which roots, trifoliate leaves, stolons and inflorescences emerge (Hancock, 1999). The strawberry plant produces stolons (runners), which are aerial stems that run over the soil surface. Stolons generally develop two nodes (Hancock, 1999). The first node usually remains dormant whereas the second node produces a daughter plant, which is able to survive on its own after two to three weeks (Strand, 1994).

Strawberry cultivars are usually divided into three groups depending on their response to photoperiod: ever-bearing, June-bearing and day-neutral (Hancock, 1999). Ever-bearing plants, which are not commonly grown, initiate flower buds mostly under the long days of summer (Stewart and Folta, 2010). June-bearing cultivars initiate flower buds when day length is less than 14 hours which occurs in the fall (Stewart and Folta, 2010). Clery, Wendy, Jewel, Sonata and Valley Sunset are few examples of June-bearing cultivars grown in Quebec. Day-neutral cultivars are insensitive to photoperiod in regard to flower induction (Stewart and Folta, 2010) and thus produce flowers and fruits continuously during the growing season. Seascape, Monterrey and Albion are among the most popular day-neutral cultivars in Quebec.

2.1.1 Production systems

Over the last decades, strawberry production has evolved to provide fruits over a longer period. Although most Quebec producers are still growing strawberries using the matted row system, an increasing number of producers are now using a combination of different production systems. In the matted row system, fruits are harvested from both mother and daughter plants (Hancock, 1999). June-bearing strawberries are planted in the spring at a low density (Thireau and Lefebvre, 2014). During the first summer, flower trusses are removed and stolons are allowed to form daughter plants (Thireau and Lefebvre, 2014). Fruits are harvested during a short period at mid-summer for the two or three following years (Thireau and Lefebvre, 2014). Every year after harvest, the field is usually renovated: plants are mowed down and rows are narrowed. Then, in the fall plants are covered with straw to protect them from cold (Thireau and Lefebvre, 2014).

Contrary to the matted row system, in plasticulture systems, stolons are removed and fruits are only harvested from mother plants (Hancock, 1999). In this system, plants are grown on raised beds covered with plastic mulch under which a drip irrigation system is installed (Lantz et al., 2010). Raised beds provide better soil aeration and drainage while plastic mulch helps to increase soil temperature and control weeds (Hancock, 1999). Both June-bearing and day-neutral cultivars can be used in plasticulture systems. In Quebec, day-neutral cultivars are planted in the spring at a high density and flowers trusses are removed during the first four to six weeks after planting (Zerouala, 2008). Depending of the regions, fruits are harvested from late July or August until the first frost. Although some growers keep parts of their fields for an early harvest the next spring, this is usually an annual production. June-bearing cultivars grown in plasticulture systems can be planted in the spring or more rarely in the fall. When planted in the spring, a small first harvest occurs the first year and another harvest occurs around mid-June during the second year (Novafruit, n.a.). Some growers keep their fields for a third year but plants are more prone to frost, diseases or insects. Thus, combining both matted row and plasticulture systems enables growers to harvest strawberries over a longer period.

Other techniques are used for extending the season: varieties with different earliness, different types of planting stock (fresh and dormant bare root and plug plants), staggered planting dates, winter row covers and high tunnels. Winter row covers are mainly used to hasten the harvest in the spring even though they are useful to protect strawberry plants against winter cold (Lacroix et al., 2017). They can be used either in matted row or plasticulture systems. Winter row covers are usually placed over the rows in the late fall and kept until bloom (Thireau and Lefebvre, 2014). Winter row covers may be made with clear polyethylene, spunbonded polyester, and spunbonded polypropylene (Wells, 1996).

Plastic tunnels are non-heated and are used to extend the harvest in the spring or in the fall (Rowley et al., 2010). Strawberries grown under tunnels can be planted directly in the soil or in containers (Demchak, 2009). Plastic tunnels provide several advantages compared to field production: they protect crops from rain; they often increase yields of crops; they improve fruit quality; and they decrease incidence of several diseases (Demchak, 2009). On the other hand, a few disadvantages of high tunnels are frequently observed: two-spotted spider mites, white flies, and thrips are more problematic in high tunnels (Demchak, 2009).

2.1.2 Diseases of strawberry

Strawberry growers must cope with numerous diseases affecting their production, most of them being caused by fungi. Verticilium wilt (*Verticilium dahliae*) and red stele root rot (*Phytophthora fragariae var. fragariae*) are two examples of occasional fungal diseases caused by telluric organisms (Lambert et al., 2007). Anthracnose fruit rot (*Colletotrichum acutatum*), gray mold (*Botrytis cinerea*) and crown rot (*Phytophthora cactorum*) may cause fruit rot whereas leaf scorch (*Diplocarpon earlianum*), Ramularia leaf spot (*Mycosphaerella brunnea*) and angular leafspot (*Xanthomonas fragariae*) are common foliar diseases of strawberry plants (Lambert et al., 2007). Powdery mildew (*Podosphaera aphanis*) is another disease affecting strawberry for which incidence has increased in Quebec over the last years (Tellier, 2017).

2.2 Powdery mildew of strawberry

2.2.1 Symptoms and crop losses

Powdery mildew can infect all aerial parts of the strawberry plant (Maas, 1998). Symptoms vary depending on cultivars and disease intensity. At the beginning of the disease, the most frequently observed symptom is white patches of mycelium on the leaf surface (Amsalem et al., 2006). As the disease progress, an increase in the mycelium coverage of leaves can lead to a reduction in photosynthesis and eventually to defoliation (Amsalem et al., 2006; Maas, 1998). Reddish irregular spots may also appear on the upper leaf surface and leaves may curl upward (Lambert et al., 2007). Both infected flowers and fruits may be covered by white mycelium. Infected flowers may produce less pollen, and even wilt or die (Carisse and Bouchard, 2010). Infected fruits may fail to ripen (Carisse and Bouchard, 2010) whereas ripe fruits may remain soft or have a shortened shelf life (Spencer, 1978).

Most crop losses are caused by flower and fruit infections rather than by the reduced photosynthetic rate due to leaf infections (Carisse and Bouchard, 2010). However, leaf infections can act as an inoculum source for flower and fruit infection (Carisse et al., 2013b). Up to 30% yield losses have been observed under Quebec conditions with the Seascape cultivar in open fields (Carisse et al., 2013b). Crop losses are also known to be variable depending on many factors such as the year, the cultivar and the production system (Darnell et al., 2003).

2.2.2 *Podosphaera aphanis*

Powdery mildew of strawberry is a polycyclic disease caused by *Podosphaera aphanis* (Wallr.), formerly called *Sphaerotheca macularis* f. *fragariae* (Harz) Jacz (Carisse et al., 2013b). This fungus is an ascomycete which belongs to the Erysiphaceae family (Glawe, 2008). It is an obligate plant pathogen, meaning that it needs living plant tissues in order to survive and reproduce (Glawe, 2008). *P. aphanis* is also specific to the genus *Fragaria* (Peries, 1962) .

Life cycle of *P. aphanis* can involve either an asexual state (mycelium and conidia) or both asexual and sexual (chasmothecia or cleistothecia) states (Gadoury et al., 2010; Glawe, 2008). An infection begins when a conidium, or an ascospore released from a mature cleisthotecium, germinates on a strawberry plant (**Figure 2.1**). A germ tube then forms which elongates in order to form a hypha with appressoria, penetration pegs and haustoria (Bélanger, 2002). These structures allow the fungus to obtain nutrients from the plant (Glawe, 2008). After infection occurs, hyphae (or mycelium) develop superficially on the plant, elongate, and form new branches (Glawe, 2008). Eventually, these hyphae allow the formation of reproductive structures such as conidiophores and cleistothecia (Glawe, 2008).

Conidiophores are the asexual structures from which chains of conidia are produced (Glawe, 2008). Conidia of *P. aphanis* are uninucleate hyaline single cells measuring 28-33 x 15-20 µm (Boesewinkel, 1980). They have the shape of a barrel when turgid and they contain granules called fibrosin bodies (Boesewinkel, 1980; Glawe, 2008). Conidia are dispersed by the wind (Peries, 1962).

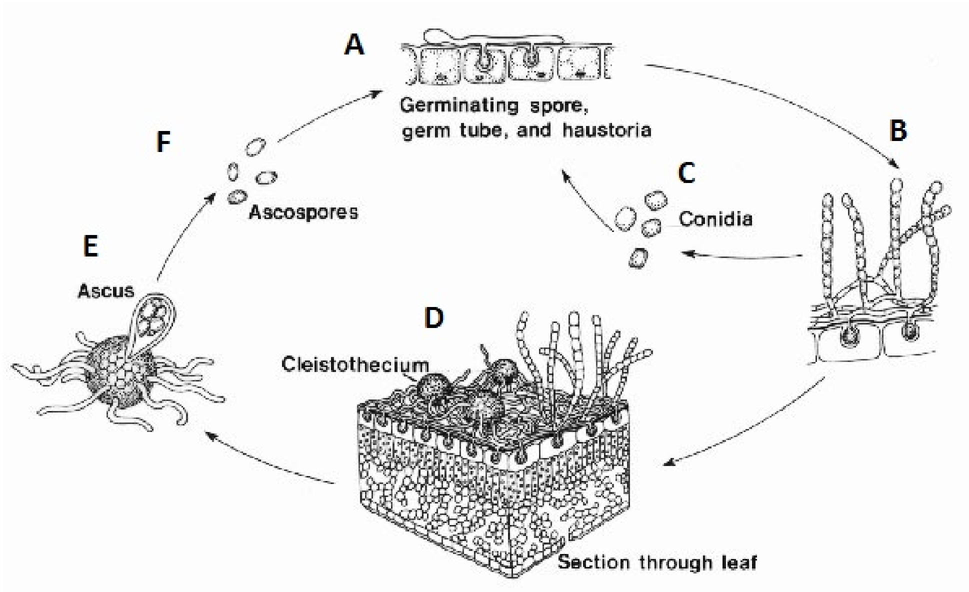


Figure 2.1 Life cycle of *Podosphaera aphanis*.
Infection begins when a conidium or ascospore germinates (A); Mycelium and chains of conidia are produced (B); Conidia are dispersed by the wind and can infect other tissues (C). Powdery mildew of strawberry being a polycyclic disease, the cycle A-B-C can be repeated many times during the season; In the fall, cleistothecia may be produced and overwinter on the strawberry plant (D); Mature cleistothecia release ascospores in the spring (E); Ascospores can act as a source of primary inoculum (F). Modified from Schumann (1991).

Contrary to conidia, which are always part of *P. aphanis* life cycle, cleisthotecia are rarely observed in some regions (Howard and Albregts, 1982; Peries, 1962). According to Gadoury et al. (2010), this may be partly explained by the fact that the pathogen is heterothallic. Thus, the presence of two compatible mating types of *P. aphanis* is required for the formation of cleisthotecia. Moreover, the ability of *P. aphanis* cleisthotecia to act as a source of primary inoculum in the spring has long been questioned (Amsalem et al., 2006; Maas, 1998; Peries, 1962). It was only recently proved that cleisthotecia of *P. aphanis* can release germinable and infectious ascospores during the spring (Gadoury et al., 2010).

Once morphologically mature, cleisthotecia are dark, concavo-convex with a diameter of approximately 90 µm (Gadoury et al., 2010). They contain only one ascus per cleisthotecium and they form hyphal outgrowths that are mixed with mycelium (Gadoury et al., 2010; Glawe, 2008). Gadoury et al. (2010) also showed that cleistothecia of *P. aphanis* are very persistant to strawberry leaves in comparison to other powdery mildew pathogens. Consequently, cleistothecia of *P.*

aphanis are more prone to stay near the crown from where new leaves emerge in the spring (Gadoury et al., 2010).

2.2.3 Influence of weather conditions on *P. aphanis*

The development of *Podosphaera aphanis* on strawberry plants is influenced by environmental conditions such as temperature, relative humidity and rainfall. Temperature influences germination, growth and sporulation of *P. aphanis*. The minimal temperature at which an infection can occur is around 5°C (Peries, 1962), at which point the mycelium grows slowly until temperatures reach 18 to 22.5°C - optimal for infection, growth and sporulation (Peries, 1962; Sombardier et al., 2009). Between 25 and 30°C, a rapid drop in growth rate can be observed (Miller et al., 2003). No sporulation occurs between 5 and 13°C (Blanco et al., 2004; Peries, 1962). At an average daily temperature of 15°C, Blanco et al. (2004) measured a peak concentration of airborne conidia between 13h and 15h.

High relative humidity is necessary for conidia germination (Blanco et al., 2004). A maximal conidia germination rate was observed with relative humidity between 97 and 100%, but decreased as soon as relative humidity was around 90% (Peries, 1962). Even under ideal temperature and relative humidity conditions, the presence of free water on leaves could inhibit the development of *P. aphanis* (Blanco et al., 2004). Moreover, rain decreases airborne conidia concentration and can inhibit sporulation (Blanco et al., 2004).

2.2.4 Ontogenic resistance

Strawberry plants develop ontogenic resistance to powdery mildew (Asalf et al., 2014; Carisse and Bouchard, 2010). The ontogenic resistance is defined as the ability of a plant (or a part of the plant) to resist infection with aging (Populer, 1978). In the case of strawberry, susceptibility of leaves and berries to powdery mildew decreases exponentially with age (Asalf et al., 2014; Carisse and Bouchard, 2010). Thus, flowers, green berries and not fully expanded leaves are highly susceptible while unfold leaves and pink and mature berries are almost resistant to powdery mildew (Asalf et al., 2014; Carisse and Bouchard, 2010).

2.2.5 Influence of production systems

The development of powdery mildew and its impact may vary depending of the production systems. On June-bearing cultivars grown in open fields, fruits are usually harvested at the beginning of July, whereas the onset of powdery mildew generally occurs after this period. Hence, it is not frequent to observe direct yield losses during the current season (Carisse and Bouchard, 2010). However, new leaves emerging from mown-off plants are highly susceptible to powdery mildew (Carisse and Bouchard, 2010) and severe epidemics may occur. Under mild winter conditions, severe epidemics occurring in the fall did not affect the yield of the subsequent year (Berrie and Burgess, 1997). However, it is not known if winter survival of diseased plants can be affected under colder winter conditions (Carisse and Bouchard, 2010).

On day-neutral cultivars grown in open fields, fruits are generally harvested from August to October, which means that susceptible flowers and fruits are constantly present during this period. Powdery mildew infections can be severe and cause direct yield losses during August and September, especially on susceptible cultivars (Carisse and Bouchard, 2010).

Powdery mildew is known to be problematic under protected cultures. Conditions under high tunnels are highly favorable to powdery mildew development because leaves are protected from rainfall (Xiao et al., 2001). Powdery mildew also develops following a different spatial pattern in high tunnels compared to open fields. For the same level of disease incidence, severity was higher under high tunnels compared to open fields, suggesting that high tunnels promote auto-infection of plants due to lower wind speed in tunnels (Carisse et al., 2013a).

2.2.6 Powdery mildew management

Preventive methods

Several methods are known to have a preventive although limited effect on powdery mildew of strawberry. Cultivar resistance is one of them. Although no cultivar is completely resistant to powdery mildew, susceptibility to the disease varies greatly among the cultivars (Bouchard, 2008; Nelson et al., 1996). Essays conducted in Quebec showed that cultivars Chambly, Jewel and Seascape are very susceptible whereas Annapolis and Aromas are almost insensitive to the disease (Bouchard, 2008).

Other elements have been pointed out, mostly based on field observations, for their preventive role against powdery mildew: avoiding excess nitrogen input responsible for important development of young susceptible leaves (Xu et al., 2013), considering that *P. aphanis* spores are wind-dispersed when choosing field location, avoiding field renovation during windy conditions and harvesting the most infected fields first (Tellier, 2017).

Fungicide use

Despite the use of preventive methods, fungicide use often is the only efficient way to control powdery mildew. Powdery mildew management programs usually aim at controlling the disease on foliage, which prevents berries damages (Carisse et al., 2013b). Provincial guidelines recommend applying fungicides when weather conditions are favorable to powdery mildew infections and to make sure young susceptible leaves and flowers are protected (Tellier, 2017).

However, management of the disease is variable depending of the production systems and of the risk acceptance of each grower. For example, some producers apply fungicides regularly from the emergence of the first leaves to harvest whereas others start applying fungicides from the onset of the disease (first symptoms). After harvest of June-bearing cultivars, management of powdery mildew is also variable between growers due to a lack of information concerning effects of post-harvest powdery mildew: some producers continue to apply fungicides at regular intervals whereas others chose not to apply (Carisse et al., 2013a).

Sixteen fungicides are currently registered in Canada for strawberry powdery mildew management (Firlej et al., 2017). NOVA™ (myclobutanil), PRISTINE WG™ (boscalid and pyraclostrobin), QUINTEC™ (quinoxyfen), FLINT™ (trifloxystrobin) and LIME SULFUR™ (calcium polysulphide) are among the most used pesticides. Growers are advised to alternate fungicides with different modes of action to prevent resistance (Tellier, 2017).

Development of resistance is important issue: resistance to demethylation-inhibiting fungicides (such as myclobutanil) by powdery mildew populations has been reported in France (Sombardier et al., 2010), while some Quebec producers observed a reduced efficiency of pesticides NOVA™ and PRISTINE WG™ (Firlej et al., 2017; Lafontaine et al., 2014)

2.2.7 Recent advances

Most recent papers on strawberry powdery mildew concern the use of silicon and UV irradiation as potential control methods for the disease. Ouellette et al. (2017) recently showed that strawberry plants have silicon (Si) transporters and can accumulate Si. A reduction of powdery mildew severity was observed on strawberry plants grown in a soilless substrate under tunnel that received constant soluble Si fertilization (Ouellette et al., 2017). Use of UV-C irradiation followed by a period of darkness once a week was also effective in reducing powdery mildew incidence on strawberry plants (Janisiewicz et al., 2016).

Recent studies could improve the management of strawberry powdery mildew. Carisse et al. (2013b) recently showed that a positive linear relationship exists between disease severity and seasonal crop losses. In day-neutral strawberries, 5% crop losses were reached when an average of 17% leaf area diseased was observed from the beginning of infection (Carisse et al., 2013b). However, because the assessment of disease severity is difficult and time-consuming, Carisse et al. (2013a) developed three models (for June-bearing in open fields and under high tunnels and for day-neutral in open fields) for estimating disease severity based on incidence, which is easier to assess.

Airborne conidia concentration is another variable that could be used to assess the presence of *P. aphanis*. A positive linear relationship between daily airborne conidia concentration (ACC) and disease severity was observed (R^2=0.94) (Van der Heyden et al., 2014).

2.3 Decision-making in agriculture

As farm managers, strawberry growers make different types of management decisions : strategic, tactical and operational decisions (Bouma, 2007). Strategic decisions are major decisions influencing the economic, environmental and social sustainability of the farm (Bouma, 2007). For example, it can be the choice of a production system, a shift towards organic farming, etc. Tactical decisions are medium-term decisions such as the choice of cultivars and fertilizer rates. Operational decisions are day-to-day decisions : when to apply fertilizers or when to spray pesticides (Bouma, 2007). Decision support tools for plant diseases are usually developed to help growers make operational decisions.

2.3.1 Decision support tools for plant disease management

Rational management of plant diseases implies that fungicides are sprayed when there is a risk of disease development (Carisse, 2009). This risk can be assessed based on variables such as cultivar sensibility, scouting data, past and upcoming weather conditions and growth stage of the crop (Carisse, 2009). Rational disease management leads to an optimization of pesticide efficiency and a reduction of resistance development (Carisse, 2009). However, rational disease management is complex and requires the integration of numerous variables to decide if a fungicide spray is needed (Gent et al., 2011). This difficulty has led to the development of tools that help producers when it comes to the management of a disease (Gent et al., 2011). These tools can take several forms such as spreadsheets, databases, geographic information systems, simulations models, decision trees or other more complex systems (Shtienberg, 2013).

However, even though decision support tools are available for many crops and diseases, their adoption by producers is variable (Shtienberg, 2013). According to Shtienberg (2013), decision support tools for predicting fungicide applications are more used for extensive crops than for intensive crops. This would be due to a lower financial risk of a false-negative action (no fungicides are applied when it would have been required) for extensive crops (Shtienberg, 2013).

2.3.2 Decision support tools for powdery mildews

Several decision support tools have been developed for the management of grape and tomato powdery mildews. Chellemi and Marois (1991) developed a model predicting the population growth of *Uncinula necator* (causing agent of powdery mildew of grape). The model is based on equations that calculate germination, penetration and sporulation rates based on variables such as temperature and presence of water on the host surface. The *UC Davis Powdery Mildew Risk Assessment Model* is another model for grape powdery mildew (Gubler et al., 1999). It is composed of two parts: an ascospore and a conidial stage. The first part uses both the daily average temperature and hours of leaf wetness to calculate a risk level for ascospore infection, whereas the second part uses hourly temperature to calculate a disease risk index (Gubler et al., 1999). More recently, Carisse et al. (2009b) developed a model for the management of grape powdery mildew in Quebec. The model, based on the accumulation of degree-days (with a base temperature of 6 °C), helps to decide when to start fungicide spray programs (Carisse et al., 2009b)

Guzman-Plazola (1997) developed a model for the management of tomato powdery mildew (*Leveillula taurica* (Lev) Arn) in California. The model uses variables related to temperature, relative humidity and leaf wetness to assess the number of conducive, moderate and non-conducive days over a period of six days. Depending of the number of conducive days during a period, the model predicts the expected severity of the disease and makes a spray recommendation (Guzman-Plazola, 1997).

2.3.3 Decision support tools for strawberry powdery mildew

Several decision support tools have been developed for the management of strawberry powdery mildew (**Table 2.1**). In the United Kingdom, a rule-based prediction system using weather variables has been developed to identify risk of powdery mildew development under tunnel (Dodgson et al., 2009; Parker et al., 2008). The system calculates the percentage of completion of a disease cycle based on time requirements under suitable conditions for germination, growth and sporulation of *P. aphanis*. Once a life cycle is completed, a high risk day is predicted which can be used for guiding pesticide applications (Parker et al., 2008).

In Italy, a decision support system called SafeBerry has also been developed (Eccel et al., 2010). SafeBerry calculates a potential risk index which combines a basic and a daily risk index. Once the potential risk index is known, measured and forecasted temperature are used to determine if the environment is conducive for disease development and a recommendation is given (Eccel et al., 2010).

In France, the *Centre technique au service de la filière fruits et legumes* (Ctifl) has been developing a predictive model for strawberry powdery mildew (Bardet and Vibert, 2011). As part of the model, five stages of *P. aphanis* life cycle (dispersion, infection, mycelium growth, sporulation and disease progression) are modeled in function of weather data such as temperature, relative humidity and rain. Then, a risk index is calculated for a 4-day mobile period (Bardet and Vibert, 2011). The model is available through the web platform Inoki as a paid service (Ctifl, 2017).

In the United States, the *UC Davis Powdery Mildew Risk Assessment Model*, developed at first for grape powdery mildew (Gubler et al., 1999), was adapted for strawberry powdery mildew (Hoffman et al., 2002). The *UC Davis Powdery Mildew Risk Assessment Model* for strawberries was tested under Quebec conditions by Bouchard (2008). A modified version of the model including spore measurements was also tested, which resulted in a lower number of fungicide applications (Bouchard, 2008). The author concluded that a predictive tool considering only temperature was not complete, but that adding one or many other variables (such as airborne conidia concentration) could improve the predictive system.

Table 2.1 Decision support tools developed in United Kingdom, France, Italy and United States for the management of strawberry powdery mildew.

	UK (Dodgson et al., 2009)	**Ctifl (Bardet and Vibert, 2011)**	**SafeBerry (Eccel et al., 2010)**	**Gubler-Hoffman (Bouchard, 2008; Hoffman et al., 2002)**
Input	Temperature, relative humidity and leaf wetness from sensors in the field.	Temperature, relative humidity and rain from sensors in the field.	Basic index: cultivar susceptibility, overhead irrigation, type of sprayer, … Daily index: phenological stage, disease incidence in the tunnel, … Suitability: temperature.	Two versions of the index tested by Bouchard (2008): the original version and a modified version using spore samplers. Original index: temperature Modified index: temperature and airborne conidia concentration.
Description	Calculates the percent of completion of a disease cycle based on the number of hours with favorable conditions for germination, growth and sporulation.	Risk index based on favorable conditions for the different parts of *P. aphanis* life cycle.	1. Risk determination based on a basic risk index and a daily risk index. 2. Determination of temperature suitability for disease development based on measured and forecasted temperature.	The index takes a value between 0 and 100. In general, points are added when four consecutive hours of temperature between 18-27 °C are observed during a day; otherwise, points are deducted.
Output	Predicts a high-risk day when a disease cycle is completed.	Graphical representation of periods suitable for dissemination, infection and mycelium growth.	Recommendation for action (spray, …) and suggestion of pesticides.	Original: The index value is linked with a recommendation of time interval between pesticide applications and spray material. Modified: Both the index value and the airborne conidia concentration are considered for the recommendation.
Validation	Tested on four tunnels (2 newly planted and 2 established) in UK.	Tested in the Southwest of France in tunnels and open fields.	Tested at three locations in 2007 in tunnels situated in northern Italy.	Original index tested in California. Both indices tested in open fields at two sites in the province of Quebec in 2006 and 2007.
Number of fungicide applications required	Same number or fewer fungicide applications compared to grower practices.	No information available.	Fewer fungicide applications compared to common practice of growers in the area.	**California**: Fewer fungicide applications compared to a 14-day schedule. **Quebec**: Same number or more fungicide applications compared to grower practices. Adding spore samplers to the model reduced the number of fungicide applications compared to grower practices.
Disease control and impact on yield	Few information available on disease incidence. No information available on impact on yield.	No information available on disease incidence. No information available on impact on yield.	Reduction of disease incidence compared to untreated plots. No information available on impact on yield.	**California** (few information available): Disease incidence greater than the 14-day schedule and no significative yield reduction. **Quebec**: Similar control to grower practices for the original and modified versions of the index. Similar yield to grower practices for both versions.

As mentioned previously, these decision support tools for strawberry powdery mildew are conceived to help growers make operational decisions and thus, could eventually improve the sustainability of strawberry production.

2.3.4 Sustainability

Although there is no consensus about the definition of sustainability, the most cited definition is from the Bruntland Report (FAO, 1987). According to this report, sustainable development is a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The concept of sustainability has also been specifically defined for agriculture. Ikerd (1993) states that a sustainable agriculture should be able of "maintaining its productivity and usefulness to society indefinitely" and that it should "conserve resources, protect the environment, produce efficiently, compete commercially, and enhance the quality of life for farmers and society overall." Another definition provided by the Food and Agriculture Organization of the United Nations (FAO, 1989) describes sustainable agriculture as an agriculture that "conserves land, water, and plant and genetic resources and is environmentally non-degrading, technically appropriate, economically viable and socially acceptable".

Although the wording is different from one definition to another, both definitions recognize the multi-dimensional aspect of sustainability in agriculture. Environment, economy and society are generally identified as the three dimensions of sustainability, although governance is sometimes considered as the fourth dimension (FAO, 2014a).

For each dimension of sustainability, several key elements can be pointed out. A farm considered economically sustainable is able to make profit and to pay adequately his workers. It usually produces in a way that is efficient. Moreover, such a farm needs to be resilient, by being able to deal with risk and to adapt to changes (FAO, 2014b). A farm that is environmentally sustainable conserves flora and fauna biodiversity and minimizes its negative impacts on water, land and atmosphere. It also uses efficiently resources such as energy, water, and materials (FAO, 2014b). On a farm that is socially sustainable, farmers and workers have employment condition that do not threat their health and safety, and they receive a fair income for their work (FAO, 2014b).

2.3.5 Sustainability assessment of agricultural systems

Assessing the sustainability of an agricultural production is complex (Sadok et al., 2008). Indeed, it involves the assessment of different options (for example different cropping systems) by considering many criteria that are sometimes conflicting (Sadok et al., 2008). This is why it is usually considered as a decision-making problem (Dent, 1995; Sadok et al., 2008).

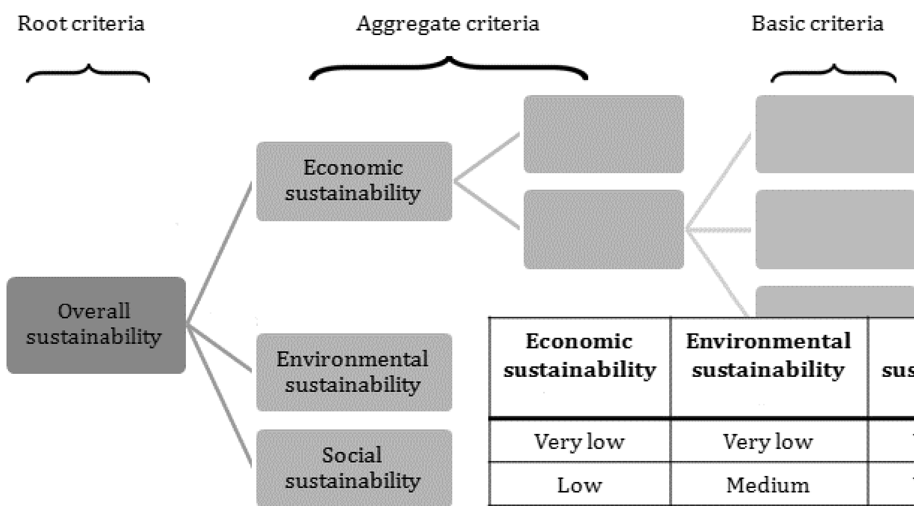
Decision-aid methods have been developed for helping sustainability assessment (Sadok et al., 2008). Most of these methods are multi-criteria decision-aid (MCDA) methods (Sadok et al., 2008). Numerous MCDA methods exist and can be divided into two categories: multi-objective decision-making (MODM) methods and multi-attribute decision-making (MADM) methods. MODM methods are used when there are an infinite or very high number of options to assess. They are based on the optimization of mathematical models (Sadok et al., 2008). MODM methods are not recommended in presence of both quantitative and qualitative data and in presence of missing data (Sadok et al., 2008). Contrary to MODM methods, MADM methods are used when a limited number of options are available. These methods do not rely on mathematical modeling, but on aggregation rules (Sadok et al., 2008).

In a review of the different MCDA methods, Sadok et al. (2008) concluded that decision rule-based methods (also known as qualitative multi-criteria models), pertaining to the category of MADM methods, were appropriate for sustainability assessment of agricultural systems. Indeed, qualitative multi-criteria models can handle both qualitative and quantitative values and can deal with the multiple dimensions of sustainability (Sadok et al., 2008). In order to deal with this multidimensional aspect, qualitative multi-criteria models can handle incommensurability, non-compensation and incomparability. Incommensurability means that three different dimensions (economic, environmental and social) are not necessarily measured in the same way (Sadok et al., 2008). Non-compensation refers to the possibility that a positive value for a dimension does not compensate for a negative value for another dimension. Incomparability implies that no unique value is used for ranking sustainability since it is not relevant for sustainability assessment (Sadok et al., 2008).

2.3.6 Qualitative multi-criteria models

The concept of qualitative multi-criteria models is the decomposition of a complex problem into many sub-problems easier to solve (Bohanec, 2015). All the elements that are part of the problem are called criteria (or attributes) and are organized into a hierarchical tree (Bohanec, 2015) (**Figure 2.2**). Criteria situated at the lower levels of the tree are called basic criteria whereas other criteria are called aggregated criteria.

In a qualitative multi-criteria model, the criteria are not quantitative values, but qualitative values such as “low”, “acceptable” and “good”. Criteria are aggregated from the lower levels of the tree to the higher levels. The aggregation is made using ‘if-then’ aggregation rules that can be represented on a table (**Figure 2.2**) (Bohanec, 2015).



Economic sustainability	Environmental sustainability	Social sustainability	Overall sustainability
Very low	Very low	Very low	Very low
Low	Medium	Very low	Low
Medium	High	Very high	High
...	...	...	...

Figure 2.2 Hierarchical structure of a qualitative multi-criteria model.
The complex problem “Overall sustainability” is divided into smaller problems, until basic criteria are reached. Criteria are combined into aggregated criteria using “if-then” aggregation rules, as shown on the table. According to the first aggregation rule on the table, if economic sustainability is “very low”, environmental sustainability is “very low” and social sustainability is “very low”, then the overall sustainability is “very low”. Adapted from Vélu et al. (2016a).

The value of a basic criterion is determined by one or more indicators. Distinguishing between basic criteria and indicators can sometimes be confusing. Contrary to a basic criterion which is a concern for sustainability, an indicator gives information about degree of fulfillment of a criterion and needs to be adapted for the assessed crop (Craheix et al., 2015). For example, the “nitrogen rate” could be an indicator for the basic criterion “risk of nitrate leaching”.

Indicators can be quantitative, qualitative or mixed. Quantitative indicators come from technical and economic references and can be translated to qualitative variables by using thresholds (Craheix et al., 2015). Qualitative indicators can provide information on the geographical context and are usually determined based on expert knowledge (Craheix et al., 2015). Mixed indicators are a combination of several indicators aggregated with decision rules. They are sometimes called "satellite trees" (Craheix et al., 2015). They can be developed with technical and economic references and with expert knowledge.

DEXi is a computer program specifically conceived for the development of qualitative multi-criteria models and the evaluation of different options with the model (Bohanec, 2015). DEXi has been used for the development of numerous models assessing the sustainability of cropping systems (Craheix et al., 2015). It has been used for *ex post* assessment of cropping systems, but also for *ex ante* assessment of innovative cropping systems (Craheix et al., 2015). MASC and DEXiPM are two examples of qualitative multi-criteria models developed for sustainability assessment of arable cropping systems in Western Europe (Pelzer et al., 2012; Sadok et al., 2009).

MASC (for Multi-Attribute Assessment of the Sustainability of Cropping systems) has been developed by French agronomists (Sadok et al., 2009). It has been created initially for *ex post* assessment of arable cropping systems in a given context, although it can also be used for *ex ante* assessment of innovative cropping systems (Sadok et al., 2009). A first version of MASC, consisting in 32 input criteria and 22 aggregate criteria, was released to research centers and agricultural schools. Feedback from these users was used to develop MASC 2.0 (Craheix et al., 2012). MASC 2.0 now includes 39 basic criteria instead of 32 (Craheix et al., 2012). It also has a better sensitivity at the level of the overall sustainability which means that it has a better capacity to distinguish between different cropping systems (Craheix et al., 2012). The parameterization process is also more flexible. Users have the possibility to modify the indicators and to change the weights of the different criteria. It also allows users to better take into account the regional context and their own vision of sustainability (Craheix et al., 2012).

The main difference between MASC and DEXiPM is that the first one was mainly developed for *ex post* assessment and the latter, for *ex ante* assessment of cropping systems (Pelzer et al., 2012). Moreover, DEXiPM is composed of more criteria than MASC, with 52 basic criteria (Craheix et al., 2015). The objective of DEXiPM was to design and assess innovative cropping systems with low use of pesticides and targeted users were mostly scientists (Messéan et al., 2010).

Connecting text

The following chapter focused on powdery mildew of strawberry. As mentioned previously, the existing risk indices for this disease are either not documented or poorly validated. The aim of chapter 3 was to develop a weather-based index for predicting the development of strawberry powdery mildew.

Chapter 3: Development of indices for predicting the development of strawberry powdery mildew

M. Gendron, O. Carisse and V. Gravel

3.1 Abstract

Powdery mildew is considered as a major constraint in strawberry production. This disease caused by the ascomycete *Podosphaera aphanis* (Wallr.) can infect all aerial parts of the strawberry plant. Up to 30% yield losses have been observed in the province of Quebec. Several studies show that the development of strawberry powdery mildew is enhanced by new production techniques such as plasticulture systems with day-neutral cultivars and the use of high tunnels. Currently, management of powdery mildew is mainly based on fungicide applications. The objective of this study was to predict the development of strawberry powdery mildew. The data were collected from 2006 to 2011 at the Agriculture and Agri-Food Canada experimental farm in Frelighsburg and at six commercial farms situated in the province of Quebec. Disease and airborne conidia concentration assessments were performed one to three times weekly from May to September. Weather data (air temperature (°C), relative humidity (%) and rainfall (mm)) were obtained from automatic weather stations situated on the farms. Two weather-based indices were developed by cumulating daily hours of favorable (index A) and optimal (index B) weather conditions (temperature, relative humidity and rainfall) for conidia germination. A positive linear relationship between the weather-based indices and disease severity was observed, for 75% and 68% of the epidemics of June-bearing cultivars in open fields showing a R^2 over 0.6 for indices A and B, respectively. Two weather and inoculum-based indices (A_i and B_i) were developed by combining daily values of the weather-based indices and airborne conidia concentration. However, including spore measurements did not improve the indices compared to the weather-based indices. Graphical representations of disease severity revealed sites where some powdery mildew epidemics started earlier and developed faster than other epidemics exposed to similar weather conditions. These observations show that weather conditions alone are not sufficient to explain disease development. Further models on strawberry powdery mildew should include additional variables (i.e., the “age’ of the strawberry field or the presence of susceptible leaves).

3.2 Introduction

Powdery mildew of strawberry is a disease affecting strawberry production worldwide (Glawe, 2008). It is caused by the obligate pathogen *Podosphaera aphanis* (Wallr.), which can infect all aerial parts of the plant (Maas, 1998). First signs of powdery mildew are usually white patches of mycelium and conidia on the abaxial leaf surface (Amsalem et al., 2006). As the disease progress, patches can cover the entire leaves and lead to defoliation (Amsalem et al., 2006; Maas, 1998). Foliar infections cause indirect loss by reducing photosynthesis, but also act as a source of inoculum for flower and fruit infections, which are responsible for direct yield loss (Carisse and Bouchard, 2010). Infected flowers may produce less pollen, wilt or die, whereas infected fruits may fail to ripen, remain soft or have a shortened shelf life (Carisse and Bouchard, 2010; Spencer, 1978).

Powdery mildew development is influenced by different factors such as weather conditions, cultivar susceptibility, phenological stage of the crop and production systems (Darnell et al., 2003). Temperatures between 18 and 25°C are optimal for conidia germination, lesion growth and sporulation; high relative humidity is required for conidia germination; and rainfall has a detrimental effect on conidia (Blanco et al., 2004; Peries, 1962; Sombardier et al., 2009). Although no cultivar is completely resistant to powdery mildew, disease susceptibility varies among cultivars. Jewel and Seascape, two of the most popular cultivars in the Quebec province, are considered to be susceptible to powdery mildew (Bouchard, 2008). Susceptibility of leaves and berries to powdery mildew decreases exponentially with age (Asalf et al., 2014; Carisse and Bouchard, 2010). Thus, flowers, green berries and not fully expanded leaves are highly susceptible while pink and mature berries and unfold leaves are almost resistant (Asalf et al., 2014; Carisse and Bouchard, 2010). In open fields, the disease is more problematic for day-neutral cultivars than for June-bearing cultivars. Indeed, day-neutral cultivars bear susceptible flowers and fruits from mid-July to September when powdery mildew epidemics can be severe, whereas June-bearing cultivars bear susceptible flowers and fruits in late spring and beginning of summer, which is generally before disease onset (Carisse and Bouchard, 2010). Powdery mildew is also known to be more problematic under high tunnels due to favorable weather conditions for its development (Xiao et al., 2001).

Although actual management of strawberry powdery mildew is variable, it is mostly based on pesticide use. Fungicides are sprayed regularly either from the emergence of the first leaves or from the first symptoms to harvest (Carisse et al., 2013a). The management of powdery mildew of strawberry has also led to development of fungicide resistance in the province of Quebec (Firlej et al., 2017; Lafontaine et al., 2014).

In one of the few studies on crop losses, foliar severity was found to be the best predictor of subsequent crop losses for day-neutral strawberry in open field: 5% crop loss was reached when an average of 17% leaf area diseased was observed since the first symptoms (Carisse et al., 2013b). However, assessing disease severity on leaves is difficult and time-consuming. In order to facilitate disease assessment, Carisse et al. (2013a) developed models allowing foliar severity to be estimated from disease incidence for June-bearing cultivars grown in open fields and in plastic tunnels and for the day-neutral cultivar Seascape in open fields.

Although disease severity and incidence are good predictors of crop losses, predicting disease development is of major interest. The use of airborne conidia concentration and weather conditions to predict disease development has been studied. A linear relationship between disease severity and daily airborne conidia concentration (ACC) was found by Van der Heyden et al. (2014). Another way of predicting disease development is by using weather data. However, the difficulty of this approach relies in the wide range of temperature and relative humidity under which strawberry powdery mildew can develop (Amsalem et al., 2006; Miller et al., 2003; Peries, 1962). Despite this difficulty, models for predicting the development of strawberry powdery mildew were developed in other countries. In the United Kingdom, a prediction system calculates the percent of completion of a disease cycle based on temperature, relative humidity and leaf wetness (Dodgson et al., 2009; Parker et al., 2008). Once a disease life cycle is completed, the system predicts a high risk day which can guide pesticide applications (Parker et al., 2008). In Italy, the decision support system SafeBerry calculates a disease risk index which combines a basic risk index (based on cultivar susceptibility, presence of overhead irrigation, plant density, etc.) and a daily risk index (based on phenological stage of the crop, disease incidence, time of disease onset, etc.) (Eccel et al., 2010). The disease risk index is combined to the suitability of the temperature to make a recommendation of action (do not spray today, etc.) (Eccel et al., 2010). In France, a predictive model calculates the risk of powdery mildew based on suitable weather conditions for the different parts of *P. aphanis* life cycle (Bardet and Vibert, 2011). Finally, in United States, a risk index developed at first for grape powdery mildew was adapted for strawberry powdery mildew (Hoffman et al., 2002). Based on the index value, a fungicide and an interval between treatments are suggested (Bouchard, 2008). However, these models were either poorly documented or not validated under a wide range of conditions. The objective of this work was to develop weather and inoculum-based indices for predicting the development of strawberry powdery mildew.

3.3 Materials and methods

3.3.1 Sampling sites

The data were collected from 2006 to 2011 at the Agriculture and Agri-Food Canada experimental farm in Frelighsburg and at six commercial farms situated in the province of Quebec (**Table 3.1**). Data were collected in fields planted with the June-bearing cultivars Jewel, Darselect, Chambly and Cavendish and the day-neutral cultivar Seascape, and in high tunnels planted with the June-bearing cultivars Jewel, Darselect and Chambly (**Table 3.1**). Data were collected during the first or second year of production for the June-bearing cultivars. No fungicide was sprayed.

3.3.2 Disease assessment

Disease assessment was performed one to three times weekly from May to September (**Table 3.2**). Powdery mildew severity was assessed on 10 randomly selected plants per field. Severity was assessed on both sides of the three youngest fully expanded leaves of each plant (Carisse et al., 2013a). Disease severity corresponded to the proportion of the leaf covered with white sporulating lesions and was noted on a scale from 0 to 100%, by 5% steps (Carisse et al., 2013a). Mean severity over 10 plants was calculated and used for model development. The change in the mean disease severity over time will be referred to as an epidemic (Carisse et al., 2013b).

Table 3.1 Location of the different sampling sites and cultivars used for data collection at the different sampling sites for the different years.

Site abbreviation	Site	Latitude	Longitude	Sampling year					
				2006	2007	2008	2009	2010	2011
				June-bearing – Open fields					
FRE	Frelishburg	45°03′12″N	72°51′42″W	Cav[a], Cha, Dar, Jew	Cav, Cha, Dar, Jew	Cav, Cha, Dar, Jew	Cav, Cha, Dar, Jew	Cav, Cha, Dar, Jew	Cav, Cha, Dar, Jew
GADJ	St-Amable	45°42′06″N	72°57′52″W	Dar, Jew	Cav, Cha, Dar, Jew		Dar, Jew	Dar, Jew	
BEAM	Ste-Madeleine	45°35′13″N	73°03′40″W		Cav, Cha	Cav, Cha			
GAUB	Ange-Gardien	45°22′33″N	72°54′30″W			Cha, Dar, Jew	Cav, Cha, Dar, Jew		
RODM	Saint-Paul-d’Abbotsford	45°25′55″N	72°51′09″W			Cha			
				June-bearing – High tunnels					
GADJ	St-Amable	45°42′06″N	72°57′52″W	Dar, Jew	Cha, Dar, Jew	Dar, Jew	Dar, Jew	Dar, Jew	
BEAM	Ste-Madeleine	45°35′13″N	73°03′40″W		Cha	Cha			
GAUB	Ange-Gardien	45°22′33″N	72°54′30″W			Cha, Dar, Jew	Cha, Dar, Jew		
RODM	Saint-Paul-d’Abbotsford	45°25′55″N	72°51′09″W			Cha			
				Day-neutral – Open fields					
FRE	Frelishburg	45°03′12″N	72°51′42″W	Sea	Sea	Sea			
STFAM	Ile d’Orléans	46°55′06″N	70°58′35″W	Sea	Sea				
STPAU	Saint-Paul-d’Abbotsford	45°25′60″N	72°52′60″W		Sea				

[a] Cav: Cavendish, Cha: Chambly, Dar: Darselect, Jew: Jewel, Sea: Seascape.

3.3.3 Airborne conidia concentration assessment

Airborne conidia concentration was assessed one to three times weekly from May to September (**Table 3.2**). Two rotating-arm impaction spore samplers were situated in the center of each field. Samplers were rotating for 20 minutes every hour from 8 am to 8 pm (Carisse et al., 2013b). The number of spores was counted under a microscope at 250x magnification (Carisse et al., 2013b) and transformed to a number of conidia per cubic meter (Carisse and Bouchard, 2010). Conidia of *P. aphanis* were identified based on their morphology: they measure 20 to 23 × 13 to 20 µm, have a barrel shape when turgid, and contain granules (Mukerji, 1968).

3.3.4 Weather data

Weather data (air temperature (°C), relative humidity (%) and rainfall (mm)) were obtained either from automatic weather stations (CR-21X, Campbell Scientific Inc., Edmonton, AB, Canada) situated on the farms or from the closest weather station of Environment and Climate Change Canada (Government of Canada, 2017.). Data were collected from automatic weather stations every 15 minutes and transformed into hourly averages.

Table 3.2 Date of the first and last disease and airborne conidia concentration assessments for the different sites and years and total number of assessments per epidemic.

Site abbreviation	Year	Date of the first assessment[a]	Date of the last assessment[a]	Number of assessments[b]
		June-bearing – Open fields		
FRE	2006	187	277	14
	2007	165	276	15
	2008	180	268	14
	2009	165	257	15
	2010	128	249	15
	2011	184	274	14
GADJ	2006	172	232	19
	2007	172	244 or 251	19 or 20
	2009	172	252 or 255	20 or 21
	2010	172	253	19
BEAM	2007	164	230	23
	2008	128	229	15
GAUB	2008	164	269 to 290	16 to 19
	2009	172	231 to 245	18 to 24
RODM	2008	164	267	31
		June-bearing – High tunnels		
GADJ	2006	172	233	19
	2007	172	226	20
	2008	164 or 172	233 or 247	21 to 24
	2009	172	233 or 240	20 or 21
	2010	172	226	19
BEAM	2007	164	230	23
	2008	126	245	15
GAUB	2008	149 or 172	191, 221 or 241	19 or 24
	2009	164 or 172	219 to 248	17 to 24
RODM	2008	142 or 147	202 or 213	15 or 16
		Day-neutral – Open fields		
FRE	2006	147	276	56
	2007	142	275	58
	2008	147	276	56
STEFAM	2006	147	276	56
	2007	142	275	58
STPAU	2007	142	275	58

[a] Day of year.
[b] Total number of assessments per epidemic over a growing season.

3.3.5 Model development

Weather-based indices

A weather-based risk index was developed based on *P. aphanis* life cycle. Since weather conditions needed for germination are more restrictive than for sporulation or conidia dissemination (Miller et al., 2003), a disease development index was calculated based on favorable conditions for germination. Temperatures of 15 to 30 °C, relative humidity of at least 60%, with no rainfall were considered as weather conditions favorable for germination of *P. aphanis* conidia (Peries, 1962; Sombardier et al., 2009). A value of "1" was attributed to an hour that met these three conditions. Powdery mildew being a polycyclic disease, these hours were accumulated throughout the season which resulted in the cumulative index "A" representing the number of hours during which weather conditions were favorable for *P. aphanis* germination (**Table 3.3**).

Table 3.3 Example of the calculation method for the weather-based index A.

Day of year[a]	Hour	Temperature (°C)	Relative humidity (%)	Rainfall (mm)	Favorable conditions[b]	Index A
120	23	…	…	…	…	…
121	0	10.2	72.9	1	0	9
121	1	9.3	89.6	2.7	0	9
121	2	9.8	92.6	2.5	0	9
121	3	10.4	93.1	3.4	0	9
121	4	10.8	93.6	2	0	9
121	5	11.7	89.9	0.1	0	9
121	6	12.2	89.8	0.6	0	9
121	7	11.8	95.2	0.8	0	9
121	8	12.2	95.4	0.4	0	9
121	9	12.6	96.8	0.6	0	9
121	10	13.5	95.5	0	0	9
121	11	17.0	85.4	0	1	10
121	12	17.5	83.0	0	1	11
121	13	19.0	73.1	0	1	12
121	14	…	…	…	…	…

[a] The data comes from the site GADJ in 2009 for the day of year 121 (May 1st) which was around the beginning of the growing season.

[b] 1 is indicated if the following conditions are met: temperature of 15 to 30 °C, relative humidity of at least 60% and no rainfall; otherwise, 0 is indicated.

A second version of the index ("index B") was developed using optimal weather conditions instead of favorable conditions. Thus, temperatures of 18 to 22.5 °C, relative humidity of at least 75%, with no rainfall were considered as optimal conditions for germination of *P. aphanis* conidia (Peries, 1962; Sombardier et al., 2009). A value of "1" was attributed to an hour that met these three conditions, and the hours were accumulated throughout the season, which resulted in the second cumulative index.

Weather and inoculum-based indices

A third (A_i) and a fourth index (B_i) were developed by combining each of the weather-based indices with the presence of airborne conidia. Index A_i was calculated by multiplying daily values of the weather-based index A by the airborne conidia concentration measured the same day (**Table 3.4**). Similarly, index B_i was calculated by multiplying daily values of the weather-based index B by the airborne conidia concentration measured the same day.

Table 3.4 Example of the calculation method for the weather and inoculum-based index A_i.

Day of year[a]	Daily value of index A	Airborne conidia concentration (conidia/m^3)	Index A_i
172	22	16	352
174	8	26	208
177	20	33	660
179	23	42	966
186	8	35	280
189	18	64	1 152
191	9	113	1 017
196	8	198	1 584
203	20	151	3 020
205	24	102	2 448
208	19	383	7 277
215	14	402	5 628
222	16	869	13 904
225	18	580	10 440
229	22	445	9 790
232	19	633	12 027
239	0	559	0
246	12	813	9 756
249	0	1348	0
252	1	1284	1 284

[a] The data comes from the site GADJ for the growing season 2009 for the cultivar Darselect.

3.3.6 Model evaluation

For every epidemic, the index A was plotted on a graph with the severity observed seven days later to compare their evolution. This lag time of seven days between the index and the observed severity was chosen because the latent period of *P. aphanis* generally varies between 4 and 9 days (Sombardier et al., 2009). Then, for every epidemic, the index A was evaluated by fitting a simple linear regression between the index and the severity observed seven days later. The coefficient of determination (R^2) was calculated for every epidemic. The same steps were repeated for the weather-based index B and the weather and inoculum-based indices A_i and B_i. Analyses were performed in R 3.3.0 (R Core Team, 2016).

As a second step, for all observations of the 45 epidemics of June-bearing cultivars in open fields, a simple linear regression was fitted between the index A and the severity observed seven days later and the coefficient of determination (R^2) was calculated. The same method was followed for June-bearing cultivars grown in high tunnels and for the open-field-grown day-neutral cultivar Seascape. The same steps were repeated for the weather-based index B and for the weather and inoculum-based indices A_i and B_i. Analyses were once again performed in R 3.3.0 (R Core Team, 2016).

3.4 Results

3.4.1 Disease assessment

Powdery mildew severity of June-bearing cultivars planted in open fields and under high tunnels generally increased over the season as it can be observed for the site GADJ in 2009 (**Figure 3.1**). Maximum severity values reached in open fields (up to 30-40 % leaf area diseased) were generally lower than under high tunnels (up to 40-60%) (**Figure 3.1**). Moreover, different disease development was sometimes observed under similar weather conditions (same site and year) for June-bearing cultivars planted both in open fields and under tunnels. For example, at the site GADJ in 2009, two epidemics of the cultivar Jewel followed a different development pattern (**Figure 3.2**). In this case, the difference seems rather to be related to the field as it can be observed on **Figure 3.2**.

For day-neutral cultivars planted in open fields, disease severity tended to increase in the beginning of the season and decrease in the end of the season. For example, at the sites FRE and STEFAM in 2006 and 2007, disease severity began to increase around the end of June (DOY 180), reached maximum values in July and August (DOY 200 to 225) and decreased afterward (**Figure 3.3**). Level of disease severity was variable depending on sites, with maximum severity values between 25 and 90 % leaf area diseased (**Figure 3.3**). Moreover, at a few sites (e.g., at the site STEFAM in 2007), disease severity values of adjacent assessment dates showed large differences (**Figure 3.3**).

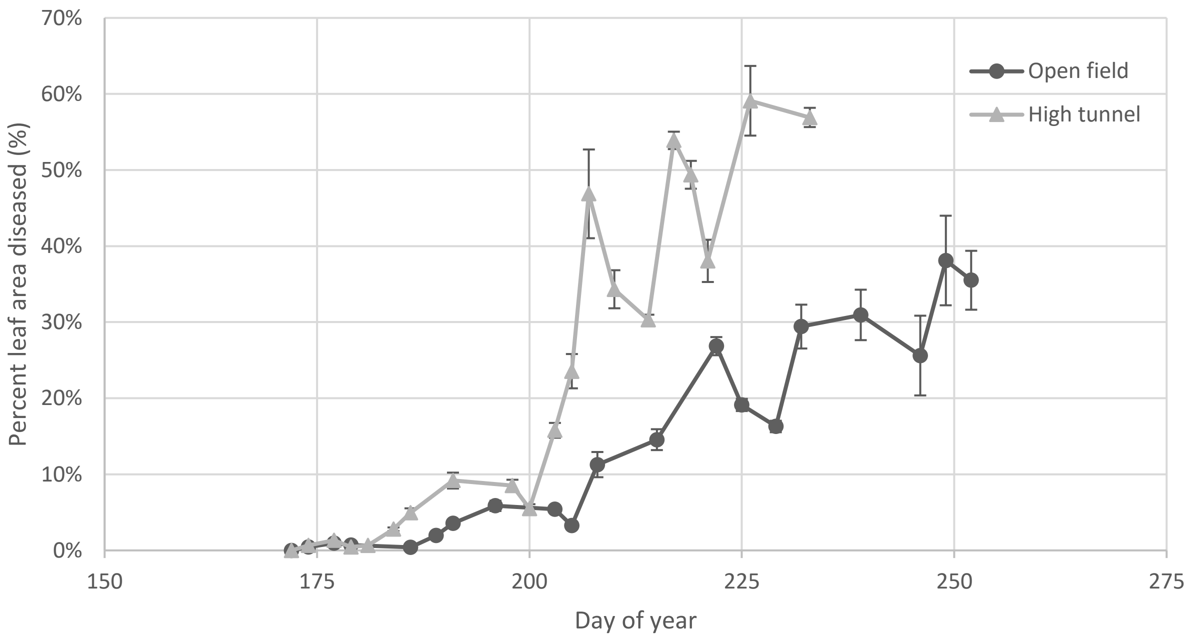


Figure 3.1 Temporal progress of percent leaf area infected by *Podosphaera aphanis* for June-bearing strawberry planted in open fields and under high tunnels at the site GADJ in 2009. The error bars indicate the standard deviation.

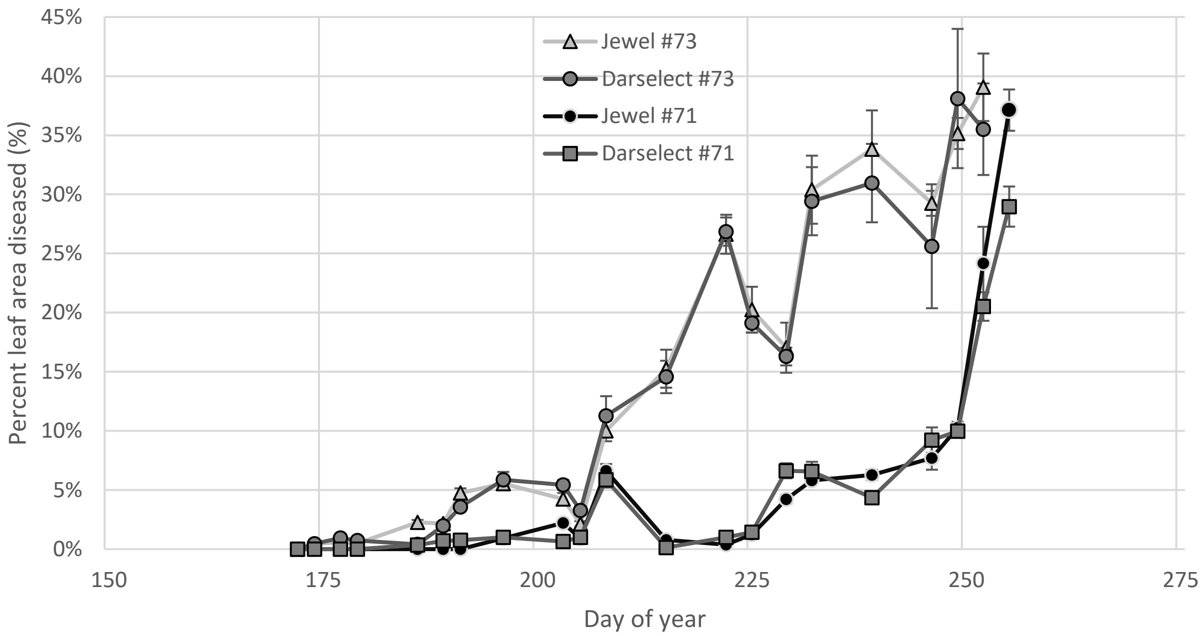


Figure 3.2 Temporal progress of percent leaf area infected by *Podosphaera aphanis* for June-bearing strawberry planted in open fields at the site GADJ in 2009. "#71" and "#73" refer to fields 71 and 73. The error bars indicate the standard deviation.

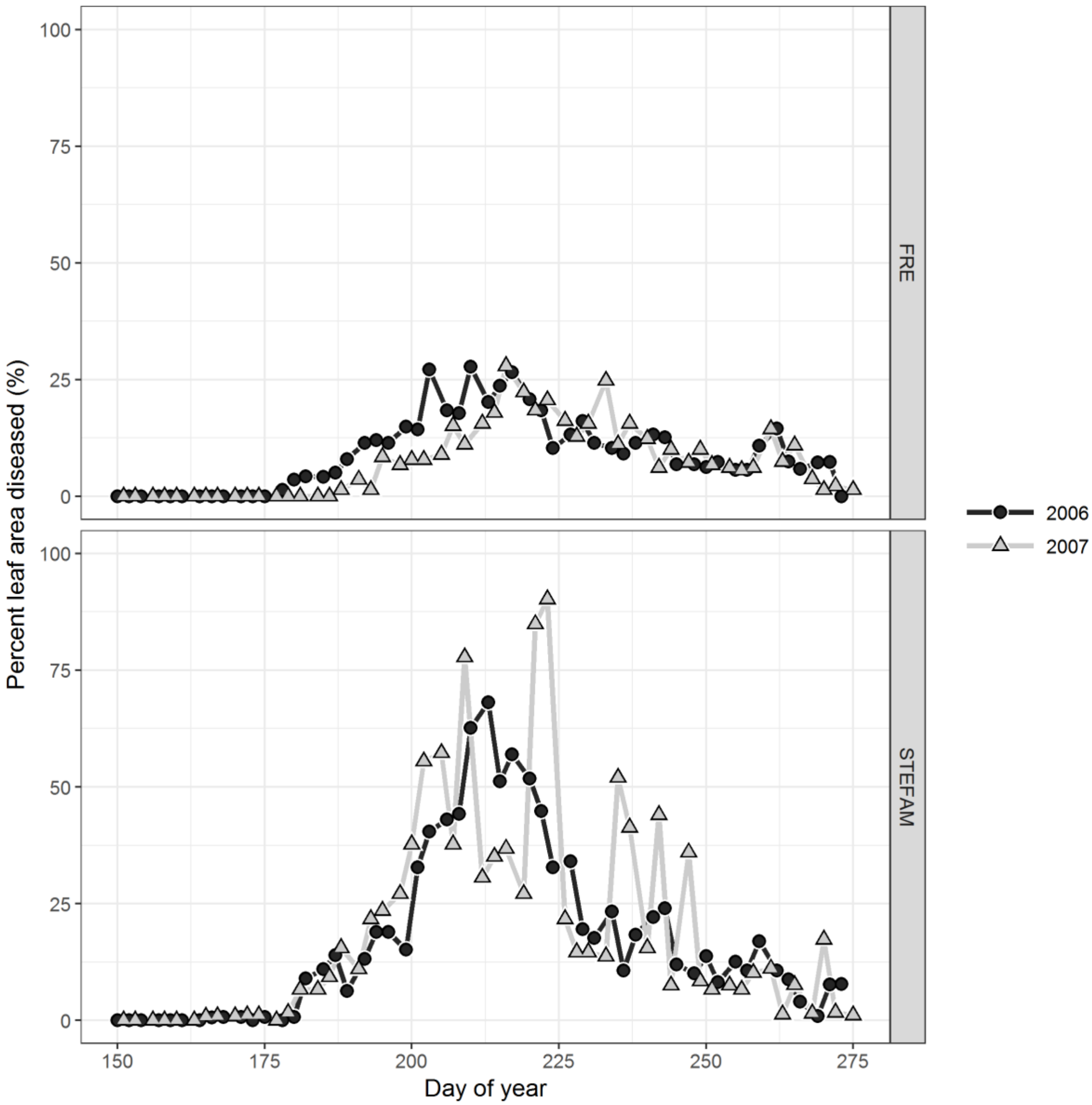


Figure 3.3 Temporal progress of percent leaf area infected by *Podosphaera aphanis* for the day-neutral cultivar Seascape in open fields at the sites FRE and STEFAM in 2006 and 2007.

3.4.2 Airborne conidia concentration assessment

Airborne conidia concentration (ACC) followed a similar trend to disease severity for June-bearing cultivars planted in open fields and high tunnels and for the day-neutral cultivar planted in open fields, as it can be observed for the sites GADJ and FRE in 2007 (**Figure 3.4**). Maximum values of ACC were generally around 800 to 1500 conidia/m^3 for June-bearing cultivars planted in open fields, from 2000 to 2500 for June-bearing in high tunnels, and from 2000 to 10 000 for day-neutral in open fields.

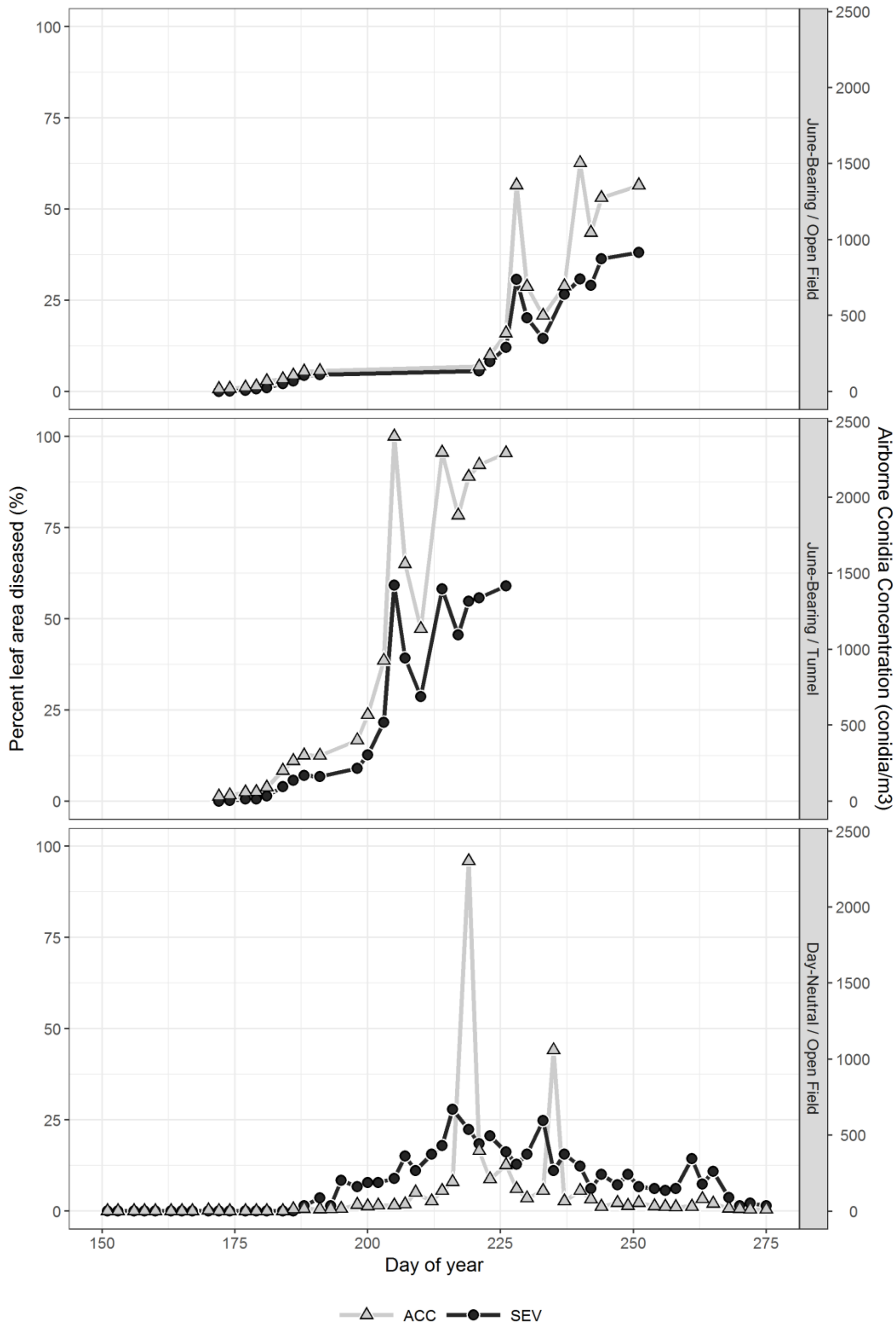


Figure 3.4 Temporal progress of percent leaf area infected by *Podosphaera aphanis* and airborne conidia concentration (a) in open fields and (b) under high tunnels for the June-bearing cultivar Darselect at the site GADJ in 2007, and (c) in open fields for the day-neutral cultivar Seascape at the site FRE in 2007.

3.4.3 Model development

Weather-based indices

The weather-based indices A and B tend to increase linearly over the season before reaching a plateau (**Figure 3.5**). For example, at the site GADJ in 2009, the index A started to increase around the beginning of May (DOY 130) and reached a plateau around the end of September (DOY 270) at values of 1500-1700 hours of favorable weather conditions (**Figure 3.5**). At the same site and year, the index B started to increase around the end of June (DOY 175) and reached a plateau around the end of August (DOY 235) at values of approximately 500 hours of optimal conditions for *P. aphanis* germination (**Figure 3.5**). For both indices, only a small difference was observed between the indices calculated with weather data in open fields compared to high tunnels (**Figure 3.5**).

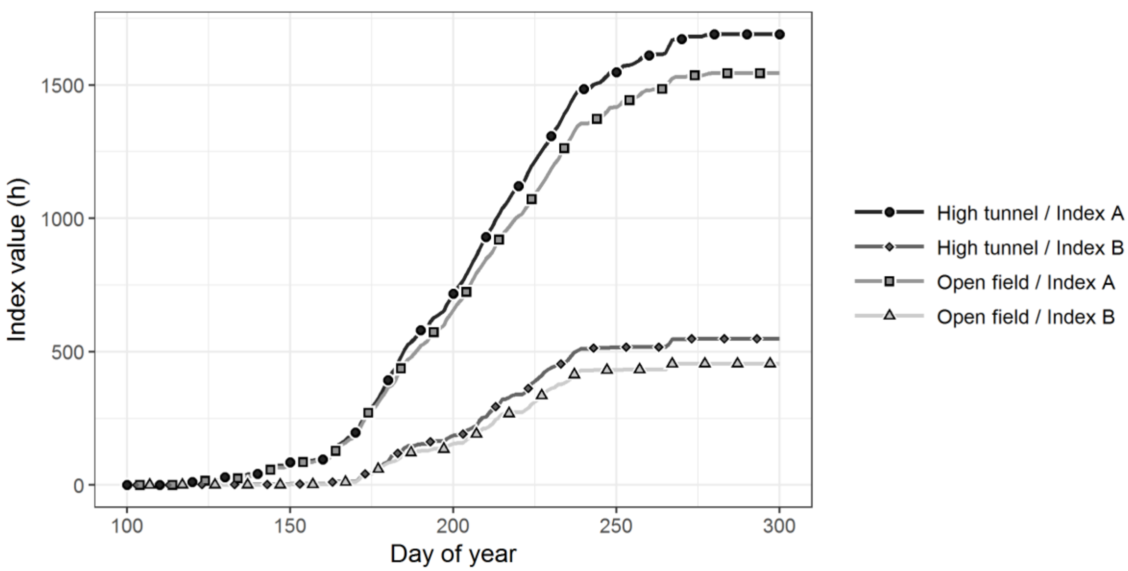


Figure 3.5 Temporal progress of the weather-based indices A and B at the site GADJ in 2009 in open fields and under high tunnels.

Weather and inoculum-based index

The weather and inoculum-based indices A_i and B_i for June-bearing cultivars in open fields and under high tunnels tend to increase non-linearly in the beginning of the season and be variable afterwards. For example, at the site GADJ in 2009, the indices A_i and B_i started to increase around the end of June (DOY 180) and reached their maximum values around mid-August (DOY 215-

230) (**Figure 3.6**). For day-neutral cultivars in open fields, the weather and inoculum-based indices A_i and B_i also tend to increase non-linearly in the beginning of the season and reach their maximum values in August. Then, both indices decrease in the end of the season, as observed at the site FRE in 2007 for the cultivar Seascape (**Figure 3.6**).

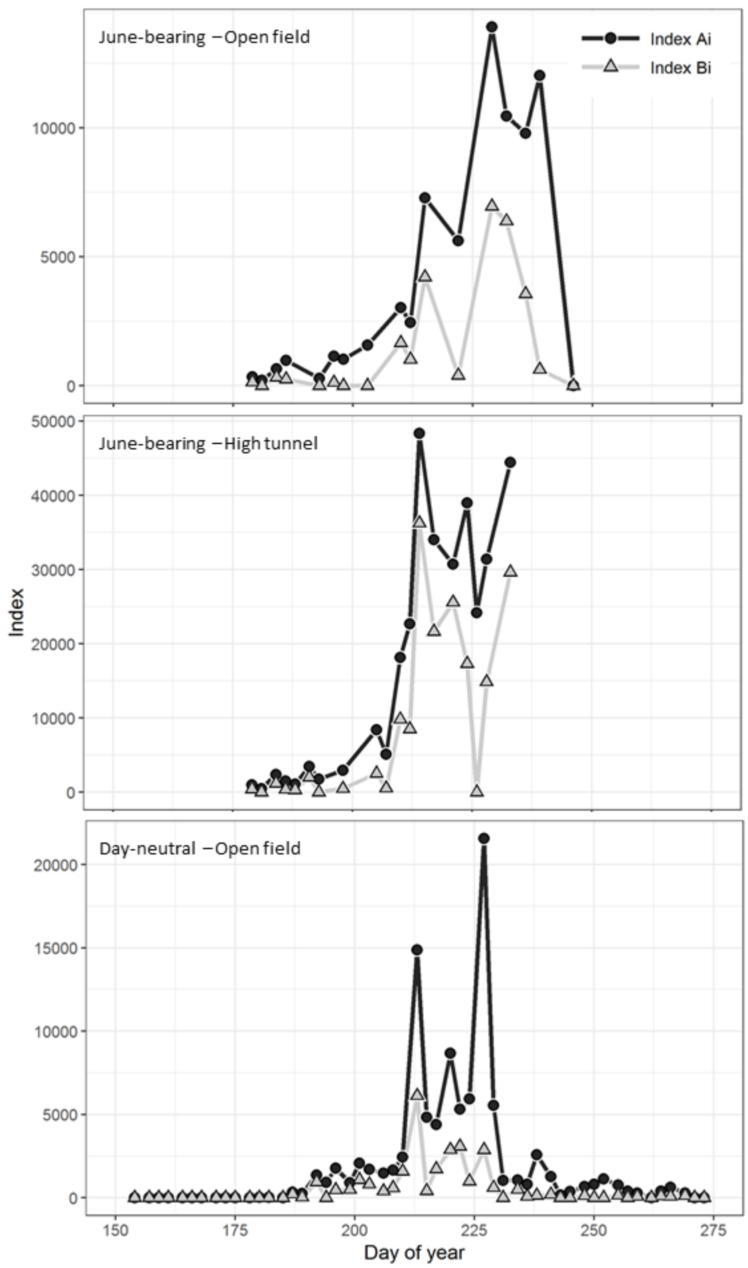


Figure 3.6 Temporal progress of the weather and inoculum-based indices A_i and B_i at the site GADJ in 2009 in open fields and under high tunnels (cv Darselect) and at the site FRE in 2007 for the day-neutral cultivar Seascape in open fields.

3.4.4 Model evaluation

For every epidemic, all four indices (A, B, A_i and B_i) were plotted on a graph with the disease severity observed seven days later to compare their evolution. Three epidemics and their related indices are shown on **Figures 3.7** and **3.8**. The scales for the y-axis vary depending of the graphs since the aim was to compare the evolution of the indices and disease severity irrespective of their values.

The coefficient of determination (R^2) for the simple linear regression between the different indices and the severity observed seven days later was calculated for every epidemic (**Appendix 1**). An example is shown for two epidemics of the June-bearing cultivar Darselect at the site GADJ in 2009 (**Figure 3.9**). It should also be mentioned that for the weather-based indices, cumulative values (indices) are compared to non-cumulative values of disease severity. The number of epidemics for which the coefficient of determination (R^2) was higher than 0.8, between 0.6 and 0.85 and lower than 0.6 are presented in **Table 3.5**. For June-bearing cultivars in open fields, 13% and 18% of the epidemics showed a R^2 over 0.85 for indices A and B, respectively. For June-bearing cultivars under high tunnels, 37% and 31% of the epidemics showed a R^2 over 0.85 for indices A and B, respectively. For day-neutral cultivars in open fields, none of the three epidemics showed a R^2 over 0.85 for indices A and B.

The coefficient of determination (R^2) for the simple linear regression between the four indices and the severity observed seven days later was also calculated per production system (June-bearing cultivars in open fields, June-bearing cultivars under high tunnels and day-neutral cultivar in open fields), as shown in **Figures 3.10** and **3.11**. When all observations of the June-bearing cultivars in open fields were grouped, coefficients of determination (R^2) of 0.41 and 0.36 were observed for indices A and B, respectively. For June-bearing cultivars under high tunnels, the coefficients of determination R^2 were 0.55 and 0.50 for indices A and B. For day-neutral cultivars in open fields, the R^2 were 0.09 and 0.11 for indices A and B.

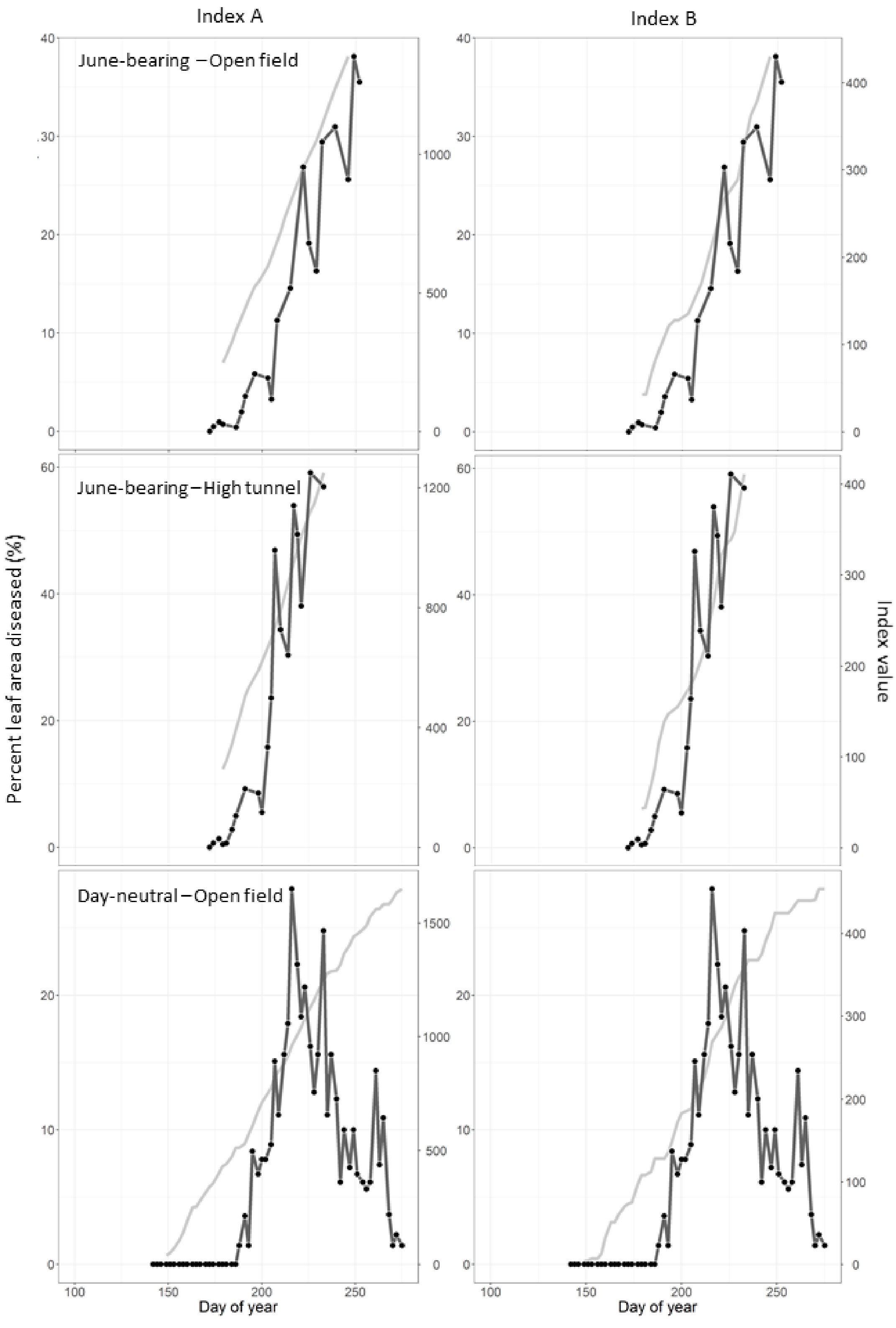


Figure 3.7 Temporal progress of percent leaf area infected by *Podosphaera aphanis* (black line) and the weather-based indices A and B (gray line). The data comes from the site GADJ in 2009 for the June-bearing cultivar Darselect in open fields and under high tunnels and from the site FRE in 2007 for the day-neutral cultivar Seascape in open fields.

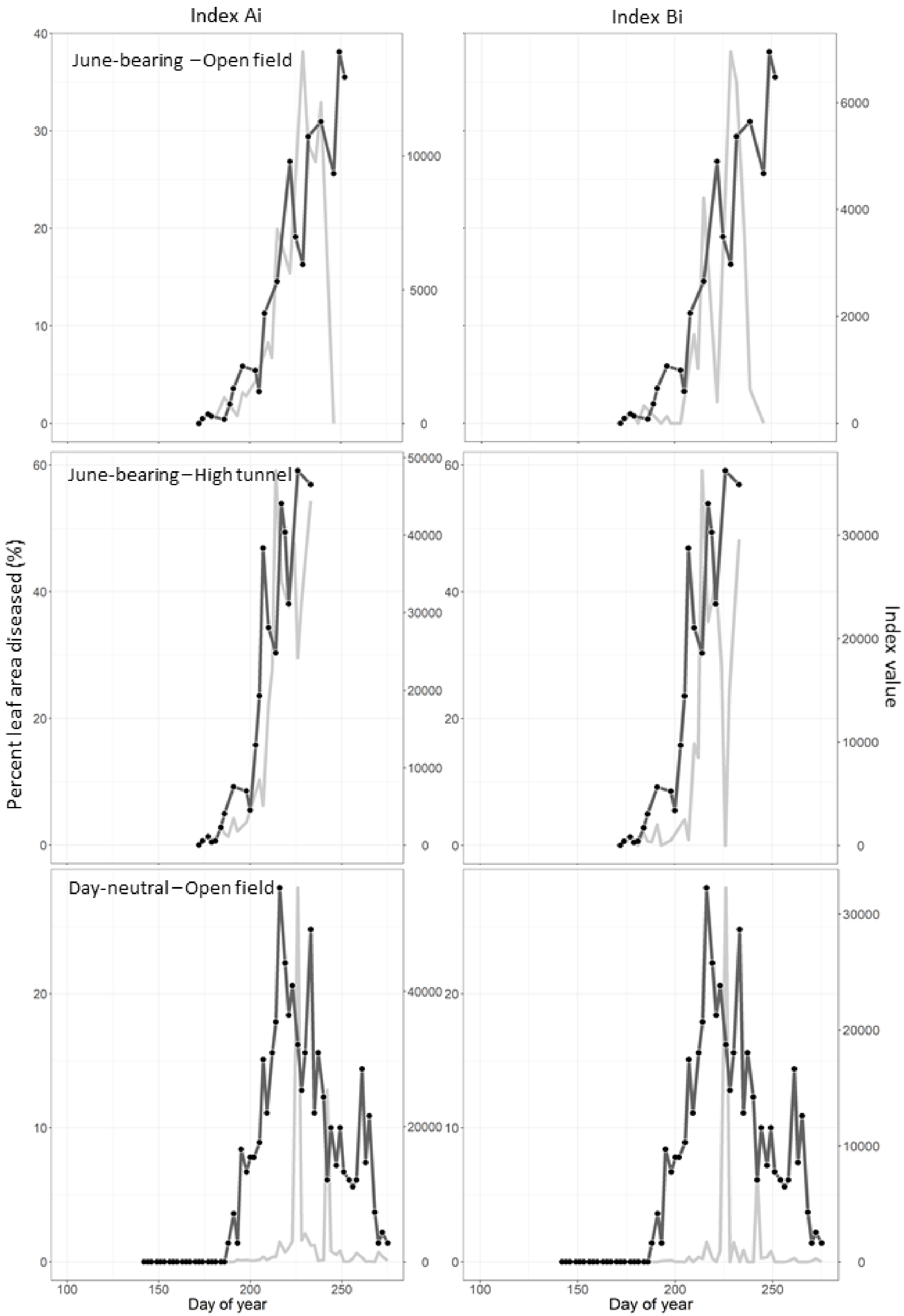


Figure 3.8 Temporal progress of percent leaf area infected by *Podosphaera aphanis* (black line) and the weather and inoculum-based indices A_i and B_i (gray line). The data comes from the site GADJ in 2009 for the June-bearing cultivar Darselect in open fields and under high tunnels and from the site FRE in 2007 for the day-neutral cultivar Seascape in open fields.

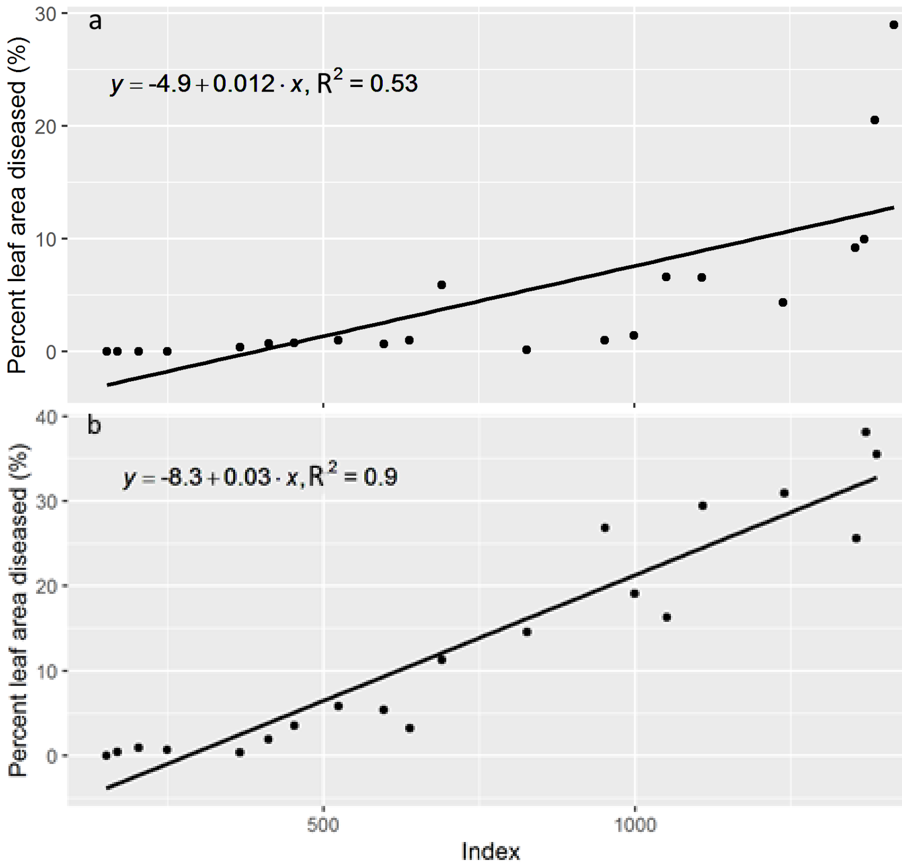


Figure 3.9 Simple regression analysis between the index A and the observed severity at the site GADJ in 2009 for the June-bearing cultivar Darselect in open fields for the fields 71 (a) and 73 (b).

Table 3.5 Number of epidemics for which the coefficient of determination (R^2) for the simple linear regression between the different indices and the severity observed seven days later is higher than 0.85, from 0.6 to 0.85 and lower than 0.6.

Indices	$R^2 > 0.85$	$0.85 \geq R^2 \geq 0.6$	$R^2 < 0.6$	Total number of epidemics
June-bearing – Open fields				
Index A[a]	8	37	15	60
Index B[b]	11	30	19	60
Index A_i[c]	0	9	27	36
Index B_i[d]	0	4	32	36
June-bearing – High tunnels				
Index A	13	19	3	35
Index B	11	22	2	35
Index A_i	4	10	18	32
Index B_i	0	5	28	33
Day-neutral – Open fields				
Index A	0	0	3	3
Index B	0	0	3	3
Index A_i	0	0	3	3
Index B_i	0	0	3	3

[a] Index A: Hours during which weather conditions were favorable for conidia germination.
[b] Index B: Hours during which weather conditions were optimal for conidia germination.
[c] Index A_i: Daily value of index A x airborne conidia concentration (ACC).
[d] Index B_i: Daily value of index B x ACC.

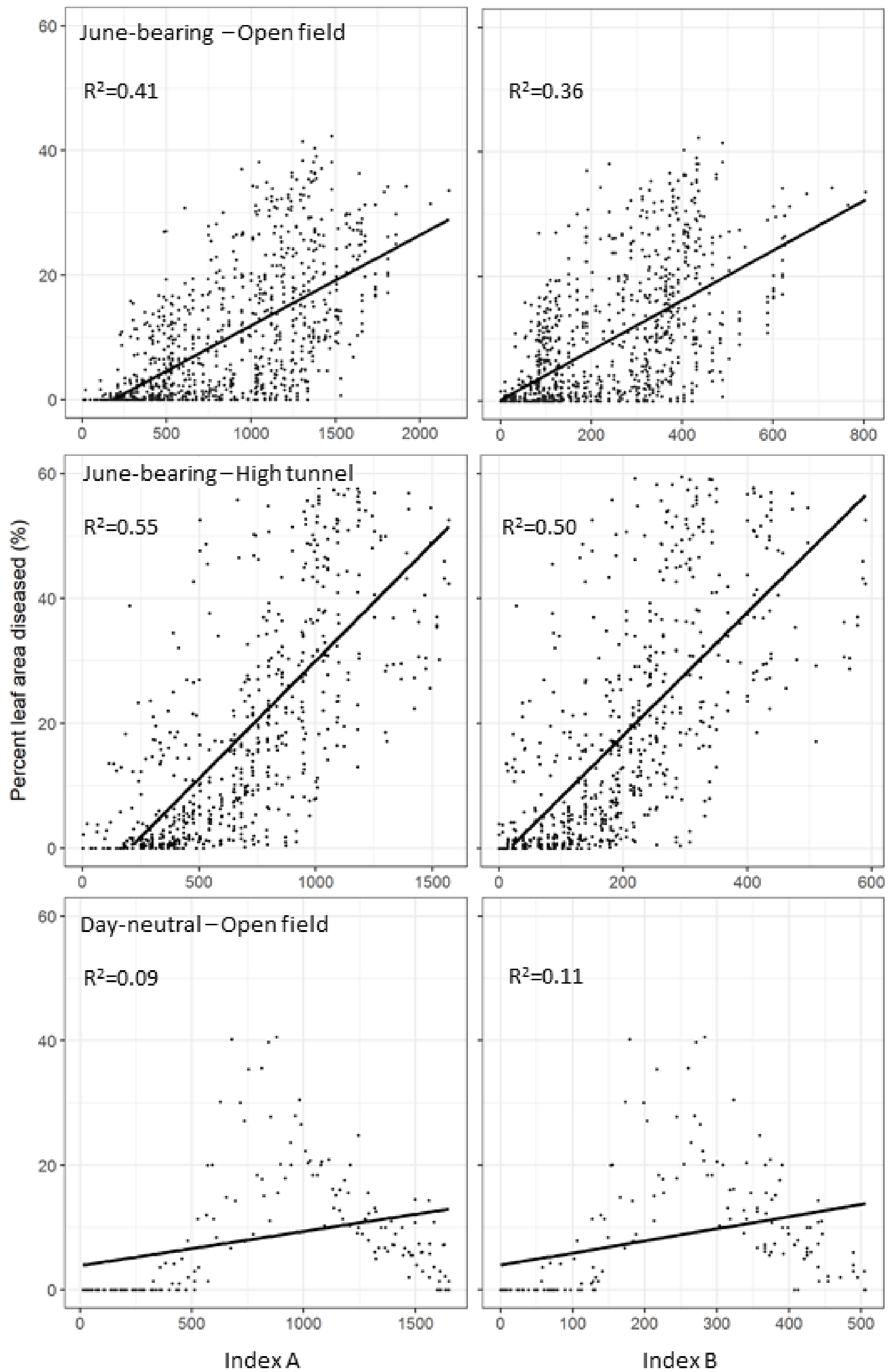


Figure 3.10 Simple regression analysis between the weather-based indices A and B and the severity observed seven days later for all observations of June-bearing cultivars grown in open fields and under high tunnels, and for day-neutral cultivar Seascape in open fields.

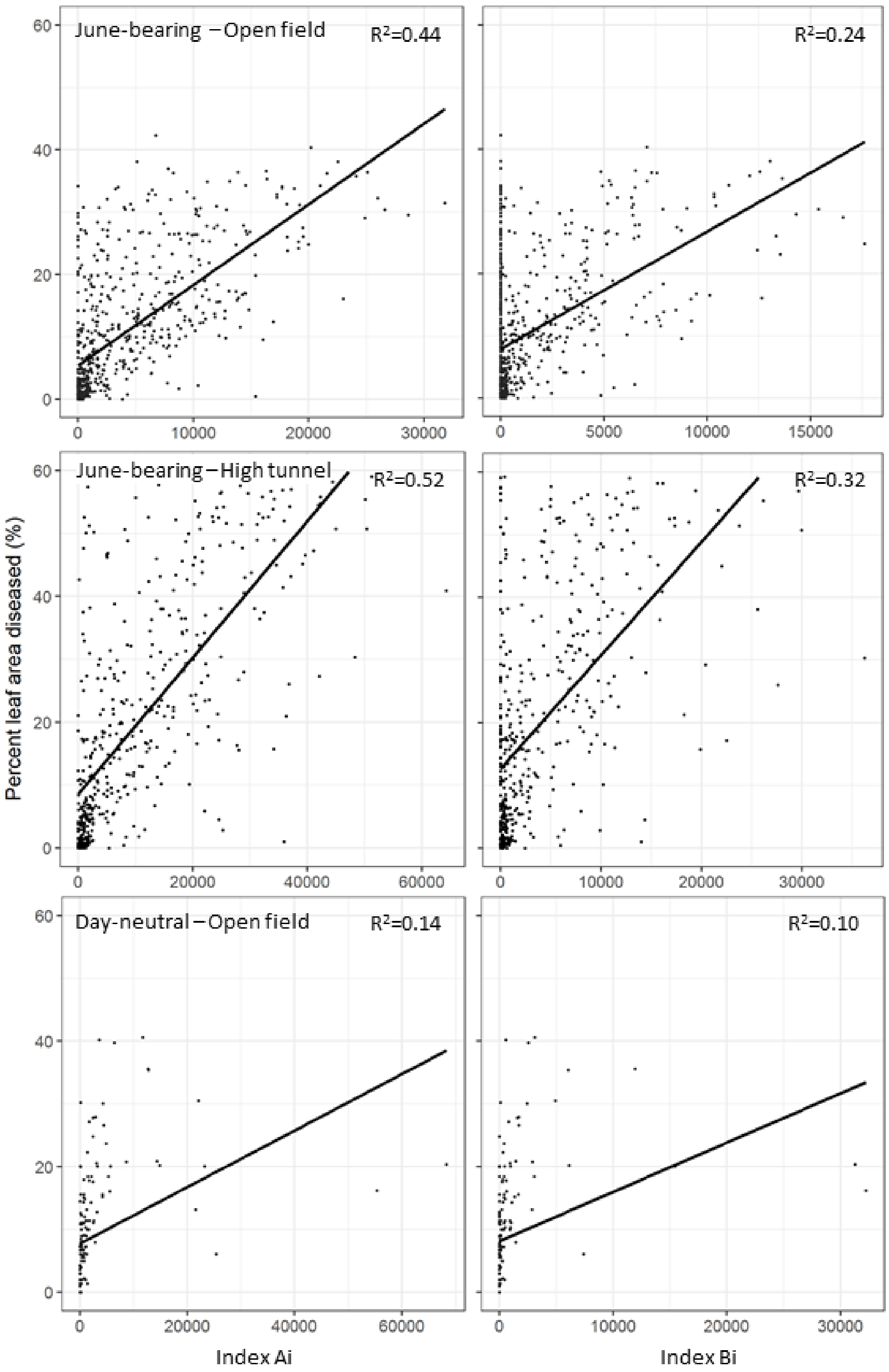


Figure 3.11 Simple regression analysis between the weather and inoculum-based indices A_i and B_i and the severity observed seven days later for all observations of June-bearing cultivars grown in open fields and under high tunnels and for day-neutral cultivar Seascape in open fields.

3.5 Discussion

The objective of this study was to predict the development of strawberry powdery mildew. Two weather-based indices and two weather and inoculum-based indices were developed. The weather-based indices were developed by cumulating hours of favorable (index A) and optimal (index B) weather conditions for conidia germination. Both weather-based indices increase linearly over time before reaching a plateau around the end of the growing season. A positive linear relationship between both weather-based indices and disease severity was observed. The coefficient of determination was over 0.6 for 75% and 68% of the June-bearing epidemics in open fields for the indices A and B respectively. However, when a linear regression was fitted between one index and all disease severity observations pertaining to one production system (e.g., June-bearing in open fields), the variation explained by the linear regression was lower (R^2=0.41 for index A and R^2= 0.36 for index B). These results suggest that the weather-based indices A and B can better predict the trend of disease development (e.g., increase or decrease) rather than the actual values of disease severity.

One important difficulty in predicting the development of strawberry powdery mildew is the wide range of weather conditions favorable to its development (Peries, 1962; Sombardier et al., 2009). Indeed, *P. aphanis* can develop at temperatures ranging between 5°C to 30°C and at a relative humidity as low as 12% (Amsalem et al., 2006; Peries, 1962).

A way to improve weather-based models would be to consider the interaction among weather variables. It has been shown that the combination of temperature and relative humidity influences the germination rate of *P. aphanis* (Amsalem et al., 2006; Peries, 1962). Another avenue to explore would be the effect of temperature on the rate of disease development. This could be achieved by considering the effect of temperature on the latent period of *P. aphanis,* which is around 10 days at 12 °C but can decrease to 4 days when temperature reaches 22 ◦C (Sombardier et al., 2009). However, in presence of a polycyclic disease, modelling life cycles occurring simultaneously at different rates poses a technical challenge. To cope with this difficulty, dynamic simulation systems such as STELLA® can be used since they are conceived to facilitate the development of such dynamic models. For example, STELLA® has been used to model the temporal progress of airborne inoculum of *Bremia lactucae* Regel, the fungus responsible for lettuce downy mildew (Fall et al., 2016).

Graphical representations of the disease severity data revealed several sites where powdery mildew development was different on strawberry plants of the same cultivar exposed to similar weather conditions. Indeed, several epidemics started earlier and developed faster than other epidemics of the same cultivar situated at the same farm but in different fields. In these situations, there may have been slight differences in weather conditions. Indeed, the weather data used for the experimental plots situated at commercial farms did not come from weather stations situated in the field, but from the closest weather station of Environment and Climate Change Canada. However, it would be surprising that small differences of weather conditions would be the only cause of the different disease development. The difference seemed to be linked to one or more factors related to the field.

Thus, the results of this study suggest that weather conditions alone would not be sufficient to explain powdery mildew development. This is in agreement with Parker et al. (2008) who developed a prediction system for strawberry powdery mildew based on weather conditions. During the validation process, they noted that powdery mildew development was influenced by the "age" of the strawberry field: disease developed more slowly on new sites compared to established sites (Parker et al., 2008). They explained this time lag by the presence of mycelium overwintering in the plants of established sites, which would accelerate disease development (Parker et al., 2008). The authors of SafeBerry, another prediction system for strawberry powdery mildew, also suggested that temperature alone cannot explain powdery mildew initiation and development since they sometimes observed no symptom even in presence of optimal temperature for powdery mildew development (Eccel et al., 2010). Thus, the prediction system SafeBerry, in addition to assessing the suitability of temperature for powdery mildew development, includes other parameters (e.g., phenological stage of the plants, disease incidence in the tunnel, time since last treatment, cultivar susceptibility, presence of disease at less than 50 or 10 m at planting day, incidence of disease in the nursery, type of sprayer, presence of overhead irrigation, tunnel height, density of plants per meter and mulching with black plastic) (Eccel et al., 2010).

Bouchard (2008) also suggested including other variables than temperature after testing the Gubler-Hoffman risk index for strawberry powdery mildew under Quebec conditions. Indeed, the Gubler-Hoffman risk index, which is mostly based on the presence of temperature between 18 °C and 27 °C, generally reached its maximum risk value in the beginning of the growing season and stayed high all season long (Bouchard, 2008). Based on these results, Bouchard (2008) concluded that a prediction system only based on temperature was not complete and tested a system combining the Gubler-Hoffman risk index and spore sampling. Although the combination of the index and spore sampling did reduce the number of fungicide treatments while achieving a control of the disease similar to the Gubler-Hoffman risk index, it needs to be validated under a larger range of conditions.

In the present study, it was decided to include airborne conidia concentration to the weather-based indices in order to predict the development of strawberry powdery mildew. Daily values of the weather-based indices A and B were multiplied by the airborne conidia concentration and compared to disease severity seven days later. However, including spore measurements did not improve the indices compared to the weather-based indices. One explanation would be that the values of the indices were null when no hour of favorable or optimal conditions for conidia germination was observed during a day, even though conidia could in fact germinate. Indeed, conidia of *P. aphanis* remain viable for a few days: the highest germination rate would be reached by 48 hours after infection (Miller et al., 2003) and conidia would still be viable after 96 hours (Peries, 1962). Thus, considering that favorable or optimal conditions could have been observed during the previous or subsequent days, the weather and inoculum-based indices A_i and B_i are most likely underestimating disease development.

A second explanation for the poor performance of the indices A_i and B_i could be that airborne conidia concentration (ACC) seems to be representative of disease severity in the field during the same period, whereas the indices were assessed by comparing them with the disease severity observed seven days later. This strong relationship between ACC and disease severity has been observed in other studies on strawberry powdery mildew (Van der Heyden et al., 2014) and grape powdery mildew (Carisse et al., 2009a).

Even though a virulent pathogen is present and environmental conditions are favorable to its development, a disease will only develop in presence of a susceptible host (Agrios, 2005). The presence of a susceptible host was not considered in the indices developed as part of this project. However, it has been shown that the strawberry plant is not always susceptible to *P. aphanis*. Only young leaves, flowers and young fruits are susceptible to *P. aphanis* infections; unfold leaves and pink and mature fruits are almost resistant (Asalf et al., 2014; Carisse and Bouchard, 2010).

Based on the results of this work, it was therefore possible to identify avenues that need to be explored as part of future studies on the development of strawberry powdery mildew. Amongst them figure the interactions between weather variables, the use of dynamic simulation models, the effects of variables related to the field ("age" of the field, disease history and microclimatic conditions) as well as the ontogenic resistance of the strawberry plant.

Connecting text

The previous chapter was about the development of a weather-based index to predict the evolution of strawberry powdery mildew, which is a problematic disease in strawberry production in Quebec. When effective, risk indices or predictive models for disease development can help daily decision-making and contribute to reduce the number of fungicide applications. On the other hand, reducing the number of pesticide applications can also be achieved by favoring more sustainable cropping systems. The following chapter focused on the development of a framework for assessing the environmental, economic and social sustainability of strawberry cropping systems.

Chapter 4: Assessing the environmental, economic and social sustainability of strawberry cropping systems

M. Gendron, O. Carisse and V. Gravel

4.1 Abstract

Over the last decades, strawberry production in Quebec has evolved in response to consumers' demand for high quality fruits all year round. Growers are gradually adopting new production techniques such as plasticulture, winter row covers or high tunnels. Growers are also asked to produce fruits in an environmentally friendly and socially responsible way, while maintaining a high profitability for their production. In this context, assessing the sustainability of strawberry production is necessary albeit complex. The objective of this study was to develop a framework for assessing the environmental, economic and social dimensions of sustainability of different cropping systems for strawberry. This framework was developed using a multi-criteria analysis model, which is a hierarchical structure that divides a complex problem into smaller elements easier to assess. As part of the framework, the economic, environmental and social dimensions of sustainability were divided into 11, 11 and 4 basic criteria, respectively. The DEXi software was used for the development of the framework. A reference scenario, corresponding to the most common growing practices in Quebec, was defined and used as a comparative basis. As part of the validation process of the framework, two different scenarios were assessed: an integrated pest management (IPM) strategy and another strategy based on an inappropriate use of pesticides. Assessment results were consistent since the IPM strategy showed a better environmental sustainability compared to the pesticide-based strategy. Ultimately, the multi-criteria decision support framework could be used as part of a didactic tool for growers and stakeholders to promote environmentally sustainable practices within the strawberry industry.

4.2 Introduction

Strawberry growers in the province of Quebec have been facing several challenges over the last decades. They have to compete with strawberries imported all year round from USA at low prices in addition to adapt to the increasing consumers' demand for fruits produced in a socially responsible and environmentally friendly way (ÉcoRessources Consultants, 2012a). Stakeholders of the strawberry sector have put many efforts to address these challenges, which resulted in the evolution of the Quebec strawberry production systems. For example, cropping systems such as plasticulture with day-neutral cultivars now allow an extension of the harvest period (Urbain, 2005). Use of winter row covers and high tunnels are other examples of new techniques that have been implemented (Urbain, 2005). In order to favor cropping systems that are the most environmentally friendly and socially responsible, it is important to assess the strengths and weaknesses of the different systems. Moreover, it is relevant to know if the development of a cropping system should be prioritized over another depending of a particular context (Craheix et al., 2015). Such assessments are complex due to the numerous cropping systems, the different practices within each system, as well as the different contexts. However, assessing the sustainability of the strawberry production is essential for making it more sustainable (Sadok et al., 2009).

Many definitions have been provided for sustainability, all of them emphasizing its multidimensional aspect which includes economic, environmental and social dimensions (FAO, 2014a, 1989; Ikerd, 1993). The idea of "maintaining productivity and usefulness to society in the long term" is also common to all definitions (FAO, 1989; Ikerd, 1993). Such definitions are theoretical and need to be translated into more practical criteria before being used for sustainability assessment (Craheix et al., 2015). Indicators and frameworks have been developed for assessing sustainability of agricultural systems. Those indicators have been developed at different scales (landscape, farm, cropping system or field) depending of the objectives (Pelzer et al., 2012). For a framework to be useful for sustainability assessment, it has to meet certain criteria. It should be easy to use, meaning that a trade-off between simplicity and consideration of most of the criteria should be pursued (Pelzer et al., 2012). A framework should also be able to assess actual systems, but also allow the assessment of innovative practices (Pelzer et al., 2012). Another important criterion is its ability to deal with the multidimensional aspect of sustainability. It is indeed essential for an assessment framework to integrate social, economic, and environmental information in addition to handle possible divergences between the objectives (e.g. improvement of environmental sustainability may lead to a decrease of economic sustainability) (Sadok et al., 2009).

Since sustainability assessment requires to deal with both convergent and divergent objectives and to use different types of information, it can be considered as a decision-making problem (Dent, 1995; Sadok et al., 2008). Multi-criteria decision-aid (MCDA) methods have been developed for helping decision-making (Sadok et al., 2008). Among MCDA methods, decision rule-based methods (also known as qualitative multi-criteria models) are adapted for sustainability assessment of cropping systems since they can use both qualitative and quantitative information as inputs and they can handle the multidimensional aspect of sustainability (Sadok et al., 2008). The concept of qualitative multi-criteria models is the decomposition of a complex problem into many sub-problems easier to solve (Bohanec, 2015). All the elements that are part of the problem are called criteria and are organized into a hierarchical tree (Bohanec, 2015). Criteria situated at lower levels of the tree are called basic criteria whereas others are called aggregated criteria. Criteria are aggregated from the lower levels of the tree to the highest level by using 'if-then' aggregation rules (Bohanec, 2015).

DEXi is a software specifically conceived for the development of qualitative multi-criteria models and the evaluation of different options (Bohanec, 2015). DEXi has been used for the development of models assessing the sustainability of cropping systems such as genetically modified crop, arable cropping systems, apple orchards, vineyard and field vegetables (Aouadi, 2011; Craheix et al., 2015; Mouron et al., 2010). Such models have been developed for *ex ante* assessment of innovative cropping systems and for *post ex* assessment of current cropping systems (Craheix et al., 2015). MASC and DEXiPM are two examples of qualitative multi-criteria models developed for assessing the sustainability of arable cropping systems in Western Europe (Pelzer et al., 2012; Sadok et al., 2009). Since no framework has been developed for assessing the sustainability of strawberry cropping systems, it was the objective of this project.

4.3 Materials and methods

4.3.1 General description

In order to assess the sustainability of strawberry production, a multi-criteria decision support framework was developed with the DEXi software (Bohanec, 2015). The approach described by (Craheix et al., 2015) was followed with a few modifications (**Figure 4.1**): "Description of a reference scenario" was added as a third step, and the framework development ended at the validation step.

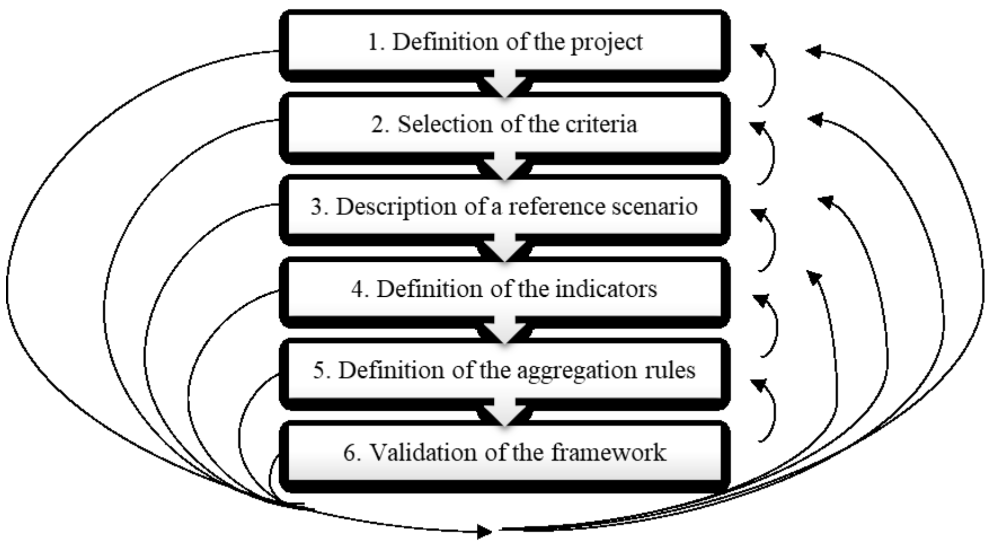


Figure 4.1 A multi-criteria decision support framework for assessing the sustainability of strawberry production was developed by following the six steps represented in the boxes. The process is iterative, which is represented by the arrows. Adapted from Craheix et al. (2015).

4.3.2 Definition of the project

As a first step of the framework development, several aspects were defined: the temporal and spatial scales, the future users, the main use (*ex ante* or *ex post* assessment) and the collaborators (Craheix et al., 2015). The cropping system, defined as "a set of management procedures applied to a given, uniformly treated agricultural area" (Sebillotte (1990), cited by Craheix et al. (2015)), was the assessment scale selected for most of the criteria. The management of each crop of the rotation (tillage, sowing, fertilisation and protection) is normally included in the cropping system (Pelzer et al., 2012). However, it was decided to consider only certain aspects of crop rotation (length, crops and addition of organic inputs) for this project. This decision was taken to simplify the framework and to focus on sustainability assessment for strawberry production. Moreover, it was decided to extend the spatial scale for several criteria such as the flora and fauna diversity in order to consider the presence of natural habitats at the farm scale.

Advisors and strawberry growers were identified as the targeted users of the framework. The framework was developed with the purpose of facilitating discussions between growers and their advisors. It was conceived to allow both *ex ante* and *ex post* assessments. Thus, the framework could be used when growers are planning to implement new methods, in order to get an overview of the whole cropping system. It could also be used for identifying strengths and weaknesses of an actual cropping system. Several collaborators, identified subsequently as "experts", were identified at the beginning of the project. They are public advisors recognized for their knowledge and experience in strawberry production. These experts were asked for their feedback throughout the development of the tool.

4.3.3 Selection of the criteria

A top-down approach was used to select the criteria for assessing the sustainability of a strawberry cropping system, which means that the overall sustainability was first divided into the three dimensions of sustainability: economic, environmental and social dimensions (**Figure 4.2**) (Craheix et al., 2015). Then, each dimension was divided into subcomponents, and so on.

The economic dimension of sustainability was divided into the viability and the profitability of the cropping system (**Figure 4.3**) (Pelzer et al., 2012). The viability was assessed based on the stability and the need for specialized equipment (Vélu et al., 2016b). The stability of the system encompasses the risk of yield loss due to biotic and abiotic factors and the autonomy towards labor and pesticides. The profitability was assessed by the production cost and the production value. In total, 11 basic criteria were selected for assessing economic sustainability.

The environmental dimension of sustainability was divided into biodiversity, impact on resources and resources use (**Figure 4.4**) (Pelzer et al., 2012; Sadok et al., 2009). Similarly, biodiversity was divided into fauna and flora diversity (Pelzer et al., 2012); the impact on resources, into water quality, impact on soils and air quality (Pelzer et al., 2012; Sadok et al., 2009); and resources use, into water use and waste disposal. In total, 11 basic criteria were identified for assessing environmental sustainability.

The social dimension of sustainability was divided into workers' health and management difficulty (**Figure 4.5**). Compared to DEXiPM in which social sustainability was divided into three criteria (supply chain, interaction with society and farmer*)* (Pelzer et al., 2012), only the sub-criterion concerning the farmer was kept for the present framework. This choice of not considering the two other criteria (supply chain and interaction with society) was made in order to keep the hierarchical tree as simple as possible, and because there was no expert in sociology involved in the project. In total, four basic criteria were identified for assessing the social sustainability.

It was decided to assess the degree of fulfilment of the criteria on a comparative basis. Thus, every basic criterion was divided into three levels (worst, similar or better), where the level "similar" corresponded to a reference scenario (see section 4.3.4). It was then possible to assess if a cropping system performed worst, similar or better than a reference scenario for every basic criterion.

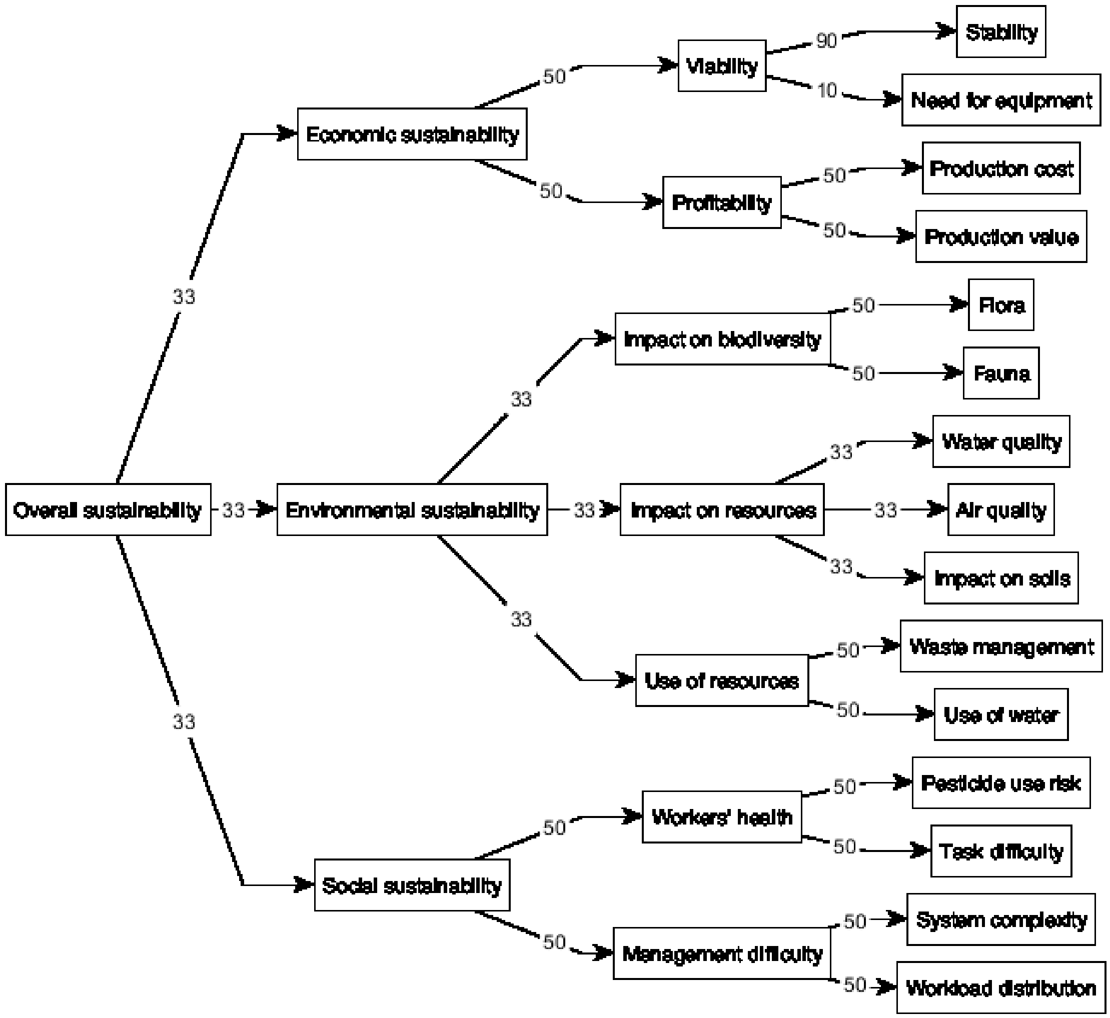


Figure 4.2 The first levels of the hierarchical tree for assessing the sustainability of a strawberry cropping system are represented. The numbers represent the weight of each criterion calculated from the aggregation rules.

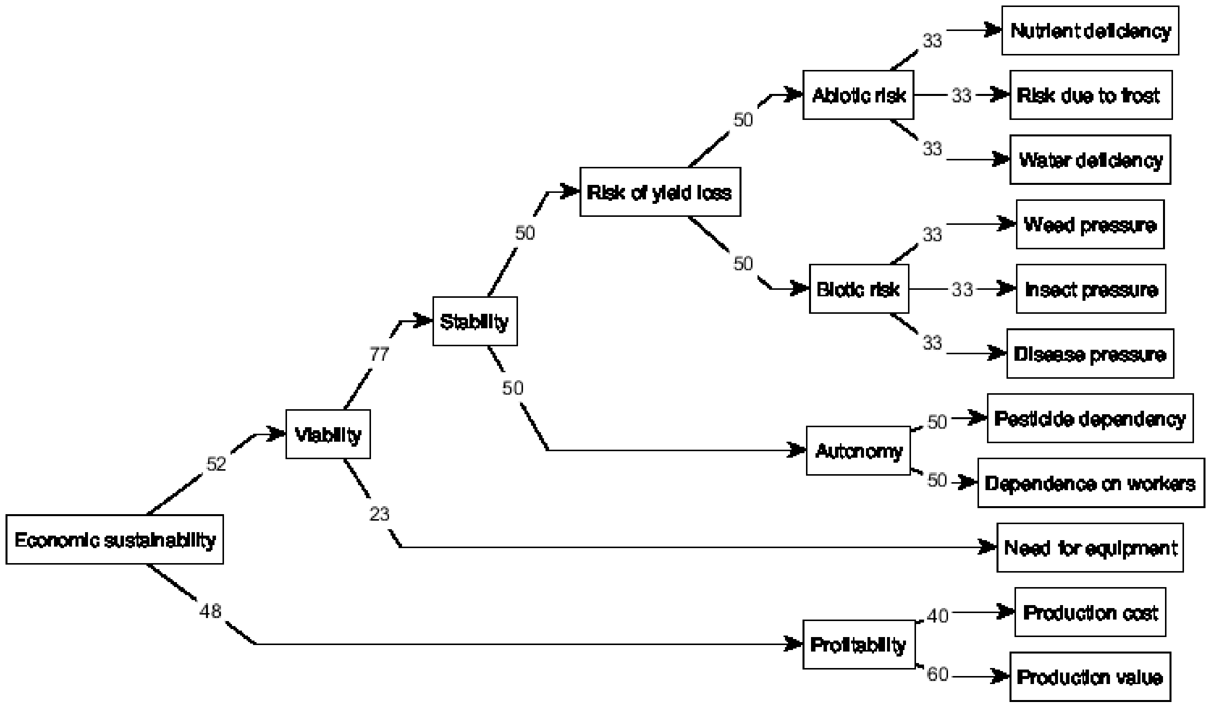


Figure 4.3 Hierarchical tree composed of the criteria selected for assessing the economic sustainability. The numbers represent the weight of each criterion calculated from the aggregation rules.

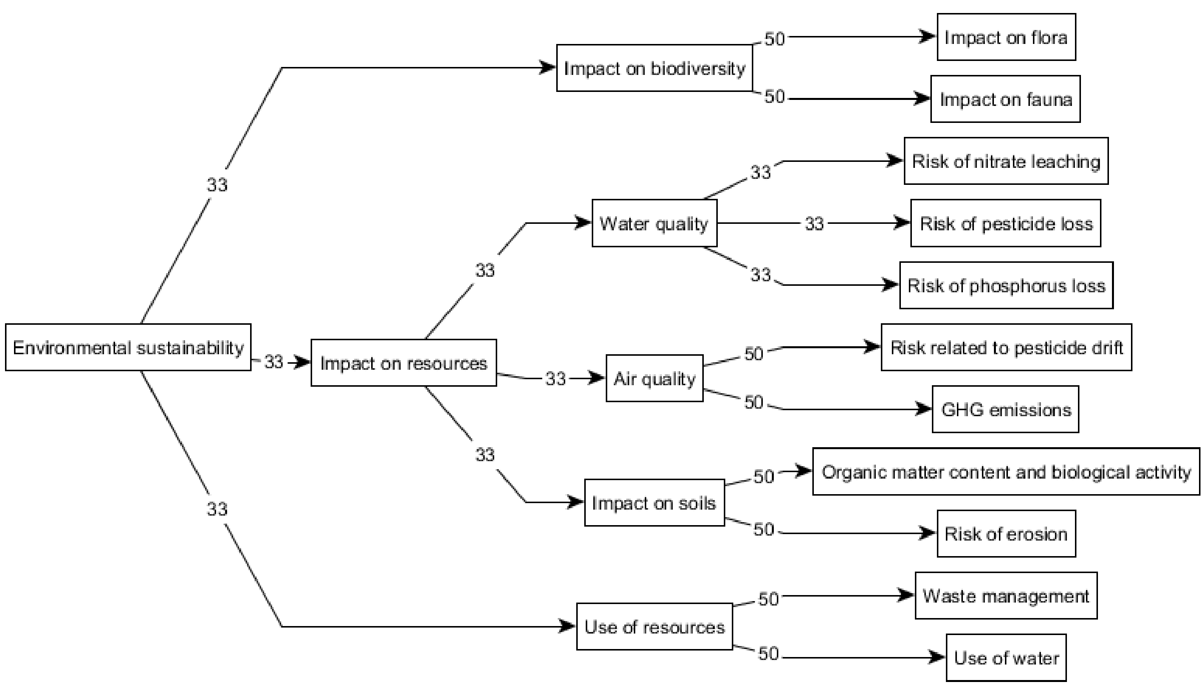


Figure 4.4 Hierarchical tree composed of the criteria selected for assessing the environmental sustainability. The numbers represent the weight of each criterion calculated from the aggregation rules.

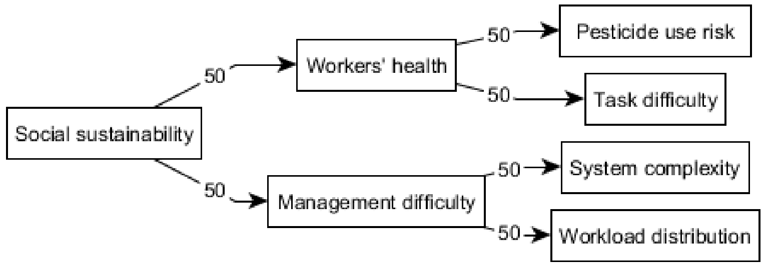


Figure 4.5 Hierarchical tree composed of the criteria selected for assessing the social sustainability. The numbers represent the weight of each criterion calculated from the aggregation rules.

4.3.4 Definition of a reference scenario

The reference scenario was intended to be representative of most common growing practices in the province of Quebec. Experts were consulted to identify the most common practices, which were identified as a matted row system using June-bearing cultivars. The information concerning the production costs (i.e. inputs, machinery use, labor requirement,…) and the production value (i.e. yields, selling price,…) came from the most recent available economic references for the matted row system (CRAAQ, 2014a). The fertilizing practices were taken from the provincial recommendations for the matted row system (CRAAQ, 2010). Other information on cropping practices came from a technical guide for strawberry production in Quebec (Thireau and Lefebvre, 2014). The portrait of the reference scenario was completed based on expert knowledge of strawberry production in Quebec. A more detailed description of the reference scenario is included in the **Appendix 2**.

4.3.5 Selection of the indicators

For every basic criterion, indicators were identified based on literature and on technical and economic references (**Table 4.1**). The selected indicators were either qualitative, quantitative or mixed. Quantitative indicators were used when numeric values could be transformed into qualitative classes by using thresholds (Craheix et al., 2015). For example, the pesticide dependency was assessed by dividing the annual production value by the annual cost of pesticides (**Table 4.2**). Then, the ratio obtained could be classified into one of the three categories by the user. Qualitative indicators were used when the description of a system or a practice was sufficient to classify a cropping system (Craheix et al., 2015). For example, a qualitative indicator was used to assess the complexity of the cropping system (**Table 4.3**). Mixed indicators, which correspond to the grouping of many indicators into an independent tree (called a "satellite tree"), were used when more than one indicator was needed for assessing a basic criterion (Craheix et al., 2015). For example, the basic criteria "Pesticide use risk" was assessed by developing a satellite tree with the following indicators: frequency of pesticide applications, respect of restricted entry intervals, use of adequate personal protective equipment and toxicity of the pesticides used (**Figure 4.6**).

Table 4.1 List of the indicators selected for all basic criteria describing the economic, environmental and social dimensions of sustainability of strawberry cropping systems. For every basic criterion, the indicator type (quantitative, qualitative or mixed) is indicated and the indicators are listed.

Basic criteria	Quantitative	Qualitative	Mixed	Indicators
Economic sustainability				
Nutrient deficiency		x		Fertilization management
Risk due winter or frost injuries			x	Production system Irrigation system
Water deficiency		x		Irrigation management
Weed pressure			x	Herbicide use Risk of resistance Mechanical and manual control Cultural practices
Insects pressure			x	Insecticide use Risk of resistance Biological control Cultural practices
Disease pressure			x	Fungicide use Risk of resistance Crop rotations Drainage Irrigation system
Pesticide dependency	x			Costs of pesticides vs production value
Dependence on workers	x			Number of hours worked by employees versus production value
Need for equipment		x		Production system
Production cost			x	Cost of inputs and machinery use Labor cost Other costs
Production value			x	Yield Selling price

Table 4.1 (cont'd) List of the indicators selected for all basic criteria describing the economic, environmental and social dimensions of sustainability of strawberry cropping systems. For every basic criterion, the indicator type (quantitative, qualitative or mixed) is indicated and the indicators are listed.

Basic criteria	Quantitative	Qualitative	Mixed	Indicators
Environmental sustainability				
Impact on flora		x		Presence of natural or semi-natural habitats
Impact on fauna			x	Frequency of pesticide applications Choice of pesticides Moment of applications Presence of natural or semi-natural habitats
Risk of nitrate leaching			x	Nitrogen fertilization management Water management Soil texture
Risk of pesticide loss			x	Pesticide handling and applications Risk of pesticide drift Presence and respect of buffer zones Frequency of pesticide applications
Risk of phosphorus loss			x	Phosphorus fertilizer rates Runoff and erosion risks
Risk of pesticide drift			x	Frequency of pesticide applications Spraying equipment Weather conditions during spraying
Greenhouse gas emissions			x	Use of material (plastic mulches, drip tubes, …) Use of irrigation
Organic matter content and biological activity		x		Addition of organic inputs
Risk of erosion			x	Soil cover during the fall/winter Presence of slopes
Waste management			x	Disposal of empty containers Use of plastic mulches and drip irrigation
Use of water			x	Irrigation system Production system Use of decision support tools
Social sustainability				
Pesticide use risk			x	Frequency of pesticide applications Respect of restricted entry intervals Use of proper personal protective equipment Toxicity of the products (health risk index)
Physical difficulty		x		Description of the tasks
System complexity		x		Description of the cropping system
Workload distribution		x		Description of the work distribution

Table 4.2 The basic criterion "Pesticide dependency" is assessed with a quantitative indicator.

Better[a]	More than 51 $ of sales for 1$ of pesticides (41$ + 25% x 41$)
Similar to reference scenario	The production value is around 33 000$/ha/year and the cost of pesticides is around 800$/ha/year. (33 000$/800$= 41 $ of sales for 1$ of pesticides)
Worst[a]	Less than 31$ of sales for every 1$ of pesticides (41$-25% x 41$)

[a] The values provided above are for information purposes only and should not be considered as fixed threshold values.

Table 4.3 The basic criterion "System complexity" is assessed with a qualitative indicator.

Better[a]	No irrigation system is used. No row cover is used.
Similar to reference scenario	Matted row system with June-bearing cultivars with an irrigation system and use of row covers.
Worst[a]	Certifications (Canada GAP, organic), plasticulture, use of high tunnels, use of biological control, use of fertigation

[a] The description provided above is for information purposes only and should be considered as a flexible guideline.

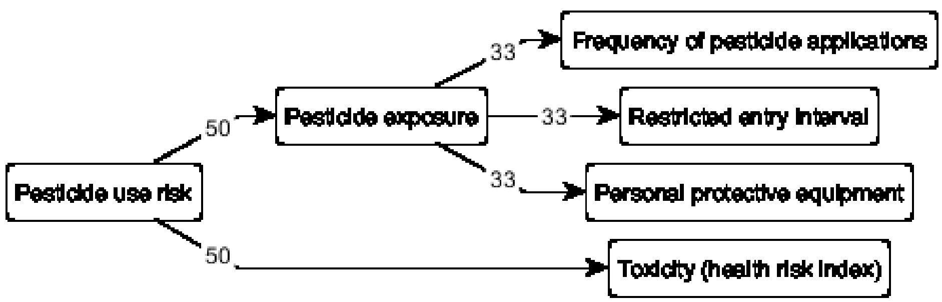


Figure 4.6 The basic criterion "Pesticide use risk" is assessed with a mixed indicator.

4.3.6 Definition of the aggregation rules

Aggregation rules were mostly defined by attributing a similar importance to every sub criteria of a parent criterion. For example, the aggregation rules for the environmental sustainability were defined to give equal weights of 33% for biodiversity conservation, 33% for impact on resources and 33% for resources use (**Figure 4.4**). However, for a few criteria pertaining to the economic dimension, the sub criteria were not given equal weights. For the criterion "viability", a higher weight was given for "stability" (77%) compared to "need for equipment" (23%) based on other multi-criteria assessment frameworks (Sadok et al., 2009; Vélu et al., 2016b). "Profitability" was divided into "production cost" (40%) and production value (60%) which is similar to what was used by Vélu et al. (2016b).

Aggregation rules of the satellite trees were also defined by giving a similar importance to every sub criteria of a parent criterion. The only exception was for the basic criterion “production cost” for which the weights of the sub criteria were determined based on economic references: cost of inputs and machinery use (24%), labor cost (52%) and other costs (24%) (CRAAQ, 2014a). Finally, for a few criteria, the sub criteria have similar but not equal weights. These slight differences are due to adjustments that were made to the aggregation rules following the validation of the framework structure. These changes allowed the framework a better capacity to distinguish between different scenarios. As suggested by Craheix et al. (2015), the aggregation rules are not fixed and could be modified by the user. However, it is recommended not to remove any criterion from the framework (Craheix et al., 2015).

To facilitate the aggregation, the number of levels per criterion was increased when walking up the tree (Bohanec, 2015; Craheix et al., 2015). Three levels (worst, similar and better) were assigned to the basic criteria, five levels (1 to 5) to intermediate criteria, seven levels (1 to 7) to the three dimensions of sustainability and nine levels (1 to 9) to the overall sustainability. Moreover, to minimize the number of aggregation rules, criteria were split into a maximum of three sub-criteria (Bohanec, 2015; Craheix et al., 2015).

4.3.7 Validation of the framework

Evaluation of the framework structure

Once a first version of the hierarchical tree of criteria was completed, experts were consulted to validate the structure of the tree. They were asked to identify any missing criterion relevant to the assessment as well as any unnecessary criterion. They were also asked to comment the structure of the tree, particularly regarding the divisions of the criteria.

As a second step, the structure of the framework was evaluated using Monte Carlo analysis (Carpani et al., 2012; Craheix et al., 2015). This method simulates inputs of the framework (values of the indicators or basic criteria) by random sampling. The results show the probability of obtaining every level of a criterion (Carpani et al., 2012). The Monte Carlo analysis was used to evaluate two versions of the framework: a draft version and the final version. The analyses were performed with the tool IZI-EVAL, which was developed for DEXi models (Craheix et al., 2015). The scripts used by the tool IZI-EVAL were coded under the R statistical package (R Core Team, 2016).

Evaluation of the framework outputs

Three different scenarios were tested with the framework. The purpose of testing these scenarios was to verify if the framework outputs were logical and corresponded to what would be expected for different contrasting scenarios.

Two scenarios similar to the reference scenario (matted row system with June-bearing cultivars) were tested. Their only difference from the reference scenario consisted in a different use of pesticides. In the first scenario, an integrated pest management strategy was implemented (mechanical and manual weeding, cover crops, use of biological control, scouting, good drainage, etc.). Practices for pesticide use were defined as optimal (different modes of action, respect of buffer zones, frequent adjustments of the sprayer, adequate personal protective equipment, etc.).

The second scenario was also similar to the reference scenario, except that pesticides were overused (no integrated pest management strategy implemented, calendar-based pesticide applications). Practices for pesticide use were defined as inappropriate (same mode of action used, buffer zones not respected, sprayer rarely or never adjusted, inadequate personal protective equipment, etc.).

The third scenario tested was an annual plasticulture system using day-neutral strawberry plants. A more detailed description of the plasticulture system is provided at **Appendix 4**.

4.4 Results

4.4.1 Validation of the framework

Evaluation of the framework structure

Monte Carlo simulations performed on a draft version of the multi-criteria assessment framework provided the occurrence frequency of the different categories of the criteria (figure 7). These results were used to modify aggregation rules when needed (i.e. avoid null occurrence of a category). Monte Carlo simulations performed following modifications show a more even distribution of the frequency of occurrence between categories (**Figures 4.7 and 4.8**).

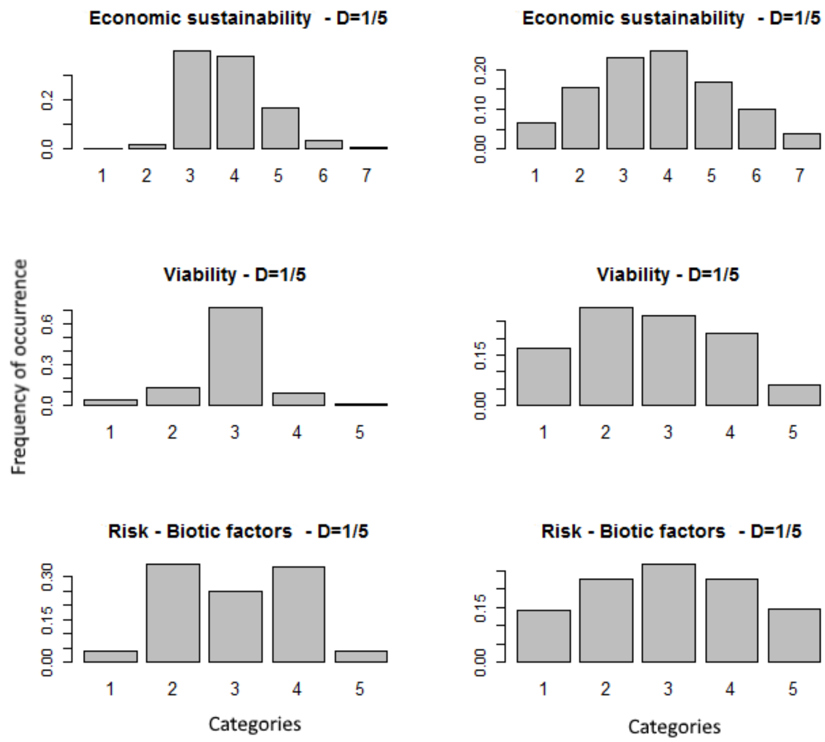


Figure 4.7 Distribution of the results of 5000 Monte Carlo simulations for three aggregated criteria (economic sustainability, viability and risk of yield loss due to biotic factors) for a draft version (left) and the final version (right) of the framework. For each graph, the sum of all the categories is equal to 1.

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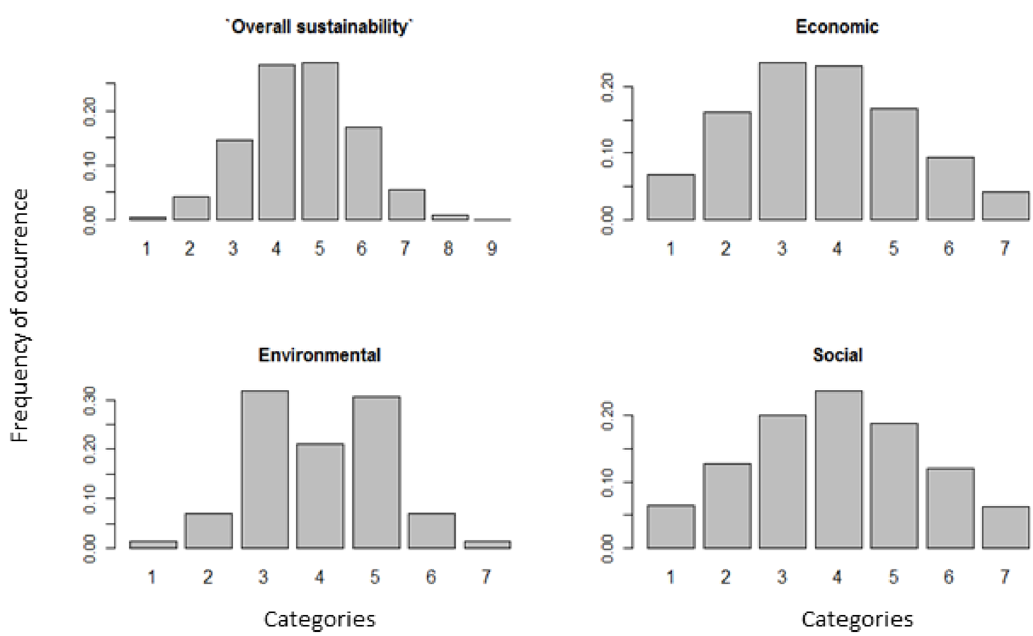

Figure 4.8 Distribution of the results of 5000 Monte Carlo simulations for the overall sustainability and the three dimensions of sustainability. For each graph, the sum of all the categories is equal to 1.

Evaluation of the framework outputs

Comparison of different crop protection strategies

The detailed results of the sustainability assessment of the two crop protection strategies (integrated pest management and pesticide-based strategy) are listed on **Table 4.4**. Most important differences between crop protection strategies are observed for the environmental dimension of sustainability (**Figure 4.9 and Table 4.4**). Environmental sustainability is higher for the integrated pest management (IPM) strategy (6/7) and lower for the pesticide-based (PB) strategy (2/7) compared to the reference scenario (4/7) (**Table 4.4**). Economic sustainability is higher for the integrated pest management (IPM) strategy (5/7) and lower for the pesticide-based (PB) strategy (3/7) compared to the reference scenario (4/7) (**Table 4.4**). Social sustainability is similar for all three crop protection strategies (**Figure 4.9 and Table 4.4**).

The higher environmental sustainability of the IPM strategy compared to the reference scenario is explained by lower impacts of the strategy on biodiversity, environmental quality and resources use (**Table 4.4**). Fauna diversity is improved due to fewer pesticide applications and selection of pesticides with lower risks for pollinators when possible. Environmental quality is also higher than the reference scenario due to improvements of water, air and soil quality. Water quality is better due to lower risks of pesticide loss (fewer pesticide applications, reduced risks of pesticide drift, adequate manipulations of pesticides, respect of buffer zones) and lower risks of phosphorus loss (reduced risks of erosion due to cover crops). Better air quality is mostly due to lower risks of pesticide drift (fewer pesticide applications, use of drift-reducing equipment and adequate pesticide application moments). Improved soil quality is due to a better soil cover by cover crops that contribute to reduce erosion and add organic matter. Resources use is improved because all empty containers of pesticides are disposed through AgriRÉCUP.

The pesticide-based (PB) strategy, on the other hand, shows a lower environmental sustainability compared to the reference scenario due to higher impacts of the strategy on biodiversity conservation, environmental quality and resources use (**Table 4.4**). The impact of the PB strategy on fauna diversity is more important due to a larger number of pesticide applications and the non-consideration of risks for pollinators when selecting pesticides. The lower environmental quality is explained by higher impacts of the strategy on water and air quality. Water quality is lower due to more risks of pesticide loss (larger number of pesticide applications, higher risks of pesticide drift, inadequate pesticide handling and non-compliance of buffer zones). The higher impact on air quality is mostly due to higher risks of pesticide drift (larger number of pesticide applications and inadequate moments for spraying). Resources use is lower because empty pesticide containers are not always disposed properly.

The higher economic sustainability of the IPM strategy compared to the reference scenario is due to a higher viability and similar profitability of the IPM strategy (**Table 4.4**). The higher viability is explained by lower risks of yield loss due to cultural practices (longer crop rotations, mowing of field borders, cover crops) and control methods (more mechanical and manual weeding, biological control agents, pesticides with different modes of action) that contribute to decrease weed, insect and disease pressure. On the contrary, the lower economic sustainability of the PB strategy compared to the reference scenario is due to a lower viability combined to a similar profitability of the PB strategy (**Table 4.4**). The lower viability is due to higher risks of yield loss due to risky cultural practices (shorter crop rotations, poor drainage) and control relying exclusively on pesticide applications without using different modes of action.

Social sustainability is similar for the IPM strategy, the PB strategy and the reference scenario. For the IPM strategy, lower risks for employees' health related to pesticide use (fewer applications, adequate personal protective equipment and use of pesticides with lower health risk index) are offset by a higher management difficulty (**Table 4.4**). For the PB strategy, higher risks for employees' health (higher pesticide use risks) are offset by a decrease in management difficulty (**Table 4.4**).

Table 4.4 Comparison between the reference scenario and the detailed results of the sustainability assessment of two crop protection strategies (integrated pest management and pesticide-based strategy) and the plasticulture system with a day-neutral variety.

Criteria hierarchy	Criteria values and assessment results			
	Reference scenario	IPM strategy	Pesticide-based strategy	Plasticulture system
Overall sustainability (9)[a]	5	6	3	3
Economic sustainability (7)	**4**	**5**	**3**	**3**
Viability (5)	3	4	2	2
Stability (5)	3	4	2	3
. Autonomy (5)	3	3	3	3
.. Pesticide dependency (3)	2	3	1	2
.. Dependence on workers (3)	2	1	3	2
. Risk of yield loss (5)	3	4	2	3
.. Due to biotic factors (5)	3	5	1	2
… Weed pressure (3)	2	3	1	2
… Insects pressure (3)	2	3	1	1
… Disease pressure (3)	2	3	1	2
.. Due to abiotic factors (5)	3	3	3	4
… Risk due to frost (3)	2	2	2	3
… Water deficiency (3)	2	2	2	2
... Nutrient deficiency (3)	2	2	2	2
Need for equipment (3)	2	2	2	1
Profitability (5)	3	3	3	3
Production cost (5)	3	2	4	1
Production value (5)	3	3	3	5
Social sustainability (7)	**4**	**4**	**4**	**3**
Workers' health (5)	3	4	2	2
Pesticide use risk (3)	2	3	1	1
Physical difficulty (3)	2	2	2	2
Management difficulty (5)	3	2	4	3
System complexity (3)	2	1	3	1
Workload distribution (3)	2	2	2	3

[a] The number in parentheses indicates the number of levels corresponding to the indicated criterion.

Table 4.4 (cont'd) Comparison between the reference scenario and the detailed results of the sustainability assessment of two crop protection strategies (integrated pest management and pesticide-based strategy) and the plasticulture system with a day-neutral variety.

Criteria hierarchy	Criteria values and assessment results			
	Reference scenario	IPM strategy	Pesticide-based strategy	Plasticulture system
Environmental sustainability (7) [a]	**4**	**6**	**2**	**2**
Biodiversity (5)	3	4	2	2
Impact on flora (3)	2	2	2	2
Impact on fauna (3)	2	3	1	1
. Pesticide use (3)	2	3	1	1
. Presence of natural habitats (3)	2	2	2	2
Environmental quality (5)	3	5	2	1
Water quality (5)	3	5	2	2
. Risk of phosphorus loss (3)	2	3	2	1
. Risk of pesticide loss (3)	2	3	1	1
. Risk of nitrate leaching (3)	2	2	2	3
Air quality (5)	3	4	2	1
. GHG emissions (3)	2	2	2	1
. Risk of pesticide drift (3)	2	3	1	1
Soil quality (5)	3	5	3	1
. Risk of erosion (3)	2	3	2	1
. Organic matter content (3)	2	3	2	1
Resources use (5)	3	4	2	3
Water use (3)	2	2	2	3
Waste disposal (3)	2	3	1	1

[a] The number in parentheses indicates the number of levels corresponding to the indicated criterion.

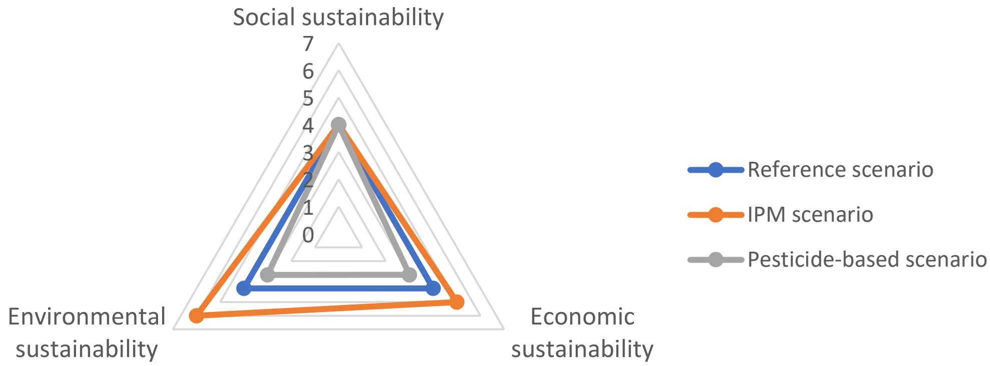

Figure 4.9 Assessment of the environmental, social and economic dimensions of sustainability for three different crop protection strategies (reference scenario, integrated pest management (IPM) strategy and pesticide-based strategy).

Comparison of two cropping systems

The annual plasticulture system, when compared to the reference scenario, shows a lower environmental sustainability (2/7), a lower economic sustainability (3/7) and a lower social sustainability (3/7) (**Figure 4.10**).

The lower environmental sustainability is due to higher impacts of the cropping system on biodiversity and environmental quality (**Table 4.4**). Fauna diversity is affected by the higher number of pesticide applications. The lower environmental quality is explained by higher impacts of the plasticulture system on water, air and soil quality. Lower water quality is caused by more risks of pesticide and phosphorus losses due to more pesticide applications and a higher occurrence of bare soil in the fall and winter (annual crop destroyed in the fall). Lower air quality is due to higher risks of pesticide drift (more pesticide applications) and higher emissions of greenhouse gas (GHG) (use of plastic mulches (indirect GHG) and higher irrigation needs (direct GHG)). Higher impacts of the plasticulture system on soil quality is caused by increased erosion risks (bare soil in the fall) and lower organic matter inputs. Resources use is similar for both cropping systems due to a better water use efficiency for the plasticulture system (use of decision support tools for irrigation management), which is offset by additional wastes (plastic mulches).

The economic sustainability of the annual plasticulture system is lower than for the reference scenario due to lower viability and profitability (**Table 4.4**). The viability is lower due to a similar stability that comes with the need for additional agricultural equipment (i.e. mulch layer, plastic mulch lifter). Profitability is similar due to the combination of a higher production value and higher production costs.

Social sustainability of the annual plasticulture system is lower than for the reference scenario (**Table 4.4**). The management difficulty is similar due to a higher complexity of the system that is offset by a better workload distribution throughout the season. The higher employees' health risks are due to higher pesticide use risks (more applications).

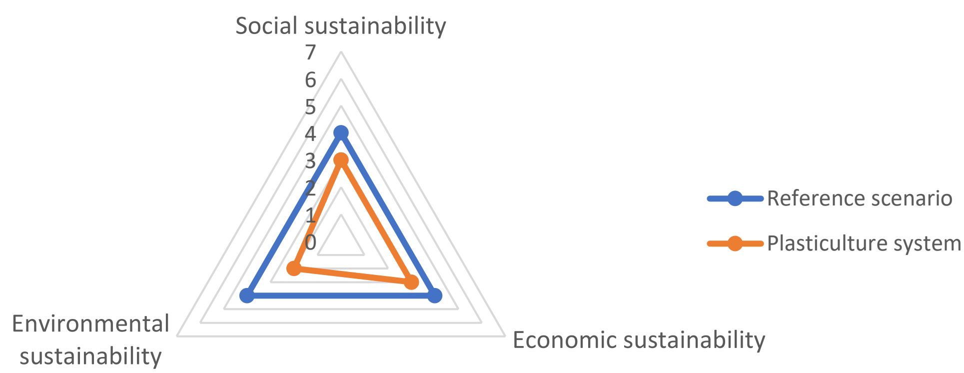

Figure 4.10 Assessment of the environmental, social and economic dimensions of sustainability for two cropping systems: the reference scenario (matted row system) and the annual plasticulture system with day-neutral cultivars.

4.5 Discussion

The objective of this project was to develop a framework for assessing the sustainability of strawberry cropping systems in the province of Quebec. A multi-criteria decision support framework was developed with the DEXi software. The assessment framework is composed of 26 basic criteria: 11 for assessing the economic dimension of sustainability, 11 for the environmental dimension, and 4 for the social dimension. The number of criteria is comparable to similar frameworks developed with DEXi: DEXiPM has 52 basic criteria; MASC 2.0, 39; and DEXiPM grapevine, 20 (Craheix et al., 2015, 2012; Pelzer et al., 2012). All basic criteria of the framework are combined into aggregated criteria with “if-then” aggregation rules until reaching root criteria (the economic, environmental and social dimensions of sustainability). The framework was validated by assessing two crop protection strategies: an integrated pest management (IPM) strategy and a pesticide-based strategy. Assessment results corresponded to what was expected: a better environmental sustainability was obtained for the IPM strategy compared to the pesticide-based strategy.

Contrary to other assessment frameworks such as DEXiPM or MASC (Craheix et al., 2012; Pelzer et al., 2012), sustainability is assessed on a comparative basis, using a reference scenario. The reference scenario is intended to be representative of most common growing practices in the province of Quebec, which were identified as a matted row system using June-bearing cultivars. The assessment is made by categorizing a practice as “worst”, “similar” or “better” than the reference scenario. Assessing sustainability of cropping systems on a comparative basis gives flexibility to the framework. Indeed, it is relatively easy to modify the reference scenario to consider the newest information available or to make it specific for a region. However, users need to be careful when interpreting results and keep in mind that the assessment is made on a comparative basis. Even though the assessment for a criterion is considered “better” or “worst” than the reference scenario, it does not necessarily mean that it is “good” or “bad”. Another negative side of the comparative assessment is the difficulty of defining a reference scenario representative of most common growing practices since they are variable depending of years, regions and experts consulted. Indeed, most common practices can evolve quickly, particularly when new problems occur (e.g. the presence of viruses in strawberry fields over the last few years).

A strength of this framework is the consideration of the three dimensions of sustainability within the same tool, a shared characteristic with models developed in Europe with the DEXi software (Craheix et al., 2015, 2012; Pelzer et al., 2012). However, there is no such tool in the Quebec province. The closest tool is a decision support tool known as “Agri-Environmental Support Plan”. This tool, which is not specific to a production, consists in a questionnaire of more than 100 questions about fertilizer management, soil conservation and health, water management, crop protection, and flora, fauna and habitat protection (MAPAQ, 2017). The assessment is made at the farm scale and is only based on environmental criteria and a few social criteria. Growers answer the questions with their advisor and they can identify elements to improve and actions that must be taken to adopt more environmentally-friendly production methods (MAPAQ, 2017). However, there is a lack of interest from several growers who do not perceive the Agri-environmental Support Plan as a tool, but rather as a requirement for obtaining financial aid for buying equipment. The framework developed as part of this project, by including all three dimensions of sustainability, could contribute to increase interest of growers for decision-support tools.

Although all dimensions of sustainability are included in the assessment framework, only four basic criteria pertain to the social dimension. This number is lower than for other similar frameworks: DEXiPM includes 16 basic criteria for the social dimension and MASC 2.0, 7 (Craheix et al., 2015, 2012; Pelzer et al., 2012). Unlike DEXiPM in which the social dimension includes the interaction of the system with society, the supply chain and the social sustainability for the farmer, only the latter aspect was kept as part of the present framework (Pelzer et al., 2012). This choice was made to keep the framework as simple as possible. Indeed, a large number of criteria can reduce the sensitivity of the framework and decrease its capacity to distinguish systems (Craheix et al., 2015).

Sensitivity analyses were conducted as part of the validation process. Monte Carlo simulations performed on a draft version of the framework showed the frequency of occurrence of the categories for the different criteria. For example, for the criterion “viability” the frequency of occurrence of the middle category (3/5) was around 70% in the draft version, meaning that the assessment results were only slightly influenced by the categories of the subcriteria. Since uniform distributions increase the capacity of the framework to distinguish cropping systems (Carpani et al., 2012), a few modifications were made to the aggregation rules in order to allow for a better distribution throughout the different categories of the criteria.

It is also important to mention a drawback to the use of Monte Carlo simulations. During simulations, inputs are randomly selected since they are assumed to be independent from one another (Carpani et al., 2012). However, in fact they are not always independent: for example, criteria related to pesticide use are present in all three dimensions of sustainability. This problem could be addressed in the future by creating correlated criteria in the model, as suggested by Carpani et al. (2012).

Another part of the validation process was the assessment of two opposite made-up crop protection strategies followed by the analysis of the results. Although the assessment results generally corresponded to the expectations, a few particular cases were noticed. For example, both the pesticide-based scenario and the IPM scenario obtained 4/7 for the social dimension of sustainability, which was similar to the reference scenario. Although it could be surprising, it was due to the improvement of the management difficulty (4/5) that offset the higher risk for workers' health (2/5) in the case of the pesticide-based scenario. The opposite situation was observed for the IPM scenario with the lower risk for workers' health (4/5) that compensated for an increase of the management difficulty (2/5). Such situations highlight the necessity to look at the assessment results of all criteria, and not only at those of the three main dimensions. Moreover, the frameworks developed with the DEXi software (e.g., DEXiPM and MASC) usually allow the users to modify aggregation rules to account for their vision of sustainability or to adapt the framework to a specific context (Craheix et al., 2015). In this case, a user could modify the aggregation rules if he considers workers' health to be more important than the complexity of the system regarding the social dimension of sustainability.

A subsequent step for developing the framework could be the formation of a designer group. Indeed, the models developed with the DEXi software by the European community were conceived by designer groups composed of 5 to 35 scientists and/or extension workers (Craheix et al., 2015). Craheix et al. (2015) emphasizes the need to work in a transdisciplinary approach, which is why they suggest involving target users (growers, advisors), experts from different fields (sociology, economy, ecotoxicology, etc.) and other stakeholders. The necessity of holding synchronous meetings is also highlighted since several decisions require debates (Craheix et al., 2015).

Another subsequent step could be to test the assessment framework with real scenarios and potential users, and use their feedback to improve the tool. The latter should be presented as a "discussion-support" tool developed with the objective to facilitate discussions between growers and their advisors. Finally, in order to remain useful, such assessment frameworks are meant to evolve to integrate new knowledge and changes in the reference scenario.

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Chapter 5: Conclusion

Over the past years, efforts have been made through the Quebec phytosanitary agricultural strategy (SPQA) to reduce risks associated with pesticide use. However, it seems unlikely that the objective of the SPQA of reducing risks related to pesticide use by 25% by 2021 will be reached. Pesticide sales for crop protection in Quebec are generally increasing: a rise of over 20% of the quantity of active ingredient (kg) was observed in 2015 compared to the level of 1992 (MDDELCC, 2015). Moreover, despite the lack of an accurate picture of the use of integrated pest management (IPM) practices by Québec growers, the evolution of the adoption of IPM practices appears to be slow (ÉcoRessources Consultants, 2012b). Amongst the main barriers to the adoption of IPM practices are the complexity, the lack of perceived benefit and the lack of support (ÉcoRessources Consultants, 2012b). These issues were addressed by both sections of the thesis.

The general objective of the thesis was to develop tools for facilitating decision-making for strawberry growers. More specifically, the objective of the first part of the thesis was to develop weather-based indices for predicting development of strawberry powdery mildew using weather, disease severity and spore concentration data. Two weather-based indices, A and B, were developed by cumulating hours with favorable and optimal weather conditions (temperature, relative humidity and rainfall) for conidia germination. For several epidemics, the weather-based indices predicted accurately disease development. For example, 18% of the epidemics of June-Bearing cultivars in open field showed a R^2 over 0.85 for the linear regression between the index B and disease severity observed seven days later. However, the weather-based indices were overall not accurate enough to predict disease development. Moreover, the weather and inoculum-based indices, A_i and B_i, did not improve the accuracy of the indices. Thus, although the indices developed as part of this project cannot be used by growers, their development showed that the evolution of strawberry powdery mildew over the growing season cannot be explained solely by weather conditions. Other variables that were not measured as part of this project seem to influence the disease. Thus, future researches should consider other field-specific variables such as the phenological stage of the crop, the "year" of the crop, disease history of the field and the presence of elements that could influence the microclimate of the field.

The second part the thesis consisted in developing a framework for assessing the environmental, economic and social dimensions of sustainability of strawberry cropping systems. The assessment framework was developed using a qualitative multi-criteria analysis model. It is composed of 11, 11 and 4 environmental, economic and social basic criteria, respectively. A reference scenario, representative of most common growing practices in the province of Quebec, was described and used as a comparative basis. Indicators were defined for each basic criterion in order to facilitate their assessment. The assessment framework was validated by comparing two made-up crop protection strategies. The results were consistent with those expected since the IPM strategy showed a better environmental sustainability than the pesticide-based strategy. Future steps should include validation of the framework with real scenarios as well as including future users of the tool in the development process. Ultimately, the assessment framework could be used as a tool for growers and stakeholders to promote environmentally sustainable practices within the strawberry industry.

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Appendix 1: Coefficients of determination (R^2) calculated for the simple linear regression between the different indices and the severity observed seven days later for open field and high tunnel epidemics.

No	Sites	Fields	Years	Cultivars	R^2 for index A	R^2 for index Ai[a]	R^2 for index B	R^2 for index Bi[a]
June-bearing in open fields								
1	BEAM	71	2007	Cavendish	0.639	0.44	0.553	0.35
2	BEAM	71	2007	Chambly	0.75	0.53	0.677	0.43
3	BEAM	71	2008	Cavendish	0.6	.	0.658	.
4	BEAM	71	2008	Chambly	0.653	.	0.71	.
5	FRE	FRE	2006	Cavendish	0.541	.	0.441	.
6	FRE	FRE	2006	Chambly	0.611	.	0.496	.
7	FRE	FRE	2006	Darselect	0.643	.	0.517	.
8	FRE	FRE	2006	Jewel	0.681	.	0.557	.
9	FRE	FRE	2007	Cavendish	0.714	.	0.699	.
10	FRE	FRE	2007	Chambly	0.767	.	0.759	.
11	FRE	FRE	2007	Darselect	0.684	.	0.673	.
12	FRE	FRE	2007	Jewel	0.645	.	0.614	.
13	FRE	FRE	2008	Cavendish	0.431	.	0.39	.
14	FRE	FRE	2008	Chambly	0.484	.	0.439	.
15	FRE	FRE	2008	Darselect	0.269	.	0.239	.
16	FRE	FRE	2008	Jewel	0.351	.	0.297	.
17	FRE	FRE	2009	Cavendish	0.739	.	0.786	.
18	FRE	FRE	2009	Chambly	0.759	0.49	0.801	0.05
19	FRE	FRE	2009	Darselect	0.682	0.18	0.717	0
20	FRE	FRE	2009	Jewel	0.692	.	0.721	.
21	FRE	FRE	2010	Cavendish	0.535	.	0.51	.
22	FRE	FRE	2010	Chambly	0.501	.	0.473	.
23	FRE	FRE	2010	Darselect	0.588	.	0.566	.
24	FRE	FRE	2010	Jewel	0.541	.	0.525	.
25	FRE	FRE	2011	Cavendish	0.698	.	0.725	.
26	FRE	FRE	2011	Chambly	0.728	.	0.764	.
27	FRE	FRE	2011	Darselect	0.754	.	0.811	.
28	FRE	FRE	2011	Jewel	0.753	.	0.812	.
29	GADJ	71	2006	Darselect	0.805	0.65	0.818	0.66
30	GADJ	71	2006	Jewel	0.656	0.29	0.666	0.4
31	GADJ	74	2007	Cavendish	0.442	0.2	0.413	0.14
32	GADJ	74B	2007	Cavendish	0.753	0.49	0.711	0.18
33	GADJ	74	2007	Chambly	0.414	0.08	0.381	0.05

34	GADJ	74B	2007	Chambly	0.75	0.46	0.704	0.2
35	GADJ	72	2007	Darselect	0.086	0.07	0.0567	0.29
36	GADJ	73	2007	Darselect	0.802	0.53	0.766	0.16
37	GADJ	71	2007	Jewel	0.534	0.44	0.481	0.19
38	GADJ	73	2007	Jewel	0.807	0.5	0.769	0.17
39	GADJ	71	2009	Darselect	0.53	0	0.547	0.01
40	GADJ	73	2009	Darselect	0.9	0.36	0.911	0.1
41	GADJ	71	2009	Jewel	0.458	0.02	0.471	0.02
42	GADJ	73	2009	Jewel	0.907	0.47	0.924	0.12
43	GADJ	73	2010	Darselect	0.835	0.35	0.808	0.09
44	GADJ	73	2010	Jewel	0.875	0.29	0.871	0.07
46	GAUB	3NT	2008	Chambly	0.767	0.08	0.736	0.03
47	GAUB	3NT	2008	Chambly	0.932	0.05	0.917	0.02
48	GAUB	36	2008	Darselect	0.803	0.34	0.758	0.09
49	GAUB	38	2008	Darselect	0.743	0.38	0.691	0.07
51	GAUB	36	2008	Jewel	0.827	0.38	0.781	0.13
52	GAUB	38	2008	Jewel	0.838	0.19	0.799	0.11
56	GAUB	38B	2009	Cavendish	0.863	0.85	0.902	0.44
57	GAUB	36	2009	Chambly	0.911	0.76	0.876	0.46
58	GAUB	38	2009	Chambly	0.796	0.51	0.81	0.59
59	GAUB	38B	2009	Chambly	0.831	0.74	0.823	0.41
60	GAUB	36	2009	Darselect	0.887	0.73	0.886	0.45
61	GAUB	38	2009	Darselect	0.745	0.52	0.756	0.5
62	GAUB	38B	2009	Darselect	0.843	0.72	0.88	0.64
67	GAUB	38B	2009	Jewel	0.825	0.84	0.875	0.79
68	GAUB	38B	2009	Jewel	0.829	0.85	0.887	0.79
70	RODM	10	2008	Chambly	0.929	0.62	0.937	0.34
June-bearing in high tunnels								
71	BEAM	T71	2007	Chambly	0.704	0.52	0.653	0.38
72	BEAM	T71	2008	Chambly	0.697	.	0.662	.
73	GADJ	T71	2006	Darselect	0.77	0.74	0.765	0.69
74	GADJ	T71	2006	Jewel	0.62	0.22	0.612	0.14
75	GADJ	T74	2007	Chambly	0.509	0.19	0.527	0.02
76	GADJ	T74B	2007	Chambly	0.839	0.66	0.855	0.49
77	GADJ	T72	2007	Darselect	0.225	0.06	0.244	0
78	GADJ	T73	2007	Darselect	0.852	0.6	0.854	0.57
79	GADJ	T71	2007	Jewel	0.674	0.28	0.701	0.36
80	GADJ	T73	2007	Jewel	0.912	0.64	0.914	0.57
86	GADJ	T71	2009	Darselect	0.704	0.76	0.76	0.38
87	GADJ	T73	2009	Darselect	0.856	0.54	0.833	0.27
88	GADJ	T71	2009	Jewel	0.558	0.4	0.604	0.53

89	GADJ	T73	2009	Jewel	0.836	0.51	0.814	0.28
90	GADJ	T73	2010	Darselect	0.788	0.09	0.802	0.14
91	GADJ	T73	2010	Jewel	0.856	0.19	0.852	0.18
92	GAUB	T3NT	2008	Chambly	0.65	0.23	0.644	0.15
93	GAUB	T36	2008	Darselect	0.896	0.94	0.925	0.8
94	GAUB	T38	2008	Darselect	0.853	0.82	0.894	0.79
95	GAUB	T38B	2008	Darselect	0.895	0.31	0.886	0.06
96	GAUB	T36	2008	Jewel	0.633	0.53	0.654	0.51
97	GAUB	T38	2008	Jewel	0.635	0.57	0.668	0.51
98	GAUB	T38B	2008	Jewel	0.882	0.38	0.891	0.17
99	GAUB	T36	2009	Chambly	0.881	0.7	0.86	0.41
100	GAUB	T36A	2009	Chambly	0.912	0.91	0.875	0.72
101	GAUB	T38	2009	Chambly	0.696	0.18	0.663	0.07
102	GAUB	T38B	2009	Chambly	0.901	.	0.899	0.12
103	GAUB	T36	2009	Darselect	0.872	0.92	0.848	0.39
104	GAUB	T38	2009	Darselect	0.677	0.08	0.654	0.08
105	GAUB	T38B	2009	Darselect	0.848	0.7	0.85	0.13
106	GAUB	T36	2009	Jewel	0.86	0.92	0.837	0.44
107	GAUB	T38	2009	Jewel	0.842	0.71	0.824	0.79
108	GAUB	T38B	2009	Jewel	0.787	0.56	0.809	0.45
109	RODM	T10	2008	Chambly	0.696	.	0.697	.
110	RODM	T10	2008	Chambly	0.653	0.72	0.643	0.57
Day-neutral in open fields								
111	FRE	FRE	2006	Seascape	0.12	0.22	0.18	0.31
112	FRE	FRE	2007	Seascape	0.27	0.05	0.27	0.04
113	FRE	FRE	2008	Seascape	0.04	0.18	0.04	0.15

[a] R^2 was calculated for epidemics with a minimum of 10 observations.

Appendix 2: Description of the reference scenario.

Production system	Matted row system. June-bearing cultivar planted in open fields.
Crop duration and harvest period	Perennial crop. One establishment year followed by two years of harvest. Harvest from mid-June to mid-July (about 3 weeks).
Planting	Mechanical planting on raised beds at low densities (16 000 plants/ha) (CRAAQ, 2014a)
Type of plants and cultivars	June-Bearing cultivar Jewel. Bare root plants (CRAAQ, 2014a)
Cultivar selection	Based on earliness, fruit quality (flavor) and yield
Mulching	Steam-sterilized straw applied over plants during winter and alley between rows is mulched with straw during harvest years
Specific operations	Flower removal during the first 4-6 weeks of the first year (Thireau and Lefebvre, 2014)
Irrigation	Drip irrigation. No decision support tool is used.
Fertility practices	Use of granular fertilizer. Establishment year: Split applications of nitrogen (55, 35 and 35 kg N/ha); 30 to 275 kg P_2O_5/ha and 30 to 275 kg K_2O based on soil analysis. First year of harvest after renovation: 40kg/ha N, P and K (CRAAQ, 2010)
Yields	First season: 12 000kg/ha; second season: 11 000 kg/ha (CRAAQ, 2014a)
Markets	Pick your own (20%), farmers' market (25%), wholesale market (52%) and transformation (3%) (CRAAQ, 2014a)
Economics	Latest available economic references for the matted row system (CRAAQ, 2014a)
Pesticide applications	Sprayer is generally calibrated once at the beginning of the season. Pesticides are not sprayed during the day when pollinators are in the field, but are sprayed during flowering. No pesticide is applied during windy conditions or when there is no wind. Buffer zones are not always respected. Equipment to reduce drift is not used.
Personal protective equipment	Adequate personal protective equipment is used for pesticide applications.
Pre-harvest and restricted entry intervals	Pre-harvest and restricted entry interval are followed.
Pesticide selection	Based on cost, efficiency and resistance risk (except for herbicides)
Fumigation	No fumigation
Weed control	Establishment year: About three herbicide applications (preplant, during season, in the fall); Mechanical weed control (about four times); Manual weeding. First harvest year: About two herbicide applications (at renovation and before mulching); Manual weeding. Second harvest year: Manual weeding; Field destruction with an herbicide.
Insect control	Based on scouting results. At least 1 application for tarnished plant bugs. At least 1 application for strawberry clipper weevil. About 1-2 applications for cyclamen mites.
Disease control	Harvest years. Grey mold: applications from flowering until harvest every 7-14 days depending of weather conditions.
Biological control	No
Crop destruction	Herbicide, and the field is plowed.

Appendix 3: Description of the indicators.

Basic criterion: Name of the basic criterion

Parent criterion: Name of the parent criterion

Description: Description of the basic criterion, if needed, and explanations regarding the choice of the indicators. Basic criteria can be assessed directly, or with a satelite tree in presence of many indicators. For every indicator, the user has to classify his cropping system into one of the three categories: better, similar or worst than the reference scenario. Then, indicators can be aggregated with the satellite tree. However, in order to shorten this document, aggregation rules are not shown below, but only in the DEXi model.

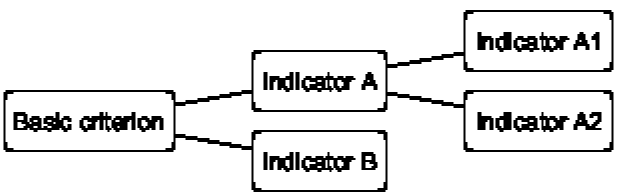


Figure 1 Example of a satellite tree for assessing a basic criterion.

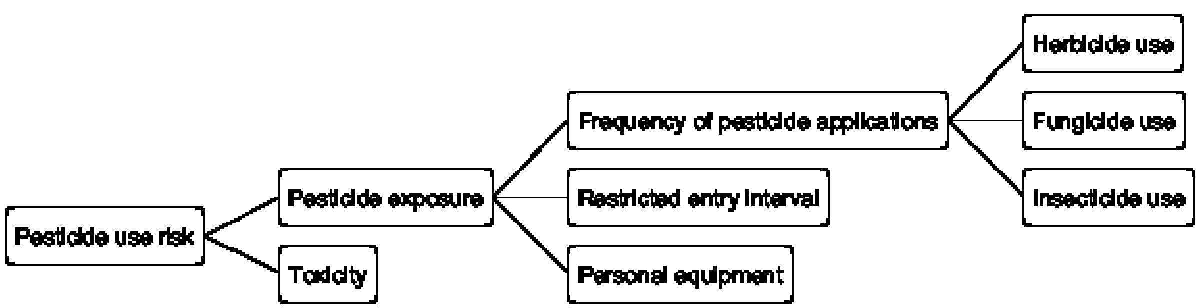
Indicator A	
Better	Examples of situations where a cropping system performs better than the reference scenario.
Similar to reference scenario	Description of the reference scenario.
Worst	Examples of situations where ther “performance” of a cropping system is worst than the reference scenario.
Indicator B	
Better	…
Similar to reference scenario	…
Worst	….
Indicator A1	
Better	…
Similar to reference scenario	…
Worst	…
...	

SOCIAL SUSTAINABILITY

Basic criterion: *Pesticide use risk*

Parent criterion: Workers' health

Description: This criterion assesses the risk for the health of workers due to pesticide applications. This risk depends on the toxicity of pesticides used and the exposure of workers to pesticides (Samuel et al., 2012). Health risk indices are available for registered pesticides in Canada. Indices takes into consideration the acute and chronic toxicity of the active ingredients, the environmental persistence, the potential for bioaccumulation, characteristics of the commercial products, and the application techniques (Samuel et al., 2012). Pesticide exposure can be reduced by using adequate personal protective equipment, respecting restricted entry intervals and minimizing pesticide applications. Personal protective equipment that should be worn before, during and after pesticide applications are described on product labels. Depending of the toxicity of the product, the required equipment can include chemical-resistant coveralls, socks and chemical-resistant footwear, chemical-resistant gloves, protective eyewear and mask approved for the type of pesticides (Samuel and St-Laurent, 2001). Respecting the restricted entry interval before going back to treated zone can reduce risk of pesticide exposure.



Herbicide use	
Better	Less than an average of 2 applications per year.
Similar	In the reference scenario, herbicides are sprayed on average twice a year. There are around three applications during the establishment year (preplant, during season, in the fall); around two applications during the first harvest year (at renovation and before mulching); and the field is "destroyed" with an herbicide at the end of the second harvest year.
Worst	More than an average of 2 applications per year.
Fungicide use	
Better	No more than an average of 2 applications per year.
Similar	During the harvest years, fungicides are sprayed every 7 to 14 days depending of weather conditions, from flowering until harvest. Considering a harvest period of 3 to 4 weeks, it consists in 2 to 6 applications.
Worst	More than 5-6 applications per year; fungicides are always sprayed every 7 days or so without considering other factors.
Insecticide use	
Better	No more than an average of 2 applications per year.
Similar	During the harvest years, insecticides are sprayed based on scouting results. There is generally a minimum of one application for tarnished plant bugs, one application for strawberry clipper weevils, and one or two applications for cyclamen mites.
Worst	More than an average of 4 applications per year; insecticides are not sprayed based on scouting results.
Restricted entry interval	
Better	Longer intervals than recommended are followed.
Similar	Restricted entry intervals are usually followed.
Worst	Restricted entry intervals are not always followed.
Personal protective equipment	
Better	Adequate personal protective equipment as described on product labels is always used for pesticide applications.
Similar	Adequate personal protective equipment as described on product labels is usually used for pesticide applications.
Worst	Adequate personal protective equipment as described on product labels is sometimes used for pesticide applications; inadequate equipment is used.
Toxicity of pesticides	
Better	The health risk index is considered when choosing a pesticide.
Similar	Pesticide selection is mainly based on cost, efficiency and resistance risk, whereas the health risk index is rarely taken into consideration.
Worst	The health risk index is never considered.

Basic criterion: *Physical difficulty*

Parent criterion: Workers' health

Description: This basic criterion represents the physical difficulty of the tasks performed by workers. Several factors can contribute to increase the difficulty level: physical efforts, uncomfortable postures, repetitiveness of a task, necessity to work fast, bad weather conditions (such as high or low temperatures or rain), and a high number of working hours (Atain-Kouadio et al., 2014). In the context of strawberry production, harvesting strawberries, removing flowers or stolons and weeding can be considered as repetitive tasks that are usually performed in an uncomfortable posture. The difficulty also lies in the fact that workers need to hurry up, that they work outside where it can be hot and sunny, and that they usually work a high number of hours.

Better	Soil-less culture where plants are elevated and where workers can harvest in a standing position; low number of working hours.
Similar	During the first year, workers plant, remove flowers and weed. Then, the following years, they harvest strawberries during approximately 3-4 weeks or a little more. Workers usually work a high number of hours per week.
Worst	Harvest lasts a longer period. Employees work a very high number of hours.

Basic criterion: *System complexity*

Parent criterion: Management difficulty

Description: This criterion characterizes the complexity of the cropping system. The complexity of a system increases when new elements are added to a system, which makes it more difficult to understand and to manage (Pannell, 1999). In the context of strawberry production, increasing the number of employees, enrolling in a certification program, or using new production techniques can contribute to increase the complexity of a production system.

Better	No irrigation system is used. No row cover is used.
Similar	Matted row system with June-bearing cultivars with an irrigation system and use of row covers.
Worst	Certifications (Canada GAP, organic), plasticulture, use of high tunnels, use of biological control, use of fertigation

Basic criterion: *Workload distribution*

Parent criterion: Management difficulty

Description: This criterion assesses the distribution of work throughout the season. The distribution of work is also closely related to the difficulty of recruiting workers, since it is harder to hire workers during only a few weeks.

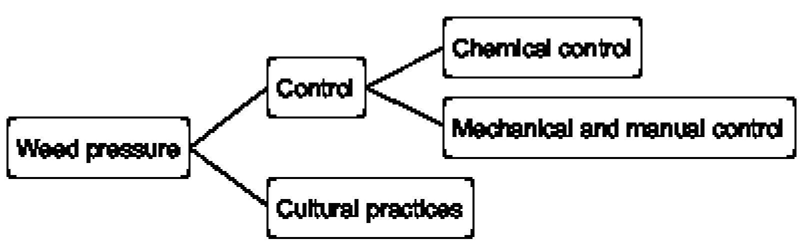
Better	Fruits are harvested during a longer period of time than the reference scenario (ex: plasticulture with day-neutral cultivars).
Similar	Fruits are harvested during a relatively short period of time during the summer. Cultivars with different “earliness” are used and row covers are used, which spreads the harvest on a few more weeks.
Worst	Harvest occurs during a short period of time. The same cultivar is used and no row cover is used.

ECONOMIC SUSTAINABILITY

Basic criterion: *Weed pressure*

Parent criterion: Abiotic risks

Description: This basic criterion describes the risk of yield losses due to weed pressure. Weeds can be problematic in strawberry production because they can reduce the development and rooting of runners during the establishment year (Pritts and Kelly, 2001). Their presence depends on many factors. A good control of the weeds, by a combination of herbicide applications and mechanical and manual weeding, is crucial especially in the planting year in order to minimize risk of yield losses (Pritts and Kelly, 2001). Moreover, in order to prevent development of resistance, it is recommended not to use a single group of herbicides with the same mode of action (Norsworthy et al., 2012). Plastic mulches are another way of reducing the weed pressure. The color black is considered to be the most effective at controlling weeds (Kasirajan and Ngouajio, 2012). The age of the field also influences the weed pressure. Indeed, the pressure of weeds, especially perennial weeds, tends to increase as the strawberry field gets “older” (Duval, 2003). Crop rotation also has an impact on weed density, although it is less important than the impact of chemical and mechanical control methods (Doucet et al., 1999).

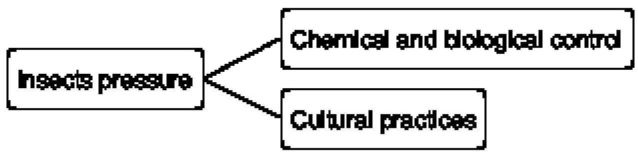


Chemical control	
Better	More herbicide applications; herbicides with different modes of action are used.
Similar	Establishment year: about three herbicide applications (preplant, during season, in the fall). First harvest year: about two herbicide applications (at renovation and before mulching). Second harvest year: field destruction with an herbicide. No special care is taken for using herbicide with different modes of action.
Worst	Less herbicide applications.
Mechanical/manual control	
Better	More mechanical weed control or more manual weeding than the reference scenario.
Similar	Establishment year: mechanical weed control (about four times); manual weeding (around 100 hours). First harvest year: manual weeding (around 25 hours). Second harvest year: manual weeding (around 50 hours).
Worst	Less mechanical and manual weeding.
Cultural practices	
Better	Annual crop, raised beds covered by plastic mulch with sterilized straw between rows.
Similar	Strawberries are harvested during two years in the same field. The alleys between rows are mulched with sterilized straw during harvest years.
Worst	Strawberries are harvested during more than two years in the same field. The alleys between rows are not mulched with straw during harvest years or the straw is not sterilized.

Basic criterion: *Insect pressure*

Parent criterion: Biotic risks

Description: This criterion describes the risk of yield losses due to the presence of insects. Several insects and mites such as tarnished plant bug, strawberry clipper weevil, spotted wing drosophila, two-spotted spider mite and cyclamen mite can cause crop losses in strawberry production (Lambert et al., 2007). They can either affect fruit quality or decrease the yield. Their presence depends on many factors such as the level of control achieved by using chemical or biological control, the age of the field and the harvest period. In order to minimize yield loss, it is generally recommended to apply insecticides when scouting results reach threshold values. It is also recommended to use insecticides with different modes of action (MOA) during the season in order to avoid resistance development (Lacroix, 2016; INSPQ et al., 2017). Use of predators can also provide a certain level of control for the two-spotted spider mite as long as weather conditions are favorable for the predator (Attia et al., 2013). Insect pressure is also influenced by factors related to the cropping system. For example, populations of several insects such as the strawberry clipper weevil can increase with the age of the strawberry field (Duval, 2003). Harvest period is also important in regard to the presence of the spotted wing drosphila (SWD). In Quebec, the first SWD are captured around mid-July every year. In order to minimize yield losses, growers are told to apply insecticides every week from the first captures (Lacroix, 2016). Until now, very few damages have been observed on strawberries harvested before the end of July (Lacroix, 2016).



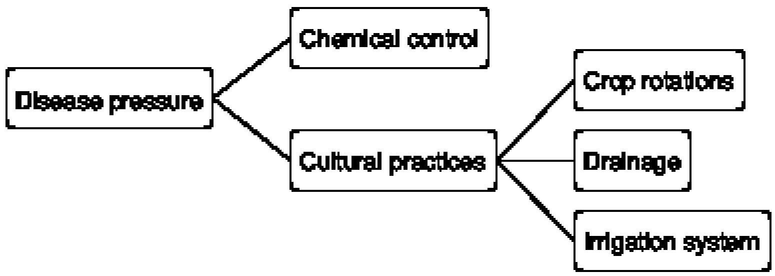
Control	
Better	In addition the reference scenario, biological control is used and a special care is made to use insecticides “compatible” with predators/parasitoids.
Similar	Insecticide are sprayed based on scouting results, which means that there is a minimum of one application for the tarnished plant bug, one for the strawberry clipper weevil and 1-2 for the cyclamen mite during the harvest years. Biological control is not used. Insecticides with different MOA are used.
Worst	No scouting, or no insecticide application. The MOA is not considered when selecting an insecticide.
Cultural practices	
Better	Annual crop of strawberry; only one year of harvest.
Similar	Strawberry fields are harvested during two years. The crop is harvested in the beginning of the summer (before the end of July).
Worst	The crop is harvested during more than two years. The crop is harvested after the end of July.

Basic criterion: *Disease pressure*

Parent criterion: Biotic risks

Description: This basic criterion describes the risk of yield losses due to the presence of diseases. Several diseases can cause of crop losses in strawberry production. Disease pressure depends on many factors such as the chemical control with fungicides, crop rotations, the drainage and the irrigation system. In order to minimize yield loss due to grey mold, it is generally recommended to apply fungicides during the flowering period (Tellier and Urbain, 2016). It is also recommended to use fungicides with different modes of action (MOA) during the season in order to avoid resistance development (INSPQ et al., 2017; Tellier and Urbain, 2016). Crop rotations of a minimum of three years without raspberries or plants from the Solanaceae family can contribute to avoid risk of several diseases such as *Verticilium dahliae* (Subbarao et al., 2007; Thireau and Lefebvre, 2014). Growing strawberry on raised beds in order to provide a good drainage is another way of reducing risks of diseases such as root rot and red stele (Duval, 2003; Lambert et al., 2007).

Finally, use of drip irrigation instead of overhead irrigation decreases the risk of grey mold and anthracnose (Bolda et al., 2017; Chandler et al., 2001).



Chemical control	
Better	Fungicide applications based on weather conditions, plant phenological stage, disease pressure of last years. Use of fungicides with different MOA.
Similar	Harvest years: fungicide applications from flowering until harvest every 7-14 days depending of weather conditions.Use of fungicides with different MOA.
Worst	The MOA is not considered when selecting a fungicide. No or almost no fungicide is used. Applications do not consider weather conditions.
Crop rotations	
Better	More than two years between two strawberry crops.
Similar	Three years of strawberry production followed by two years of another crop.
Worst	Less than two years in between strawberry crops.
Drainage	
Better	Excellent drainage.
Similar	Drainage generally good; or strawberry plants are planted on raised beds if the drainage was not good.
Worst	Poor drainage; strawberry plants are not planted on raised beds.
Irrigation system	
Similar	Drip irrigation
Worst	Overhead irrigation

Basic criterion: *Nutrient deficiencies*

Parent criterion: Abiotic risks

Description: This basic criterion describes the risk of nutrient deficiencies or surplus. Lack or surplus of one or several elements can have an impact on yield, but also on fruit size and firmness (Nestby et al., 2005). In order to maximize profitability, fertilizer applications should be done according to provincial recommendations and based on soil analyses (CRAAQ, 2010; Thireau and Lefebvre, 2014). Foliar analyses can also be part of a fertilization program (Thireau and Lefebvre, 2014).

Better	Fertilizers rates are based on soil analyses and follow the provincial recommendations. Application of fertilizers via drip irrigation. Foliar analyses.
Similar	Fertilizers rates are based on soil analyses and follow the provincial recommendations. For matted rows: Split applications of nitrogen (55, 35 and 35 kg N/ha), 30 to 275 kg P_2O_5/ha and 30 to 275 kg K_2O during the establishment year; then 40kg/ha N, P_2O_5 and K_2O after renovation (CRAAQ, 2010)
Worst	Only one application of fertilizer; fertilizer rates not based on soil analyses and provincial recommendations.

Basic criterion: *Lack or excess of water*

Parent criterion: Abiotic risks

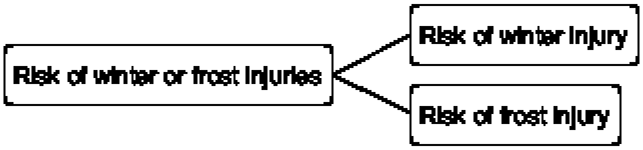
Description: This basic criterion describes the risk of yield losses due to inappropriate water management. Indeed, lack or excess of water can reduce the yield (Bergeron, 2010). This risk of yield loss is closely related to the use of an irrigation system and decision support tools such as tensiometers or water balances for managing irrigation (Bergeron, 2010).

Better	Drip irrigation or overhead irrigation systems is used. Irrigation is based on decision support tools such as a tensiometers, or water balance.
Similar	An irrigation system is used (generally drip irrigation), but no decision support tool is used.
Worst	No irrigation system is used.

Basic criterion: *Risk of winter or frost injuries*

Parent criterion: Abiotic risks

Description: This basic criterion describes the risk of yield losses due to winter or frost injuries. Winter injuries happen when ice crystals form in the cells of the crowns (OMAFRA, 2009). The plants can die, produce less fruits or be more susceptible to insects or diseases (OMAFRA, 2009). The risk of winter injury is increased if plants are situated on elevated hills or if too much nitrogen is applied in the fall (OMAFRA, 2009). Covering strawberry plants with enough straw or with winter row covers helps to reduce the risks of winter injuries (OMAFRA, 2009). Frost injuries occur when critical temperatures are reached during flowering in the spring. Flowers may freeze when temperatures reach -0.5 to -1.0 °C (Lacroix et al., 2013). The most common technique for preventing frost injuries is to use overhead irrigation for protecting flowers when temperature is closed to 0°C . Another method is to put back the straw on the plants (Lacroix at al., 2013). However, it is very time consuming and may be not feasible in many situations.



Risk of winter injury	
Better	Annual crop: strawberry plants are planted in the spring and harvested the same year. Strawberries are not planted on raised beds.
Similar	The reference scenario is a perennial crop where straw covers the plants during winter. Strawberry plants are planted on “raised” beds.
Worst	For perennial crops: not enough straw covers the plants during winter.
Risk of frost injury	
Better	Plants are not flowering early in the spring.
Similar	Perennial crop. Use of overhead irrigation in the spring if low temperatures are reached during flowering.
Worst	A system of overhead irrigation is not available for frost protection in the spring.

Basic criterion: *Dependence on pesticides*

Parent criterion: Autonomy

Description: This basic criterion describes the dependency of the cropping system towards pesticides. It can be assessed by considering the production value and the cost of pesticides (Vélu et al., 2016b). Both values used for the reference scenario come from the latest available economic references for the matted row system using June-bearing cultivars (CRAAQ, 2014a). This basic criterion is assessed by dividing the annual production value by the annual cost of pesticides. Then, the value obtained is classified into a category by the user.

Better	More than 51 $ of sales for 1$ of pesticides (41$ + 25%)
Similar	The production value is around 33 000$/ha/year and the cost of pesticides is around 800$/ha/year. (33 000$/800$= 41 $ of sales for 1$ of pesticides). Between 31$ and 51$ of sales for 1$ of pesticides.
Worst	Less than 31$ of sales for every 1$ of pesticides (41$-25%)

Basic criterion: *Dependence on workers*

Parent criterion: Autonomy

Description: This basic criterion describes the dependence of the cropping system on workers. It can be assessed by considering the production value and the number of hours worked by employees for the cropping system assessed (Vélu et al., 2016b). Both values used for the reference scenario come from the latest available economic references for the matted row system using June-bearing cultivars (CRAAQ, 2014a). This basic criterion is assessed by dividing the average annual production value of the cropping system by the average annual number of hours worked by employees.

Better	More than 41 $ of sales for 1 hour worked by an employee
Similar	The production value is around 33 000$/ha/year and the average annual number of hours worked by employees is around 1000 hours/ha. (33 000$ / 1000 hours /= 33$ of sales for 1 hour worked by an employee). Between 25$ and 41$ of sales for 1 hour worked by an employee.
Worst	Less than 25$ of sales for 1 hour worked by an employee

Basic criterion: *Need for equipment*

Parent criterion: Viability

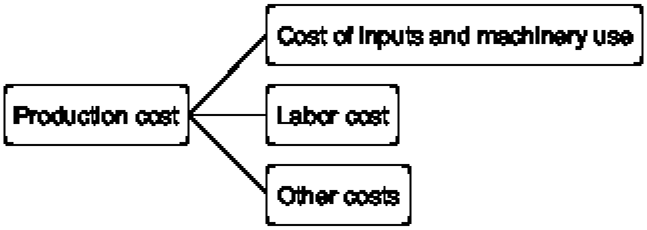
Description: This basic criterion describes the additional equipment required by the cropping system. High tunnels are an example of a specific equipment that is very expensive. Other examples could be row covers or the equipment required for plasticulture such as a mulch layer and a plastic mulch lifter.

Better	No row cover is used.
Similar	The reference scenario is a matted row system where row covers are used on a part of the field.
Worst	Equipment for plasticulture is needed. Crops grown under high tunnels or mini-tunnels.

Basic criterion: *Production cost*

Parent criterion: Profitability

Description: This basic criterion describes the production cost of the cropping system. The production cost was divided into three categories: the cost of inputs and machinery use, the labor cost and other costs including packaging. All values used for the reference scenario come from the latest available economic references for the matted row system using June-bearing cultivars (CRAAQ, 2014a). Only the hours worked by the employees were used for calculating the labor cost. A salary of 11.25$ per hour, the actual minimum wage in Quebec, was used for calculating the labor cost (CNESST, 2017).

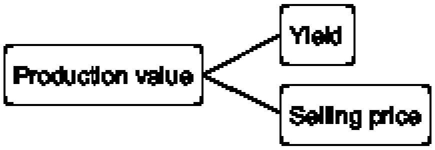


Cost of inputs and machinery use	
Better	Less than 4 150$/ha/year
Similar	Annual average cost of around 5150$/ha (4 600$ for inputs and 550$ for machinery use). Between 4 150$ and 6 150$/ha/year.
Worst	More than 6150$/ha/year
Labor cost	
Better	Less than 10 000$/ha/year
Similar	Annual average cost of around 11 025$/ha (980 hours x 11.25$/hour). Between 10 000$ and 12 000$ /ha/year.
Worst	More than 12 000$/ha/year
Other costs	
Better	Less than 4 150$/ha/year
Similar	Annual average cost of around 5 100$/ha. Between 4150$ and and 6 150$/ha/year.
Worst	More than 6 150$/ha/year

Basic criterion: *Production value*

Parent criterion: Profitability

Description: This basic criterion describes the production value which depends on the yield and the selling price. The criterion is assessed by considering a standard yield for the cropping system and the selling price, which depends mostly on the place where strawberries are sold: pick-your-own, farmers' markets, wholesale markets or transformation. Values for the yields and selling prices of the reference scenario come from the latest available economic references for the matted row system using June-bearing cultivars (CRAAQ, 2014a). The selling prices used were 3.64$/kg for pick-your-own, 6.17$/kg for farmers' markets, 3,97$/kg for wholesale markets, and 1.32$/kg for transformation (CRAAQ, 2014a).



Yield	
Better	Annual average yield of less than 6 100 kg/ha
Similar	In the reference scenario, 12 000 kg/ha of strawberries are harvested during the first year, and 11 000 kg/ha during the second year, which results in an annual average yield of around 7 650kg/ha when the establishment year is considered.
Worst	Annual average yield of more than 9200 kg/ha
Selling price	
Better	More than 25-30% of the production is sold through farmers' markets.
Similar to reference scenario	In the reference scenario, around 20% of the production is sold through pick-your-own, around 25% through farmers' markets, around 52% on wholesale markets, and 3% for transformation.
Worst	Less than 20-25% of the production is sold through farmers' markets.

ENVIRONMENTAL SUSTAINABILITY

Basic criterion: *Impact on flora diversity*

Parent criterion: Impact on biodiversity

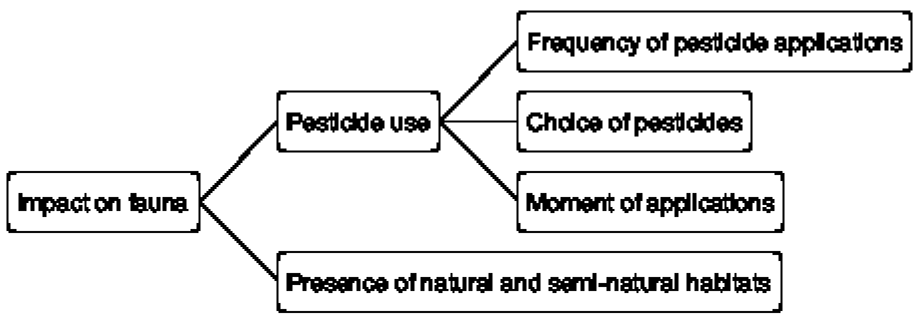
Description: This basic criterion describes the impact of the cropping system on flora. This impact can be assessed by looking at the presence of natural and semi-natural habitats at the farm scale. In a recent study, (Billeter et al., 2008) showed that the number of vascular plant species was positvely correlated with the area of semi-natural habitat in their study sites.

Better	Presence of an important proportion of natural or semi-natural habitats.
Similar	Presence of natural or semi-natural habitats at the farm scale.
Worst	No natural or semi-natural habitat.

Basic criterion: *Impact on fauna diversity*

Parent criterion: Impact on biodiversity

Description: This basic criterion describes the impact of the cropping system on fauna diversity. Fauna diversity refers to the presence and diversity of animals such as birds, small mammals, aquatic fauna and insects such as pollinators and predators. In a recent study, (Billeter et al., 2008) showed that the number of birds and arthropods species was positively correlated with the area of semi-natural habitats. Natural or semi-natural area are also known to provide habitat for many pollinators (Nicholls and Altieri, 2013; Potts et al., 2010). Pollinators can also be affected by pesticide use: the frequency of the applications, the application moments and the toxicity of the products. The more frequent are pesticide applications, the higher is the risk for pollinators. Pesticides have different levels of toxicity for pollinators (Nicholls and Altieri, 2013; Potts et al., 2010). The moment of application is also important. Indeed, insecticides can cause bee mortality by direct intoxication (Potts et al., 2010). They should not be sprayed during the day when pollinators are in the field, as specified on product labels.

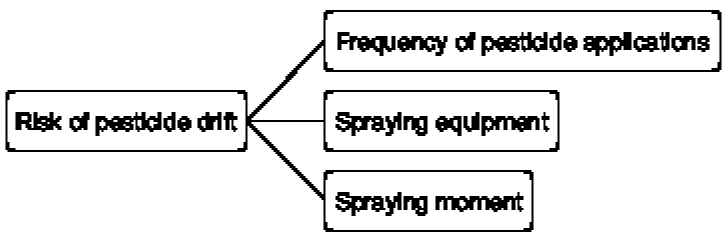


Frequency of pesticide applications (previously described)	
Choice of pesticides	
Better	Toxicity for pollinators is considered when choosing a pesticide.
Similar	Toxicity for pollinators is not considered when choosing a pesticide.
Worst	Toxicity for pollinators is not considered when choosing a pesticide; several pesticides used are very toxic for pollinators.
Moment of applications	
Better	Pesticides are not sprayed during the day when pollinators are in the field. No pesticide is applied during the flowering period.
Similar	Pesticides are not sprayed during the day when pollinators are in the field. However, pesticides are applied during the flowering period.
Worst	Pesticides are applied during the day when pollinators are in the field.
Presence of natural and semi-natural habitats (previously described)	

Basic criterion: *Risk of pesticide drift*

Parent criterion: Impact on air quality

Description: This basic criterion describes the risk of pesticide drift. Pesticide drift is the transport of pesticide droplets or particles of the treated field by climatic conditions such as the wind or an airstream (Holvoet et al., 2007). The risk of pesticide drift is influenced by the frequency of pesticide applications, the use of drift-reducing equipment and the weather conditions prevailing during pesticide applications (Gil and Sinfort, 2005; Piché, 2008). In order to reduce risk of pesticide drift, spraying equipement should be adapted to the crop and well adjusted. Use of drift-reducing equipment such as low-drift nozzles and shielded sprayers also decreases risk of drift (Piché, 2008). The optimal wind speed for spraying pesticides is between 7 and 13 km/h at 10 meters above ground. When wind speed is over 13 km/h, herbicides should not be sprayed, and over 20 km/h, insecticides ans fungicides should not be sprayed (Piché, 2008).

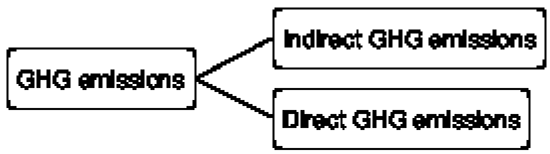


Frequency of pesticide applications (previously described)	
Spraying equipment	
Better	Drift reduction technologies such as nozzles or spray shields are used. Spraying equipement is adjusted regularly during the season.
Similar	Drift reduction technologies are not used. Spraying equipement is adjusted once at the beginning of the season.
Worst	Drift reduction technologies are not used. Spraying equipement is rarely or never adjusted.
Spraying moment	
Better	No pesticide is applied when wind speed is over 13 km/h or when there is no wind.
Similar	No pesticide is applied when wind speed is over 20 km/h or when there is no wind.
Worst	Pesticides are applied without considering wind speed.

Basic criterion: *Direct and indirect GHG emissions*

Parent criterion: Impact on air quality

Description: This basic criterion describes direct and indirect greenhouse gas emissions related to a cropping system. In a life cycle assessessment of the strawberry production in USA, (Tabatabaie and Murthy, 2016) calculated that materials are the main element contributing to global warming potential. Materials includes plastic mulch, drip tubes, floating row covers and packaging baskets. They are made with polyethylene and/or polyethylene terephthalate (PETE), for which the production requires a lot of energy (Tabatabaie and Murthy, 2016). The second element contributing to greenhouse gas emissions is the production and use of fuels for machines. According to the latest available economic references for the matted row system in Quebec, the cost of fuels for irrigation is around 60% of the total cost of fuels for cultural operations (CRAAQ, 2014a). Cost associated with planting (9%), pesticide spraying (7%), straw manipulations (7%) and mechanical weeding (4%) are low compared to irrigation costs (CRAAQ, 2014a).



Indirect GHG emissions	
Better	One of the situations: No floating row cover is used; less packaging baskets are used (more sells via pick-your-own); no drip tubes are used.
Similar	In the reference scenario, no plastic mulch is used. However, drip tubes, floating row covers and packaging baskets are used.
Worst	One of the situations: Plastic mulch is used; the crop is under a high tunnel.
Direct GHG emissions	
Better	No irrigation.
Similar	The crop is irrigated with drip irrigation. Average annual cost of irrigation is around 330$ (CRAAQ, 2014a).
Worst	Excessive irrigation.

Basic criterion: *Organic matter and biological activity*

Parent criterion: Impact on soils

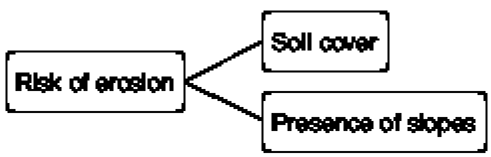
Description: This basic criterion describes the organic matter (OM) content and the biological activity of a soil. The addition of organic inputs such as green manure and animal manure and use of cover crops contribute to increase the organic matter content of soil (Matson et al., 1997). The effect of pesticides on soil micro-organisms seems to be still poorly understood (Imfeld and Vuilleumier, 2012). Thus, it will not be considered for the assessment of this basic criterion.

Better	Both animal manure (not during harvest years) and green manure are used.
Similar	Either green manure is grown or animal manure is added for other crops of the rotation.
Worst	No animal manure nor green manure is used.

Basic criterion: *Risk of erosion*

Parent criterion: Impact on soils

Description: This basic criterion describes the risk of erosion. Risk of erosion is a function of many factors such as climate, soil properties, topography, soil surface conditions and human activities (Renard et al., 1997). Erosion can be predicted in a quantitative way by using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). However, as part of this tool, only soil cover and presence of slopes will be considered for assessing the erosion risk. In Quebec, erosion and runoff occurs mostly in the end of the winter and in the beginning of the spring when the snow is melting (CRAAQ, 2010). Thus, maintaining the soil covered during this period of year has an important impact on erosion and runoff risks (CRAAQ, 2010). As fall plow and early spring plow leave the soil uncovered, they increase the erosion risk (Renard et al., 1997). The presence of long and steep slopes close to watercourses also increases the erosion risk (CRAAQ, 2010).

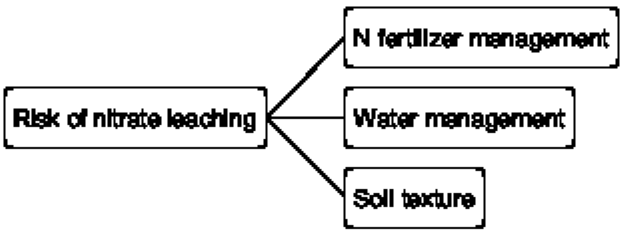


Soil cover	
Better	The plants are kept during more than three years, and the field is plowed in the fall only once every four years or more. Between growing seasons, strawberry plants are in the field, covered with straw and there is straw between rows.
Similar	Strawberry plants are kept during three years, and the field is plowed in the fall only once every three years. Between growing seasons, strawberry plants are in the field, covered with straw and there is straw between rows.
Worst	Fall plow every year; no or little vegetative cover of plants between growing seasons.
Presence of slopes	
Similar	In the reference scenario, no long and steep slope is present close to watercourses.
Worst	Presence of steep slopes close to watercourses.

Basic criterion: *Risk of nitrate leaching*

Parent criterion: Impact on water quality

Description: This basic criterion describes the risk of nitrate leaching. Nitrate leaching is influenced by N fertilizer management (N rates and split applications), water management and soil texture. In a meta-analysis assessing the efficiency of different strategies for reducing nitrate leaching, Quemada et al. (2013) found that improving water management had the biggest impact on nitrate leaching reduction, followed by improving fertilizer management, use of cover crops, and use of improved fertilizer technologies. For improving water management, water applications need to be based on crop needs (Quemada et al., 2013). Improving fertilizer management can be done by using N fertilizer rates corresponding to the crop needs (Di and Cameron, 2002) and by optimizing the timing of nitrogen applications. However, in the meta-analysis by (Quemada et al., 2013), fertigation did not reduce nitrate leaching significantly. Finally, N leaching is usually more important in sandy soils compared to fine-textured soils (Di and Cameron, 2002).

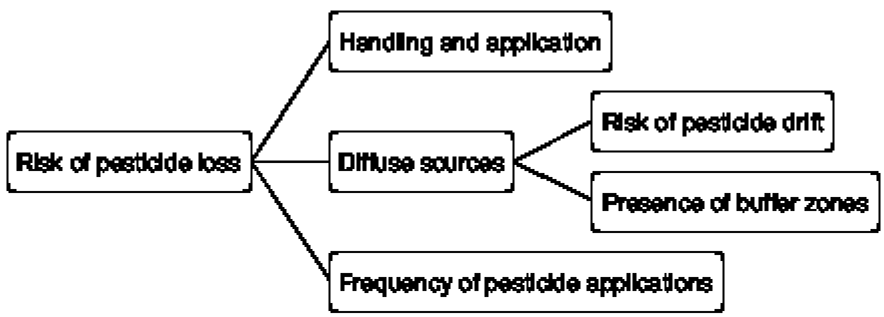


Nitrogen fertilizer management	
Better	N fertilizer rates are lower than the provincial recommendations; split applications.
Similar	N fertilizer rates are based on soil analyses and follow the provincial recommendations. For strawberries planted in matted rows: Split applications of nitrogen (55, 35 and 35 kg N/ha) during the establishment year, then 40kg/ha N after renovation (CRAAQ, 2010)
Worst	N fertilizer rates are higher than the provincial recommendations; No split applications.
Water management	
Better	Irrigation is based on decision support tools such as a tensiometers or water balance.
Similar	Irrigation is not based on decision support tools such as a tensiometers, or water balance.
Worst	Irrigation is not based on decision support tools such as a tensiometers, or water balance. Long irrigation periods.
Soil texture	
Similar	Non-sandy soil
Worst	Sandy soil

Basic criterion: *Risk of pesticide loss*

Parent criterion: Impact on water quality

Description: This basic criterion describes the risk of pesticide loss into surface water and ground water. Pesticide can reach watercourses either by drift at application, leaching and runoff and erosion (Reichenberger et al., 2007). Risk of pesticide loss is influenced by different factors such as the frequency of pesticide applications, pesticide handling and application, compliance of buffer zones for pesticide applications, and risk of pesticide drift. Holvoet et al. (2007) report several studies where the presence of pesticides in rivers was attributed for 20 to 80% to point sources contamination, such as loss during filling and cleaning the spraying equipment. The following “best management practices” can decrease pesticide lossess: cleaning sprayers in the field, careful handling and storage of pesticides, and applying diluted leftovers on the field (Reichenberger et al., 2007). Holvoet et al. (2007) pointed out several solutions for reducing diffuse sources of contamination: the reduction of pesticide use and the implementation of measures for reducing runoff, erosion and pesticide drift. The assessment of the efficiency of edge-of-fields and riparian buffers for reducing pesticide loss into waterbodies have been the object of many studies (Reichenberger et al., 2007). Although their level of efficieny was variable (Reichenberger et al., 2007), the respect of buffer zones during pesticide applications avoids applications directly in the stream.

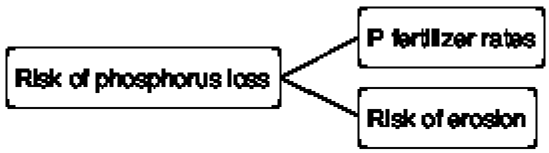


Handling and application	
Better	Pesticide handling and application are always done according to the “best management practices”.
Similar	Pesticide handling and application are generally done according to the “best management practices”.
Worst	Pesticide handling and application are rarely done according to the “best management practices”.
Risk of pesticide drift (previously described)	
Presence of buffer zones	
Better	Buffer zones are always respected during pesticide applications.
Similar	Buffer zones (as specified on product lables) are not always respected during pesticide applications.
Worst	Buffer zones are rarely respected during pesticide applications.
Frequency of pesticide applications (previously described)	

Basic criterion: *Risk of phosphorus loss*

Parent criterion: Impact on water quality

Description: This basic criterion describes the risk of phosphorus loss into watercourses. Risk of phosphorus loss into surface water depends on the source of phosphorus and of its transport (Sharpley et al., 2001). The P fertilizer rates can be considered to be an indicator for the source, wheras the runoff/erosion risk can be an indicator of the transport (CRAAQ, 2010).

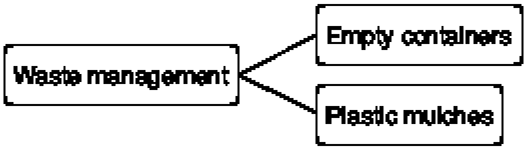


P fertilizer rates	
Better	Less than the recommended rates.
Similar	Based on soil analysis. Provincial recommendation: 30 to 275 kg P_2O_5/ha during the establishment year; then 40kg/ha P_2O_5 after renovation (CRAAQ, 2010).
Worst	More than the recommended rates.
Risk of erosion (previously described)	

Basic criterion: *Waste management*

Parent criterion: Use of resources

Description: This basic criterion describes the wastes caused by a cropping system and their disposal. Main wastes come from empty containers of pesticides and fertilizers and plastic mulches. In the province of Quebec, the AgriRÉCUP program allows growers to bring their empty containers of pesticides and fertilizers to specific locations. Containers are then recycled into other material such as agricultural drains (AgriRÉCUP, 2017). Use of plastic mulches is problematic from an environmental point of view (Kasirajan and Ngouajio, 2012), partly because there is no existing program in the province of Quebec for recycling them. Use of plastic mulches results in important wastes every year and use of biodegradable plastic mulches is a more sustainable alternative.

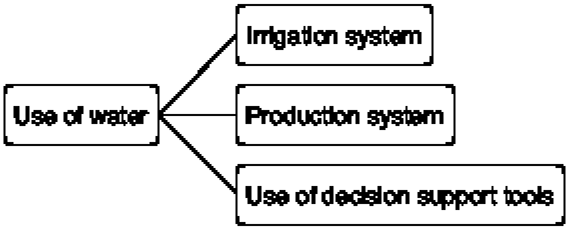


Empty containers	
Better	Disposal of all the empty containers of pesticides and fertilizers via the AgriRÉCUP program.
Similar	Disposal of most of the empty containers of pesticides and fertilizers via the AgriRÉCUP program.
Worst	Empty containers of pesticides and fertilizers generally end up in the garbage.
Use of plastic mulches and drip irrigation system	
Better	No plastic mulch and no drip irrigation system is used.
Similar	In the reference scenario, no plastic mulch is used, but there is a drip irrigation system. However, the use of biodegradable plastic mulch could be considered similar to the reference scenario.
Worst	Non biodegradable plastic mulch is used.

Basic criterion: *Use of water*

Parent criterion: Use of resources

Description: This basic criterion describes the use of water by the cropping system. Water use is hard to assess because it is variable from one year to another depending of weather conditions. However, it is influenced by the production system, the irrigation system, and use of decision support systems. The production system influences water use. Indeed, water requirements are higher under tunnels than in open fields because rainfall do not reach the crop situated under a tunnel. Moreover, perennial cropping systems where plants are flowering early in the spring may require use of overhead irrigation for frost protection (Thireau and Lefebvre, 2014). Regarding the irrigation system, drip irrigation is more efficient than overhead irrigation. Efficiency of drip irrigation is around 90-95% whereas it is around 60-75% for overhead irrigation in a field without plastic mulch (King and Stark, 1997). Use of decision support (DS) tools also influences water use. DS tools are either based on potential evapotranspiration or on soil moisture measurements (Bergeron, 2010). Decision support tools help to determine water need of the crop (Anderson, 2016) and hence, generally improve water use efficiency.



Irrigation system	
Better	No irrigation system.
Similar	Drip irrigation during season.
Worst	Overhead irrigation during season.
Production system	
Better	Crop in open field. No overhead irrigation for frost protection in the spring.
Similar	Matted row system in open field. Overhead irrigation for frost protection in the spring if needed.
Worst	Crop grown under a tunnel.
Use of decision support tools	
Better	Decision support tools (tensiometers or potential evapotranspiration) are used for managing irrigation.
Similar	Decision support tools are rarely used for managing irrigation.
Worst	Decision support tools are never used for managing irrigation.

Appendix 4: Description of the plasticulture system.

Production system	Plasticulture. Day-neutral cultivar planted in open fields.
Crop duration and harvest period	Annual crop. Harvest from mid-July to first frost (about 10-12 weeks).
Planting	Mechanical planting on raised beds covered by plastic mulch at high densities (46 000 plants/ha) (CRAAQ, 2014b).
Type of plants and cultivars	Day-neutral cultivar Seascape. “Frigo” plants.
Cultivar selection	Based on yield and fruit quality (flavor).
Mulching	Alley between rows is mulched with steam-sterilized straw.
Specific operations	Runner removal at least once during the season.
Irrigation	Drip irrigation. Decision support tools such as tensiometers are used to manage irrigation.
Fertility practices	Pre-plant: broadcast application of granular fertilizer (50 kg N/ha, P_2O_5 and K_2O rates based on soil analysis). During season: fertigation (about 70 kg N/ha and 60 kg K_2O/ha in total) (Landry and Boivin, 2014).
Yields	18 000 kg/ha (CRAAQ, 2014b)
Markets	Farmers’ market (20%), wholesale market (80%) (CRAAQ, 2014b)
Economics	Latest available economic references for the plasticulture system (CRAAQ, 2014b)
Pesticide applications	Sprayer is generally calibrated once at the beginning of the season. Pesticides are not sprayed during the day when pollinators are in the field, but are sprayed during flowering. No pesticide is applied during windy conditions or when there is no wind. Buffer zones are not always respected. Equipment to reduce drift are not used.
Personal protective equipment	Adequate personal protective equipment is used for pesticide applications.
Pre-harvest and restricted entry intervals	Pre-harvest and restricted entry interval are followed.
Pesticide selection	Based on cost, efficiency and resistance risk (except for herbicides).
Fumigation	Fumigation with chloropicrin before making beds.
Weed control	Preplant herbicide between rows once beds are made. Then, sometimes a second application, based on weed pressure.
Insect control	Based on scouting results. About 2-3 applications for tarnished plant bugs. About 2 applications for two-spotted spider mites. For spotted-wing drosophila: applications every week from around mid August.
Disease control	Beginning of fungicide applications at disease onset (powdery mildew, anthracnose), then applications every 7-14 days depending of weather conditions.
Biological control	No.
Crop destruction	Plants are mowed, plastic is removed and the field is mowed.