Agriculture and Agri-Food Canada
Agriculture et Agroalimentaire Canada

CLIMATE CHANGE **IMPACTS** ON PESTICIDE CONTAMINATION OF SURFACE RUNOFF

CASE STUDY OF EIGHT CROP/PEST COMBINATIONS FOR THE PERIOD ***1981-2040***

Canada

Climate Change Impacts on Pesticide Contamination of Surface Runoff -
Case Study of Eight Crop/Pest Combinations for the Period 1981-2040.

AAFC No. 12493E
ISBN No. 978-0-660-04982-3
Catalogue No. A59-40/2016E-PDF

Paru également en français sous le titre *Impact des changements climatiques sur la contamination de l'eau de ruissellement par les pesticides : étude de cas pour huit combinaisons cultures ennemis durant la période 1981-2040.*

For more information, reach us at www.agr.gc.ca or call us toll-free 1-855-773-0241.

Climate Change Impacts on Pesticide Contamination of Surface Runoff

Case Study of Eight Crop/Pest Combinations for the Period 1981-2040

Authors: Patrick Gagnon, AAFC[1]
Claudia Sheedy, AAFC[1]
Alain N. Rousseau, INRS-ETE[2]
Gaétan Bourgeois, AAFC[1]
Gérald Chouinard, IRDA[3]
Pierre Lafrance, INRS-ETE[2]

Contributors: René Audet, AAFC[1]
Blaise Gauvin St-Denis, Ouranos
Anne Blondlot, Ouranos
Danielle Bernier, MAPAQ[4]
Pierre-Antoine Thériault, MAPAQ[4]
Marie-Hélène April, MAPAQ[4]
Isabelle Giroux, MDDELCC[5]
Jean-Thomas Denault, MDDELCC[5]
Julie Corriveau, MDDELCC[5]

December 2015

[1] Agriculture and Agri-Food Canada
[2] Institut national de la recherche scientifique, Centre Eau Terre Environnement (Université du Québec)
[3] Institut de recherche et de développement en agroenvironnement
[4] Quebec Department of Agriculture, Fisheries and Food
[5] Quebec Department of Sustainable Development, Environment and the Fight Against Climate Change

Abstract

Climate change can have various effects on agriculture, both positive and negative. It could result in increased agricultural yields and in the growing of certain crops in new regions. However, it could also lead to more droughts, and therefore increased crop stress. Climate change could also cause an increase in pesticide use, potentially due to poleward migration of new weed species, insect pests and diseases, and to the increased occurrence and abundance of already problematic species. With the likely increase in the frequency and intensity of rain events in several parts of Canada, it appears that pesticide losses in surface runoff could increase and could potentially pose a risk to water quality.

The purpose of this project is to assess the impact of climate change on the contamination of water by agricultural pesticides for the period 1981-2040 for the following crops and pests: weeds in corn (*Zea mays*), soybean (*Glycine max*) and wheat (*Triticum aestivum*), and three insects (plum curculio (*Conotrachelus nenuphar*), apple maggot (*Rhagoletis pomonella*) and codling moth (*Cydia pomonella*)) and two diseases (fire blight (*Erwinia amylovora*) and apple scab (*Venturia inaequalis*)) in apple (*Malus pumila*). Data from 23 climate simulations were used on 28 sites in Quebec (fields or orchards), and the impact of climate on crops and their pests was assessed using bioclimatic models of the Computer Centre for Agricultural Pest Forecasting (CIPRA) software developed by Agriculture and Agri-Food Canada (AAFC). A total of 21 active ingredients were examined. Pesticide transport in soil and surface runoff was simulated using the Pesticide Root Zone Model (PRZM), version 3.12.3. A stochastic approach was used to take account of the uncertainty associated with the parameters of the transport model. The assessment was performed for certain pests only, since interactions with climate and crops are specific to each pest. To our knowledge, this project is the first Canadian case study to assess the impact of climate change on both pesticide application and pesticide losses in surface runoff. The method developed takes account of all sources of uncertainty and can be adapted to other crops and pests. This project is part of a broader objective to ensure the environmental sustainability of agricultural activities.

The results showed that climate change had a significant impact on pesticide application dates, which would be advanced an average of approximately three days for early-season pesticide applications and approximately eight days for applications later in the season in the periods 1981-2010 and 2011-2040. However, the impact of climate change on pesticide losses in surface runoff is less clear. The largest increase in losses was simulated for active ingredients used for the control of apple scab (average of 10% over a 30-year period), but this increase is not statistically significant. The main reason for this small impact is the uncertainty associated with changes in intense rainfall events. The

results showed that the bulk of the total pesticide load transported over 60 years resulted from only a few intense rainfall events that had occurred shortly after application. Natural variability in maximum daily rainfall during the pesticide application window is large. Although most of the climate simulations used show an upward trend in maximum daily rainfall during the application window, there is a considerable number of downward trends, and a small proportion of the upward trends is statistically significant.

Although the results obtained are specific to the crops, pests, regions and period (1981-2040) studied, a number of general conclusions can be drawn from the project. The results confirm that rainfall intensity following a pesticide application and the interval between a pesticide application and a rainfall event have a major impact on the extent of pesticide losses in surface runoff. This is the case at all sites and for all crop/pest combinations studied. The interval between application and rainfall is particularly important for active ingredients that degrade quickly. The availability of decision support tools for producers, such as weather forecasting models coupled with bioclimatic models, may be a good way to limit losses. Where possible, preference should be given to the use of less persistent, less mobile, less toxic active ingredients that can be incorporated directly into the soil. The use of management practices that reduce surface runoff and erosion should also be considered. However, although practices such as reduced tillage and no till can reduce runoff, they do not necessarily have any benefits in terms of pesticide losses, as they require a larger number of pesticide applications. In fact, the impact of these measures could vary from field to field. More detailed field studies should be done to obtain a better assessment of the impact of such practices.

The above observations are valid, regardless of whether or not they are made in the context of climate change. The implementation of the suggested measures depends on the tools available to producers (e.g., active ingredients, predictive models, resource persons) and on whether the tools are economically viable for producers.

Table of contents

List of figures

List of tables

1 Background

Decisions associated with agricultural practices are heavily based on climate conditions, local and international market demand (i.e., the economy), government policies and programs. These considerations affect the choice of cultivars, planting and harvesting dates and determine the presence or absence of certain crop pests, which guides the need for pesticide applications.

There is now consensus in the scientific community that humans have had a major impact on the recent increases in temperature, which is caused by an increase in greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change – IPCC, 2013). With respect to future conditions, although it is already accepted that the average global temperature will continue to rise even under optimistic scenarios (IPCC, 2013), it is difficult to determine the impact of climate change, since it depends on the policy and economic decisions that are made in the coming years, which may vary from region to region.

In light of the changing climate, agricultural practices may have to be adapted. Otherwise, their sustainability could be compromised. Climate change can have various effects on agricultural practices. While higher temperatures should produce better growing conditions in temperate regions, resulting in increased productivity for current crops and possibly the introduction of new crops, they could also benefit crop pests (Hakala et al., 2011). The current report focuses on the prediction of climate change impacts on pesticide contamination of runoff water. The contamination of runoff water depends on: (i) pesticide use (choice of product, quantity, application frequency) and (ii) pesticide transport and fate in plant cover, soil and water. These two factors are heavily dependent on climate, but also on the interval between pesticide applications and rainfall, the leaf area index of plant cover, soil properties, the slope of the land and the mobility and persistence of the pesticide. These factors involve many physical, chemical and biological processes with sometimes complex interactions. This means that the assessment of climate change impacts on pesticide contamination of runoff water requires the development of a robust method that takes various sources of uncertainty into account.

The scientific literature contains very few studies that address both climate change impacts on crop pests and on the transport of pesticides to surface waters (e.g., Koleva and Schneider, 2010; Kattwinkel *et al*., 2011). To our knowledge, no case studies have been carried out in Quebec or elsewhere in Canada.

2 Objectives

The general objective of the project is to predict the impact of climate change on changes in pesticide contamination of surface runoff for the period 1981-2040, for the following crops and pests:

- Grain corn or silage corn (*Zea mays*), soybean (*Glycine max*) and wheat (*Triticum aestivum*): weeds;

- Apple (*Malus pumila*): three insects (plum curculio (*Conotrachelus nenuphar*), apple maggot (*Rhagoletis pomonella*), codling moth (*Cydia pomonella*)) and two diseases (fire blight (*Erwinia amylovora*), apple scab (*Venturia inaequalis*)).

The project has three specific objectives:

(i) Develop a method for integrating interactions between climate, crop and pest phenology, pesticide applications and chemical and physical processes associated with the transport and fate of pesticides in runoff, as well as the various sources of uncertainty associated with each of these components.

(ii) Objectively (statistically) estimate the impact of climate change on variations in pesticide contamination of surface runoff for the period 1981-2040, for crop-pest combinations selected at the field or orchard scale.

(iii) Objectively estimate the impact of adaptation measures aimed at mitigating pesticide contamination of surface runoff.

In broader terms, the purpose of this project is to contribute to ensuring the sustainability of agricultural activities.

The study focuses on just a few crops and pests, since each pest behaves differently relative to its host and to climate variations (Bloomfield et al., 2006). The crops and pests chosen are all currently found in Quebec agriculture, and their phenology is modelled by the Computer Centre for Agricultural Pest Forecasting (CIPRA) bioclimatic model (Plouffe et al., 2014), developed by Agriculture and Agri-Food Canada (AAFC). The method developed as part of the study can be used for other pests and crops.

The predictive assessment of surface runoff contamination was conducted using the Pesticide Root Zone Model (PRZM) (Suarez, 2005), taking into consideration dissolved pesticides (directly in runoff) and adsorbed pesticides (on soil eroded by water). Previous efforts to simulate pesticide transport or to perform *in situ* quantification in agricultural fields have shown that groundwater contamination was negligible compared with surface water contamination (Lafrance et al., 1997; Cessna et al., 2010; Gagnon et al., 2014). In theory, significant groundwater contamination could occur if preferential flow existed (Bloomfield et al., 2006). This type of flow is not included in all hydrologic models. It has been shown, however, that preferential flow could play a role in contaminant transport to subsurface drains (Poirier et al., 2012) and that its impact could be modified in a context of climate change (Bloomfield et al., 2006). That being said, groundwater contamination was not examined in this project.

A stochastic approach was used to estimate the parameters of the PRZM model in order to account for the main sources of uncertainty. Given the uncertainty regarding changes in certain agricultural practices, specifically crop choice, cultivated areas, tillage and available active ingredients, changes in contamination beyond 2040 were not analyzed.

The results obtained in this project represent *in situ* contamination (in the field) and not river contamination or watershed-scale contamination. These local estimates are important for assessing the impact on headwaters (Luo et al., 2011). All agricultural sites under study are located in Quebec, since the climate data available for the period analyzed (1981-2040) covered Quebec only.

3 Literature review

This literature review focuses on the impact of climate change on pesticide contamination of surface runoff. The impact of climate changes is presented in two parts: the impact on the crop pests considered, which will have a direct effect on changes in pesticide applications; and the impact on pesticide transport in surface runoff.

3.1 Impact of climate change on crop pests

Although the prevalence of most weeds, pests and diseases is expected to increase (Bloomfield et al., 2006; Hakala et al., 2011), the assessment of climate change impacts must be carried out for each specific crop pest. This assessment is difficult to conduct, particularly because pest-crop interactions are complex and it is difficult to determine how they will actually be influenced by climate change.

3.1.1 Weeds

The impact of climate change on weeds can be positive or negative, depending on the type of weed species (C_3 or C_4) and the weed-crop interaction (Stratonovitch et al., 2012). Invasive species that are tolerant of high temperatures may become even more harmful in the future (Tungate et al., 2007). A number of these species, which currently occur only in the warmest regions of North America, could migrate northward (Wolfe et al., 2008). In addition to increasing temperatures, climate change will have an impact on other variables that may have a determining effect on weed and crop growth. For example, increased hydric stress situations could reduce the presence of weeds, particularly C_3 type (Stratonovitch et al., 2012). In addition, increased atmospheric CO_2 concentrations will enhance the growth of C_3 crops (e.g., wheat, soybean), but also of C_3 weeds. Due to their genetic diversity, weeds could benefit more than crops from increasing atmospheric CO_2 (Wolfe et al., 2008). That being said, the net effect of increasing CO_2 on yields depends on the weed-crop interaction and on future projections. For example, Stratonovitch et al. (2012) have shown that winter wheat benefited more than the weed species *Alopecurus myosuroides* according to projections of increasing temperature and CO_2 levels for the United Kingdom. Ziska (2010, 2013) has shown that soybean seed yield without weeds at ambient CO_2 concentrations was comparable to the yield of soybean in competition with *Cirsium arvense* (Ziska, 2010) and *Abutilon theophrasti* (Ziska, 2013) at CO_2 concentrations of 300 and 250 parts per million (ppm) above ambient conditions, respectively. However, CO_2 concentration has no observable impact on soybean flowering date (Ziska, 2010, 2013). A C_4 crop, such as corn, should benefit from increased temperatures, but not significantly from elevated atmospheric CO_2 (Bootsma et al., 2005). The competitive ability of corn as compared to C_3 weeds should therefore decline (Diós et al., 2010).

Increased atmospheric CO_2 concentrations can lead to a loss of efficacy of glyphosate (*N-(phosphonomethyl)glycine*), a widely used non-selective herbicide applied primarily preplant to reduced-tillage fields or to transgenic crops that are tolerant to it (Bloomfield et al., 2006; Wolfe et al., 2008; Ziska, 2010). However, it is difficult to assess whether it will be necessary, in practice, to increase the number of herbicide applications to protect crop yields without a more comprehensive analysis incorporating field conditions, i.e., taking into account several weed species simultaneously, with different atmospheric CO_2 concentrations and humidity rates (Ziska, 2013).

3.1.2 Insect pests

Insect pests are poikilothermic, which means their distribution, population density and number of generations per season is directly dependent on temperature (Rafoss and Saethre, 2003; Bloomfield et al., 2006; Hirschi et al., 2012; Gagnon et al., 2013). An increase in temperature should therefore increase the threat to crops. It should be noted, however, that this threat depends on synchronization between crop growth and pest development (Rafoss and Saethre, 2003; Luedeling et al., 2011; Gagnon et al., 2013). The impact of atmospheric CO_2 concentrations and UV-B radiation on insect pests is considered negligible compared to the impact of temperature (Luedeling et al., 2011).

With respect to the three insect species considered in this project, the studies presented in the scientific literature dealing with the impact of climate change focus primarily on the codling moth. On the basis of climate projections for the period 2045-2074, Hirschi et al. (2012) estimate that the development of a third generation will become normal for this species in some parts of Switzerland, where the current norm is two generations. Flight start would occur approximately two weeks earlier and subsequent development phases would advance by approximately three weeks (Hirschi et al., 2012). Luedeling et al. (2011) also obtain an increase of one generation from 1950 to 2070 based on the analysis of various weather scenarios in California. Analyses conducted on the basis of two weather simulations using the optimistic GHG emissions scenario A1B (Nakicenovic and Swart, 2000) show that a third generation could appear in Poland, where there are currently only two (Juszczak et al., 2013). The increase in the number of generations could be even higher if diapause, which depends on the number of hours of sunlight, but also on temperature (Stoeckli et al., 2012), occurs later. Although increased temperatures would be beneficial to codling moth development, it could also cause an increase in summer mortality. However, the possibility that codling moth could adapt to much higher temperatures has not been ruled out (Rafoss and Saethre, 2003; Hirschi et al., 2012). Chidawanyika and Terblanche (2011) have shown that the survival rate of this insect increased if the rise in temperature towards a short-duration lethal temperature occurred more gradually.

3.1.3 Diseases

As is the case for weeds, the impact of climate change should vary from one disease to another (Jones and Barbetti, 2012). Generally speaking, increased CO_2 is likely to be favourable to the development of pathogens (Gagnon et al., 2013). Infection prediction models taking into account temperature and duration of leaf wetness are a valuable tool for assessing the impact of climate change on diseases (Bourgeois et al., 2004).

To estimate the impact of climate change on apple scab, Bourgeois et al. (2004) used the output of five global climate models. The climate data were corrected for biases using observed data from an experimental site at Saint-Jean-sur-Richelieu (Quebec), converted to an hourly time step. The data were then used as inputs for bioclimatic simulations with CIPRA. Comparisons between several future horizons and the reference period (1961-1990) show that the first infections should occur earlier and that the last infections should occur at roughly the same time as is currently the case. The result is a moderate increase in the number of infections in the future. Although not addressed in their study, Bourgeois et al. (2004) mention that the characterization of the increase in winter temperature is essential for quantifying the impact of climate change on crops and crop pests.

With respect to fire blight, Hirschi et al. (2012) used climate projection data for the period 2045-2074 as inputs to the Maryblyt bioclimatic forecasting model (Steiner, 1990; Steiner and Lightner, 1996; Duffy et al., 2008). Whereas increased temperature gave an increase in the number of generations for codling moth, the signal is not as clear for fire blight. In fact, given that the infection period will occur earlier in the spring in the future, the temperature during the infection period remains more or less the same as in the past. In addition, the duration of leaf wetness, estimated on the basis of the humidity rate and defining the infection periods, does not change significantly according to the projections used (Hirschi et al., 2012).

3.2 Impact of climate change on pesticide transport

The proportion of the total mass applied that is transported by surface runoff from the field to a stream is generally less than 1% (Wauchope, 1978; Bloomfield et al., 2006), but in some cases may be as high as 5% (Burgoa and Wauchope, 1995). In Europe, the average loss due to runoff is around 0.8% (Miao et al., 2004). A study conducted on farmland under the agricultural soil-climate conditions of Quebec (Lafrance et al., 1997) has shown runoff losses of the herbicides atrazine and metolachlor of between 0.03% and 2.0% and between 0.02% and 2.6%, respectively, for the first two rainfalls following application. By comparison, tile drainage losses under the same conditions were lower, at only 0.01%. In Quebec and for concentrations in surface water, sampling conducted by the Quebec Department of Sustainable Development, Environment and the Fight Against Climate Change (formerly the Department of Sustainable Development, Environment and Parks) in four rivers in areas of intensive corn and soybean production almost systematically revealed the presence of specific pesticides, sometimes at concentrations above the guidelines for the protection of aquatic life (chronic effect; Giroux and Pelletier, 2012). The analyses, conducted over a 20-year period, show a downward trend in the concentrations of several pesticides, but an upward trend for glyphosate concentrations, which should continue in the years ahead, given the increase in the production of glyphosate-tolerant genetically modified crops (Giroux and Pelletier, 2012).

Runoff losses occur during rainfall events and, to a lesser extent, during irrigation or snowmelt. Under future conditions, average summer surface runoff may increase if maximum daily summer precipitation increases, even if average summer precipitation decreases (Dayyani et al., 2012). Hunsche et al. (2007) have demonstrated the importance of rain volume and especially rain intensity. Their analyses on apple leaves show that for a given amount of rain following an application of mancozeb (ethylenebis(dithiocarbamic acid) manganese zinc complex), fungicide wash-off increased as a function of rain intensity. The relationship between the proportion of fungicide wash-off and rain intensity is approximately linear when rain intensity is low, and approximately logarithmic when rain intensity is higher (Hunsche et al., 2007). Wash-off is highest when the interval between application and rainfall is short (Lafrance et al., 1996; Barette, 2006; Hunsche et al., 2007; Nolan et al., 2008).

The large natural variability of extreme precipitation events makes it difficult to assess the impact of climate change on precipitation and extreme flows. For example, to estimate changes in peak summer streamflow, the impact of land changes obtained by Quilbé et al. (2008; extrapolation of land changes from 1976 to 1995 to the 2025 horizon) and by Poelmans et al. (2011; increase in urban area ranging from 30 to 55%) is more significant than the impact of climate change. Nonetheless, for southern Quebec, Mailhot et al. (2012) have shown that precipitation with 2-, 5-, 10- and 20-year return periods should increase, regardless of duration (6 to 120 hours) for the period 2041-2070 compared to the period 1971-2000. They used 15 climate simulations, four of which covered the period 2041-2070, from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2007). The impact of climate change decreases with the duration of the event and uncertainty increases with the return period.

The Centre d’expertise hydrique du Québec (CEHQ, 2013) produced projections of flood and low flows for 40 watersheds in southern Quebec by coupling outputs from climate models with the HYDROTEL hydrologic model (Fortin et al., 2001a; Fortin et al., 2001b; Turcotte et al., 2003). To take into account the uncertainty of future climate, 89 climate simulations, from the Coupled Model Intercomparison Project Phase 3 (CMIP3; Meehl et al., 2007), the Canadian Regional Climate Model (CRCM; Caya and Laprise, 1999; de Elia and Côté, 2010; Paquin, 2010) and NARCCAP were used. A probable increase in maximum daily flows with 2-and 20-year recurrence intervals evaluated in summer and fall is predicted for the period 2041-2070 compared to the period 1971-2000 for the northern part of the region (Saguenay–Lac-Saint-Jean area). For southern Quebec, the variability is too high to conclude that there will be a change.

Foulon (2013) analyzed summer maximum daily flow series from 1961 to 2100 produced by 10 simulations from the CRCM coupled with the HYDROTEL hydrologic model on two southern Quebec watersheds (Bécancour and Yamaska rivers). Upward trends were detected (i.e., maximum daily flow in summer should increase), but there was uncertainty; some simulations gave negative but statistically non-significant trends.

Climate change can also have an impact on changes in available pesticide mass between application and transport by runoff. Higher temperatures could accelerate biodegradation (Bloomfield et al., 2006; Shymko et al., 2011; Balbus et al., 2013). The effect of this would be to reduce pesticide concentrations but, on the other hand, could lead to an increase in the number of applications (Bloomfield et al., 2006). It should be noted, however, that degradation is not necessarily promoted if temperatures are too high (Shymko et al., 2011). The increased temperatures could also result in increased losses by volatilization (Bloomfield et al., 2006; Balbus et al., 2013).

In addition to temperature, soil moisture content has an impact on biodegradation. However, the function that could be used to precisely express the effect of temperature and soil moisture content on biodegradation is not known for all pesticides (Shymko et al., 2011).

Drier periods would have the effect of increasing pesticide concentrations (Bloomfield et al., 2006). The CEHQ (2013) predicts generally longer and more severe low flow conditions (i.e., lower flows) during the period 2041-2070 compared to the period 1971-2000 for all of southern Quebec. For the Yamaska and Bécancour rivers, Foulon (2013) obtained statistically significant reductions for the period 1961-2100 in summer low flows on 7 and 30 days for 8 of the 10 CRCM simulations used.

3.3 Summary

The scientific literature reveals many possible interactions between species phenology (crops and pests), climate change and pesticides (application frequency, application rate, transport and fate). However, few of these interactions are currently well understood. The findings reported in the scientific literature are often specific to a particular crop, pest, region or active ingredient.

The current state of knowledge has influenced the objective set for this project. Given the specific relationship for each crop/pest combination, the crops and their pests were chosen on the basis of the knowledge of their phenology. The decision to consider surface runoff only and to disregard groundwater flow was also based in part on previous studies (Lafrance et al., 1997; Cessna et al., 2010; Gagnon et al., 2014).

The method used, which is described in detail in the following section, takes the impact of temperature on crop and pest phenology, the interaction between crop phenology and the timing of herbicide applications, and the interaction between temperature, rain, apple phenology and timing of fungicide and bactericide applications directly into account. To take the large variability in rainfall events and of the uncertainty about future climate conditions into account, 23 climate simulations were used. Potential interactions between climate (temperature, CO_2) and certain important factors, such as the pesticide application rate and the soil pesticide degradation rate, could not be taken into account because they are difficult to quantify.

4 Method and data

The assessment of changes in pesticide contamination of surface runoff includes several sources of uncertainty, including future climate, on-farm decisions and the many natural processes governing pesticide transport in water. When uncertainty is high, a probabilistic approach must be adopted to help policymakers determine whether adaptation measures are necessary (Quilbé et al., 2008).

In this project, a deterministic model of pesticide transport was coupled with a stochastic model. The stochastic model generates different pesticide application scenarios and different perimeter values for the deterministic model. For each case studied, multiple time series were generated, leading to a range of values for a variable of interest. This approach, known as the Monte Carlo method, is increasingly used to simulate pesticide transport (e.g., Carbone et al., 2002; Warren-Hicks et al., 2002; Dubus and Janssen, 2003; Holt et al., 2010; Kondo et al., 2012; Wu and Liu, 2014).

This section provides a detailed description of the method applied in this project, namely the climate simulations used, the agricultural practice scenarios selected (including phytosanitary treatments), the study sites, the transport model used, the stochastic model developed and the relevant variables selected.

4.1 Climate simulations

Precipitation and minimum and maximum daily temperatures used in this project come from 23 climate simulations (Table 1). The data were provided by the Consortium Ouranos. The simulations come from three global climate models and three different GHG emissions scenarios. The GHG emissions scenarios are projections of future emissions based on technological changes in industry and policy and economic decisions since 2000 (Nakicenovic and Swart, 2000). Of the three scenarios used, A2 is the most pessimistic (i.e., higher rate of warming in 2100) and B1 is the most optimistic. For the period prior to 2000, GHG concentrations correspond to the observed concentrations; they are thus identical for all climate simulations. For each GHG emissions scenario, five ensemble members of the third-generation Canadian coupled global climate model (CGCM3; Flato et al., 2000; Scinocca et al., 2008) are used. The difference between the members of a given model is related to the initial atmospheric conditions. The other global models used are the German model ECHAM version 5 (Junglaus et al., 2006) and the Australian model Mk version 3.5 (Gordon et al., 2002, 2010).

Table 1. Global climate model, regional climate model, scaling method and GHG emissions scenarios (Nakicenovic and Swart, 2000) for the 23 simulations used.

Global Climate Model	Regional Climate Model	Scaling	GHG Scenarios
AGCM3[1] No. 4	CRCM version 4.2 (Caya and Laprise, 1999; Paquin, 2010); North American domain (AMNO)	Daily translation (Mpelasoka and Chiew, 2009)	A2
AGCM3 No. 5			A2
ECHAM5[2] No. 1			A2
ECHAM5 No. 3			A2
AGCM3 No. 1	-		A1B
AGCM3 No. 2			A1B
AGCM3 No. 3			A1B
AGCM3 No. 4			A1B
AGCM3 No. 5			A1B
AGCM3 No. 1			A2
AGCM3 No. 2			A2
AGCM3 No. 3			A2
AGCM3 No. 4			A2
AGCM3 No. 5			A2
AGCM3 No. 1			B1
AGCM3 No. 2			B1
AGCM3 No. 3			B1
AGCM3 No. 4			B1
AGCM3 No. 5			B1
Mk3.5[3] No. 1			A1B
Mk3.5 No. 1			A2
Mk3.5 No. 1			B1
ECHAM5 No. 4			A1B

[1]AGCM3 (Flato et al., 2000; Scinocca et al., 2008)
[2]ECHAM5 (Jungclaus et al., 2006)
[3]Mk3.5 (Gordon et al., 2002, 2010)

Four simulations are generated by CRCM version 4.2 (Caya and Laprise, 1999; Paquin, 2010). In contrast to global climate models that simulate climate for the entire world, CRCM, like all regional models, simulates climate over a domain. For the four simulations used, this domain is centered on North America. This allows CRCM to have a finer horizontal grid resolution (approximately 45 km) than the global models (typically > 100 km). However, regional models need external data defining the conditions at the boundary of the simulation domain. For the four CRCM simulations used, the boundary conditions come from simulations from the AGCM and ECHAM global models (Table 1).

All simulations cover the period 1961-2100, but only the 1981-2040 period is used for the project. As mentioned in Section 2, given that phytosanitary practices evolve quickly, it was decided to forecast no more than 30 years into the future. Over the period 2001-2040, scenarios A1B and A2 are very similar; CO_2-equivalent GHG emissions in scenario A1B are even slightly higher than those in scenario A2 for the period 2001-2020 (IPCC, 2007).

The raw output of the climate models, which cover several tens or even hundreds of kilometres, do not provide a fine-scale representation of climate variations. In order to better represent climate at the farm scale, the daily translation scaling method was applied (Mpelasoka and Chiew, 2009): let *X* be a given simulated raw value (precipitation or temperature) and *p* be the proportion of all simulated raw values at that time of the year (+/- 15 Julian days) during the reference period (1961-2000) that are less than or equal to *X*. The corrected simulated value is the *p*-fractile of the distribution of the observed values at that time of the year during the reference period. For a given site, the meteorological values observed come from the closest point of Natural Resources Canada's 0.1°C x 0.1°C resolution meteorological grid (Hutchinson et al., 2009; Hopkinson et al., 2011). Scaling was performed by Blaise Gauvin St-Denis (Consortium Ouranos).

4.2 Scenarios of agricultural practices

This subsection describes the agricultural practices considered, i.e., planting, harvest and tillage scenarios and pesticide application scenarios, as well as the adaptation measures considered. In order to effectively characterize the impact of climate, all agricultural practices at a given site remained unchanged during the entire 1981-2040 period. Only practices directly related to climate could change over time.

4.2.1 Planting, harvest and tillage scenarios

Table 2 illustrates the criteria used to define the planting, harvest and tillage dates in each season for each crop. These dates are dependent on climate and vary from year to year.

Table 2. Planting, emergence, maturity, harvest and tillage for the four crops considered over a given year

<table>
<tr><th>Crop</th><th>Start of growing season (SGS; Julian days)</th><th>Start of calculation of degree days (DD; Julian days)[a]</th><th>Emergence</th><th>Maturity</th><th>Harvest date (Julian days)</th><th>End of growing season (EGS; Julian days)</th><th>Tillage date (Julian days)</th></tr>
<tr><td>Wheat</td><td rowspan="2">$\min_{j\geq j^*+4}\left(TMMP5_j > 5{,}5\ ^\circ\mathrm{C}\right)$[b]</td><td rowspan="3">SGS[d] to (SGS+7)</td><td>178 DD0[e]</td><td>1942 DJ0</td><td rowspan="3">(EGS[f]-14) to EGS</td><td rowspan="2">$\max_{j\geq j^*+4}\left(TMMP5_j > 5{,}5\ ^\circ\mathrm{C}\right)$</td><td rowspan="3">Harvest date + 1</td></tr>
<tr><td>Soybean</td><td>62 DD10</td><td>1216 DJ10</td></tr>
<tr><td>Corn</td><td>$\min_{j\geq j^*+4}\left(TMM5_j > 12{,}8\ ^\circ\mathrm{C}\right)$[c]</td><td>62 DD10</td><td>1942 DJ10</td><td>$\min_{j\geq 213}\left(T\min_j \leq 2\ ^\circ\mathrm{C}\right)$[g]</td></tr>
<tr><td>Apple[h]</td><td>60</td><td></td><td>79 DD5</td><td>1500 DJ5</td><td>260 to 274</td><td>-</td><td>-</td></tr>
</table>

[a] For wheat, soybean and corn, the start of the calculation of degree days (DD) corresponds to the planting date.

[b] $TMMP5_j = \dfrac{Tmoy_{j-4} + 4Tmoy_{j-3} + 6Tmoy_{j-2} + 4Tmoy_{j-1} + Tmoy_j}{16}$ (Atlas agroclimatique du Québec, 2012), j^* = Julian day of last spring frost, $Tmoy_j$ = average temperature on day j.

[c] $TMM5_j = \dfrac{Tmoy_{j-4} + Tmoy_{j-3} + Tmoy_{j-2} + Tmoy_{j-1} + Tmoy_j}{5}$ (Atlas agroclimatique du Québec, 2012), j^* = Julian day of last spring frost.

[d] SGS = start of growing season.

[e] DDx = degree days (base x °C) calculated using the single sine method (Baskerville and Emin, 1969).

[f] EGS = end of growing season.

[g] $Tmin_j$ = minimum temperature on day j.

[h] The values for apple correspond to the phenology of the McIntosh variety.

For wheat, soybean and corn, it was assumed that the producer would plant shortly after the start of the growing season (SGS) in order to maximize yield. The SGS was calculated using the method suggested in *Atlas agroclimatique du Québec* (2012). Accumulated degree days required for crop emergence and maturation, with the exception of apple maturation, come from the CIPRA software, which was developed by AAFC's Horticulture Research and Development Centre in Saint-Jean-sur-Richelieu. For wheat, corn and soybean, the tillage date was defined as the day following harvest. The exact date of tillage does not have a significant impact on pesticide transport, since herbicides are applied early in the season for these crops (see Section 4.2.2 for details). For apple, the start of the growing season was defined as March 1, and emergence corresponds to budbreak, as modelled in CIPRA for McIntosh (*Malus pumila* McIntosh). The harvest date was set as the end of September (between September 17 and October 1), regardless of climate conditions.

4.2.2 Pesticide application scenarios

Table 3 presents the herbicides considered, their application rate and their application window for wheat, corn and soybean. Each active ingredient was analyzed independently. The International Union of Pure and Applied Chemistry (IUPAC) name and chemical properties of each active ingredient are indicated in Appendix A. It was assumed that a single herbicide application per season was required. The herbicides selected are some of the most commonly used products in Quebec for these crops (Danielle Bernier, Quebec Department of Agriculture, Fisheries and Food, MAPAQ, pers. comm.). The application rates and phenological stages used to determine the application windows were established on the basis of information available on the SAgE pesticides website (2014; http://www.sagepesticides.qc.ca), set up by the *Centre de référence en agriculture et agroalimentaire du Québec* (CRAAQ). Some active ingredients have large ranges of application rates; the maximum application rate can be three times the minimum rate and even larger in the case of dicamba (Table 3). The application ranges were determined in order to cover all possible situations for a given crop. The degree days required to achieve the phonological stages were determined on the basis of the CIPRA models. The days with rain exceeding 1 mm were not included in the application window.

Table 4 presents the insecticides selected for apple, which are among the most commonly used products in Quebec to control the three insect pests considered in this project. The application rates and minimum preharvest intervals were obtained from SAgE pesticides (2014). The application windows were determined on the basis of information contained in the CIPRA user's guide. The first application is carried out at fruit set to protect against plum curculio. The second and third applications are designed to control the first and second generations of codling moth, respectively. The third application also controls apple maggot. In contrast to other studies conducted in warmer regions and for longer time horizons (Luedeling et al., 2011; Hirschi et al., 2012; Juszczak et al., 2013), a third generation of codling moth was not considered in this project. As in the case of the herbicides, the days with more than 1 mm of rain were excluded from the insecticide application window. Since the first application has only a 1-day application window, the application was done the day before or the day after if the amount of rain during the planned application day exceeded 1 mm.

Table 3. Herbicides considered and their application window

Crop	Active ingredient	Application rate (kg/ha)	Application window (degree days after planting[a])
Wheat	Bromoxynil	0.17	178-758 DD0[c]
	Fenoxaprop-p-ethyl	0.03-0.09	
	Pyrasulfotole	0.03-0.09	
	Thifensulfuron-methyl	0.01	
	Tribenuron-methyl	0.005	
Corn	Atrazine	0.53-1.49	1-61 DD10[c]
	Dicamba	0.29-1.14	1-182 DD10
	Glyphosate[b]	0.9-1.8	62-220 DD10[c]
	Mesotrione	0.14	1-61 DD10[c]
	S-metolachlor	0.6-1.6	1-182 DD10
Soybean	Bentazon	0.84-1.08	149-457 DD10[c]
	Glyphosate[b]	0.9-2.52	149-457 DD10[c]
	Imazethapyr	0.075-0.1	62 DD10 – 100 days to harvest
	Quizalofop-p-ethyl	0.06	149-457 DD10[c]
	Thifensulfuron-methyl	4.13-6.0	149-457 DD10[c]

[a]The planting dates are defined in Table 2.
[b]Only for genetically modified glyphosate-resistant varieties.
[c]Scenario used for the assessment of influent climate variables (Section 4.6.2). DD*x* = degree days (base *x* °C) calculated using the single sine method (Baskerville and Emin, 1969).

Table 4. Insecticides considered and their application windows (apple only)

Active ingredient	Application rate (kg/ha)	Preharvest interval	Application 1 (degree days)*	Application 2 (degree days)*	Application 3 (degree days)*
Acetamiprid	0.08-0.17	7 d	371 DD5	273-374 DD10	793-865 DD10
Phosmet	1.88	14 d			
Spinetoram	0.11	7 d			
Thiacloprid	0.14-0.21	30 d			

* The date of the start of calculation of degree days is defined in Table 2. DD*x* = degree days (base *x* °C) calculated using the single sine method (Baskerville and Emin, 1969).

The timing of fungicide and bactericide applications is more complex, as it depends on the phenological stages of apple, temperature and moisture (rain, dew). To control type I scab infections, it was assumed that the producer would apply a fungicide if the following four conditions were met: (i) it is the ascospore release period; (ii) the last treatment is no longer effective; (iii) the number of hours of leaf wetness is sufficient; and (iv) at least two days have passed since the last treatment. The ascospore release period occurs when there are between 50 and 400 accumulated degree days (base 5 °C) (calculated using the standard method) since April 1 (Carisse and Jobin, 2006). The last treatment was assumed to be no longer effective if at least one of the following three conditions were met: five or more new leaves have grown since the last treatment (see Appendix B); at least 25 mm of rain is expected in the period between two days after the last application and the day after the planned application date; or more than 10 days have passed since the last treatment. The conditions determining whether the number of hours of leaf wetness is sufficient were established by Carisse and Jobin (2006) and are presented in Appendix B.

This scenario contains a few arbitrary elements (e.g., number of leaves grown, minimum interval between two applications, accumulated rainfall threshold value) that could vary from one producer to another. However, the scenario established is realistic and could be applied by the producer (Roland Joannin, Agropomme, pers. comm.). It was assumed that the producer had effectively controlled the apple scab and, as a result, did not have to apply additional pesticides to control type II infections that could occur in the summer.

Three active ingredients were considered (Table 5). In order to better isolate the impact of the active ingredient, all applications in a given year were done with the same active ingredient. The application rates used come from information taken from SAgE pesticides (2014).

Table 5. Fungicides considered for control apple scab

Active ingredient	Application rates 1 and 2 (kg/ha)	Application rate 3 + (kg/ha)
Captan	3.0	1.5
Mancozeb	4.5	3.75
Metiram	4.8	1.13

The bactericides used for the control of fire blight are applied between the pink bud and petal fall stages (van der Zwet et al., 1990), i.e., between 197 and 313 degree days (base 5 °C) calculated using the single sine method, in accordance with the CIPRA user's guide. The start date for the accumulation of degree days is provided in Table 2. An application is made if the accumulated "risk value" of the previous four days, calculated using the CougarBlight 2010 fire blight prediction model (Smith, 2010), exceeds 100 (see Appendix C). There is a maximum of one application every four days and three applications per year. Smith (2010) also suggests that the leaves must be wet for at least three hours before an application is required. According to the model estimating the number of hours of leaf wetness developed for apple scab (Appendix B), this condition is almost always met and was not considered here. Streptomycin sulfate is the only active ingredient considered to control fire blight and is applied at a rate of 1.36 kg/ha, as suggested in SAgE pesticides (2014).

All simulated pesticide applications were spray applications. Although the application methods are not the same from crop to crop, the transport model considers all applications in the same way. It considers interception of the active ingredient to be proportional to plant cover, with the remaining active ingredient found at the soil surface, where it can infiltrate the first few centimetres of the soil (more details in Section 4.4).

The simulations are performed separately for each active ingredient in order to be able to isolate the impact of each one. Each 60-year time series is simulated assuming a single active ingredient is used. In practice, producers use different active ingredients from one application to the next in order to limit the development of resistance; they can also apply a combination of several active ingredients in a single application. Simulations taking these practices into account would have made it possible to assess the impact of climate change for real application scenarios, but the impact of each active ingredient would have been obscured.

4.2.3 Adaptation measures

Adaptation measures that could potentially reduce the quantity of pesticides transported were simulated. These measures may or may not be tied to climate. They serve to assess the impact of climate change relative to measures that may be taken in the field. It is important to note, however, that since the simulations produce in situ estimates, without taking account of transport to larger-scale environmental systems (e.g., subwatersheds, streams), adaptation measures tied to land use practices adjacent to cultivated fields, such as stream buffers (Rousseau et al., 2012; Sabbagh et al., 2013) and constructed wetlands (Lizotte et al., 2012), were not considered. The impacts of interannual measures designed to reduce pest abundance, such as crop rotation (Gagnon et al., 2013) and burning of apple leaves in the fall (Carisse and Jobin, 2006), could not be simulated as they are difficult to quantify.

Table 6. Simulated adaptation measures

Adaptation measure	Initial practice	Practice after adaptation	Cases considered
No application the day before rain	Application if $P(d) < 1$ mm	Application if $P(d)$ <u>and $P(d+1)$</u> < 1 mm	Phosmet application
Variation of the rain threshold	Application if $P(d) < 1$ mm	Application if $P(d) <$ <u>x mm (x = 0.1 or 5)</u>	Phosmet application
Reduced till	Conventional fall tillage	Reduced till in the fall, pre-seed glyphosate application	Glyphosate-resistant corn
No till	Conventional fall tillage	No till in the fall, pre-seed glyphosate application	Glyphosate-resistant corn
Soil incorporation	Pre-emergent spray application	Pre-emergent soil incorporation	Atrazine application

Table 6 presents the adaptation measures considered. To limit the run time, only certain specific cases were considered for each measure.

4.3 Study sites

Figure 1 presents the location of the 28 study sites. The sites are actual fields selected from the Generalized Crop Database of *Financière agricole du Québec* (FADQ). For each site, the plant selected, or one of the crops selected, was actually grown in 2012. Close to half of the sites are located in the southern St. Lawrence valley, around Montreal, but other sites cover the more northern part of the St. Lawrence valley, as far as Québec City, as well as Estrie, Beauce, Lac-Saint-Jean and Charlevoix-Ouest. The geographic distribution of the sites was chosen to cover a large part of the climate conditions and soil types present in Quebec's agricultural areas. The soil type at each site was determined on the basis of soil fact sheets developed by the IRDA (2013). The properties for each soil type were taken from the National Soil Database developed by AAFC's Canadian Soil Information Service (2010). The digital elevation data used in the calculation of slopes come from Natural Resources Canada (2000). The main characteristics of each site are presented in Appendix D. Given the area of the sites (< 40 ha), daily temperature and precipitation are considered homogeneous, and a single point of Natural Resources Canada's grid (Hutchinson et al., 2009; Hopkinson et al., 2011) is used for each site to represent local climate (Section 4.1).

4.4 Model of pesticide transport in water

The Pesticide Root Zone Model (PRZM) version 3.12.3 is used (Suarez, 2005). This model was developed by the U.S. Environmental Protection Agency (USEPA) and is available free of charge at http://www2.epa.gov/exposure-assessment-models/przm-version-index. This model has been extensively used, and a number of studies have shown that it produces acceptable results (e.g., Carbone et al., 2002; Singh et Jones, 2002; Warren-Hicks et al., 2002; Farenhorst et al., 2009) while requiring a relatively short run time (McQueen et al., 2007).

PRZM is a one-dimensional model that simulates, at a daily time step, pesticide transport through a vertical soil column and generates edge-of-field pesticide concentration and load values. Its inputs include meteorological data (precipitation, temperature, evapotranspiration), soil properties (Appendix D), characteristics of pesticide applications (e.g., dates, products used, rate, method) and information on agricultural practices (e.g., tillage, irrigation). This model has two main components: a hydrological component and a chemical transport component. The most important hydrological processes for this project are surface runoff and water erosion. Surface runoff is calculated using the curve number, an empirical parameter developed by the U.S Department of Agriculture (USDA, 2004) that is often used in hydrology. Erosion can be calculated using one of three equations (Suarez, 2005), all of which are based on the often used

Universal Soil Loss Equation (USLE), also developed by the USDA. The most important chemical transport parameters are the soil/water distribution coefficient (K_d), which is the product of the water/organic carbon partitioning coefficient of the pesticide (K_{oc}) and the soil organic carbon fraction, and the daily degradation rate, which is determined using the half-life of the pesticide (Dubus and Janssen, 2003). The most important PRZM parameters for the project are presented in Appendix E. For a detailed description of the PRZM model, readers may refer to Suarez (2005).

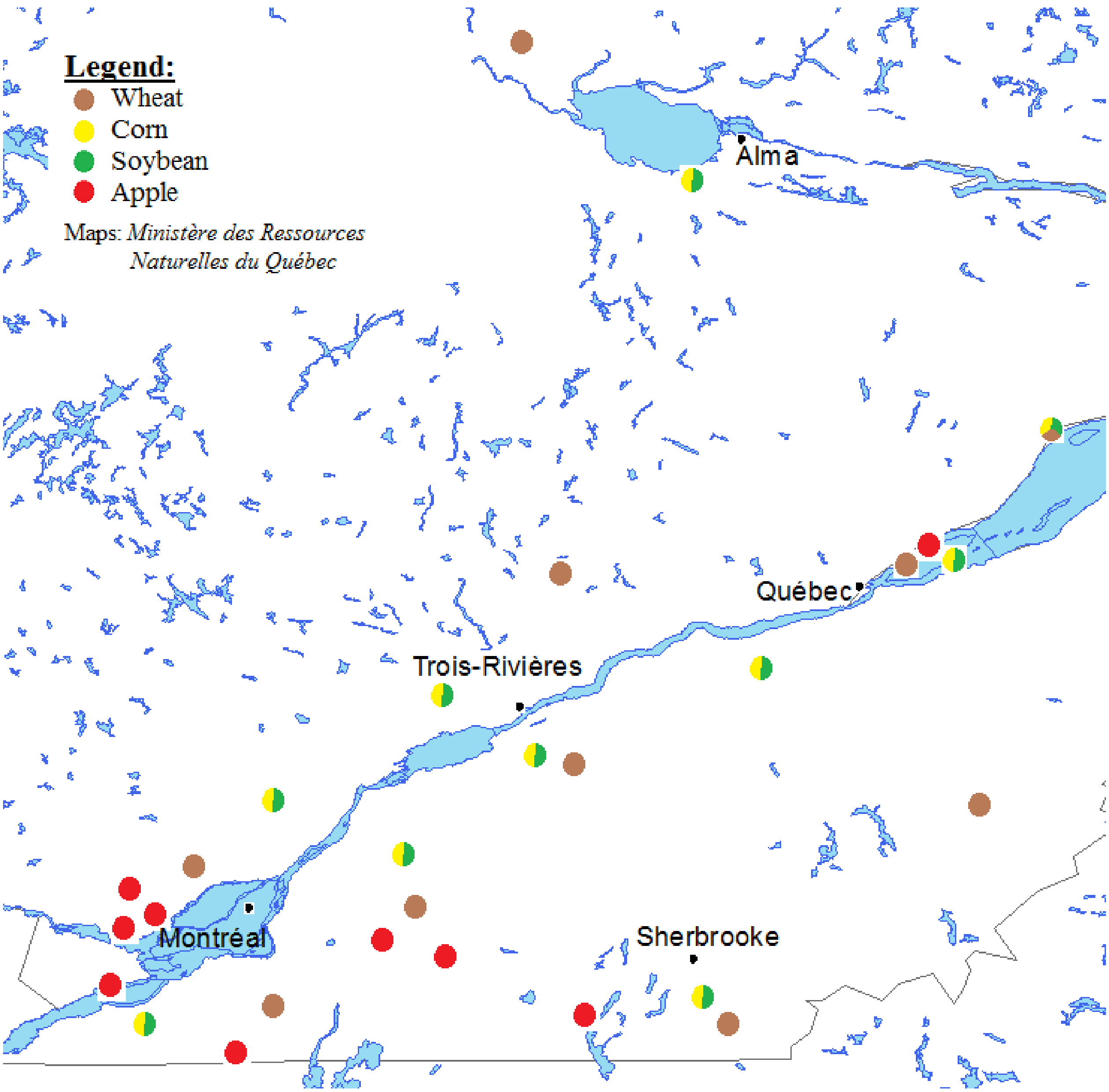

Figure 1. Study sites.

4.5 Stochastic model

In modelling, uncertainty is due to the imprecision and representativeness of the input data and by the representation of complex natural processes by simplified equations. In addition, the significant spatio-temporal variability of the values of the model parameters imposes a significant degree of uncertainty when field conditions are considered. In order to take account of the impact of these sources of uncertainty on the parameter values, parameters were selected using the Monte Carlo method (e.g., Warren-Hicks et al., 2002). For certain selected parameters of the PRZM model, a statistical distribution was specified (Appendix E). For a given parameter, the mean and standard deviation could vary from one site and one crop to another, but the shape of the distribution always remains the same. The mean and standard deviation of a parameter was adjusted on the basis of the set of values suggested in the PRZM user's manual (Suarez, 2005) and, in some cases, the variability observed between the soil layers based on AAFC soil data (2010).

For each of the 22 parameters selected, 100 pseudo-random values were uniformly generated in the interval (0, 1), resulting in a matrix of 100 x 22 pseudo-random values (Appendix F). In the remainder of the report, the set of values formed by the i^{th} random value of all PRZM parameters considered (i.e., the i^{th} line of the matrix) will be called *i*th realization ($i = \{1, \ldots, 100\}$). For each site/climate simulation/crop/active ingredient combination, 100 sixty-year series (1981-2040) were generated using the 100 realizations. The value of the parameter *j* generated in the *i*th realization is the *f*-fractile of the statistical distribution of the parameter (Appendix E), where *f* is the element (*i*,*j*) of the pseudo-random matrix (Appendix F). With the stochastic approach, it is possible to generate an interval of probable results of pesticide runoff loads rather than a single value and to better assess the impact of the parameters on the results. It should be noted that fixed values (i.e., invariant from one series to another) were used for the properties of the active ingredients (Appendix A). The impact of the values of these properties on the results was evaluated by comparing the results of different active ingredients.

4.6 Relevant variables used

The selection of response variables and possibly influent climate variables is presented in this section. There are other influent variables unrelated to climate, but given that the project deals with climate change impacts, only some of these variables were analyzed in the assessment of the impact of adaptation measures.

4.6.1 Response variables

The main response variable used is the load transported in runoff, which represents the mass of pesticides per unit area that may be transported off the field and contaminate the environment. This indicator is presented in grams per hectare (g/ha).

The analyses were conducted separately for pesticides dissolved in water and pesticides adsorbed to soil that are transported by eroded soil in runoff water. For most active ingredients, which are generally highly soluble in water, it is expected that the runoff loads transported in dissolved form are significantly larger than those in adsorbed form (Bloomfield et al., 2006; Cessna et al., 2010; Gagnon et al., 2014). The annual daily maximum values and annual means were analyzed.

The impacts of climate change were assessed by analyzing the 60-year trend and comparing the 30-year means (1981-2010 and 2011-2040). Trend analysis was conducted using the Mann-Kendall non-parametric test (Mann, 1945; Kendall, 1970), whereby the sign of the slope (positive, negative or, in rare cases, zero) is obtained and a threshold is observed, which represents the probability of obtaining as strong a trend, assuming that the data come from a stationary distribution. A trend is usually considered significant if the observed threshold is less than 5%. This non-parametric test does not require that the data fit a normal distribution, or even that variance be constant in time. The 30-year means are used to illustrate differences between the past and future, in absolute terms.

The simulated loads are also expressed as a proportion of the mass of pesticide applied per unit area. The proportion transported in runoff water is a measure of the loss of treatment effectiveness associated with surface runoff.

The annual mean concentrations and annual daily maximum concentrations by active ingredient are also presented. Pesticide concentration in runoff water is used to assess risks to the protection of certain agricultural activities (e.g., irrigation, livestock watering). This indicator is expressed in micrograms per litre (μg/L). Since the transport model used is a one-dimensional simulation (i.e., a soil column) model, the concentrations obtained are applicable to the farm scale, and are not comparable to lake or river concentrations. The concentrations presented in this report must not be used to assess the risk of contamination of aquatic organisms or drinking water.

4.6.2 Influent climate variables

The impact of climate on pesticide loads transported in runoff water is primarily due to the application dates and rainfall amounts in the days following application.

For herbicides and insecticides, the application dates primarily depend on temperature, as a function of accumulated degree days, and rainfall amounts, since according to the scenarios considered for herbicides and insecticides, applications are not permitted if there is over 1 mm of rain in a given day (Section 4.2.2). The change in the application window start and end dates was analyzed. The accumulated degree days defining the herbicide application windows are presented in Table 3 (Section 4.2.2). For corn, the window for atrazine and mesotrione (1 to 61 degree days (base 10 °C), pre-emergent) and the window for glyphosate (62 to 220 degree days (base 10 °C), post-emergent) were used. For soybean, the window covers 149 to 457 degree days (base 10 °C) accumulated since planting (window of all of the active ingredients used, except imazethapyr). The windows for the three insecticide applications for apple are presented in Table 4 (Section 4.2.2). The change in the number of days in the application window that received less than 1 mm of rain was analyzed. For all of these variables, the analysis covers only differences over 30 years. The dataset consisting of the 60 annual values contains too many equal values, which prevents trend analysis using the Mann-Kendall test.

The fungicide and bactericide application dates also depend on accumulated degree days, but primarily on moisture conditions and accumulated rainfall. For the two apple diseases used, the change in the number of applications was analyzed. Given the large number of equal values in the dataset consisting of the 60 annual values, the analysis covers only differences over 30 years.

The amount of rain following application is a determining factor in pesticide transport. The variables used are maximum daily rainfall and accumulated total rainfall during the application window. For these two variables, the Mann-Kendall test can be used to evaluate the trend over 60 years. The differences over 30 years were also analyzed. Given that the application windows are relatively short, the number of days with significant precipitation (e.g., rainfall > 25 mm) is very limited and was not analyzed.

5 Results

5.1 Changes in climate variables

In this section, the impact of climate change during the period 1981-2040 is assessed for climate variables that are likely to have an impact on pesticide transport in runoff water at the study sites (Section 4.6.2).

5.1.1 Herbicide and insecticide application dates

For each site/crop/climate simulation combination, there are 60 years, each with one herbicide application window (wheat, corn pre-emergent, corn post-emergent and soybean) or three insecticide application windows (apple). In total, this represents 230 series (10 sites x 23 climate simulations) for wheat, corn (pre-emergent and post-emergent) and soybean, and 207 series (9 sites x 23 climate simulations) for apple. Given that the application windows depend on the planting dates and because these dates vary only slightly from one realization to another (Table 2, Section 4.2.1), only the median window of the 100 realizations was used for each site/crop/climate simulation combination. The difference over 30 years was calculated for each series for each of the following variables: start date of window, end date of window and duration of window (excluding days with over 1 mm of rain).

Figure 2 presents box plots illustrating the changes in average herbicide application dates for wheat, corn (pre-emergent and post-emergent) and soybean between the periods 1981-2010 and 2011-2040, as well as variability between sites (Figure 2a) and between climate simulations (Figure 2b). The criteria defining the herbicide application windows are presented in Table 3 (Section 4.2.2). The average decrease over 30 years ranges from 2 to 6 days for all sites and for the three crops (Figure 2a). The differences are slightly larger for the window end dates than for the window start dates. The variability between climate simulations (Figure 2b) is larger than the variability between sites (Figure 2a). There are even 12 cases, out of a total of 184 (23 climate simulations x 8 variables), for which the mean differences over 30 years are positive (i.e., later application dates in the future). Six of these cases come from member 2 of CGCM3, simulated using GHG emissions scenario A2, while two cases come from the same member, simulated using scenario B1. The other four cases come from member 5 of CGCM3, simulated using GHG emissions scenario B1. It should be noted that for the window end date for soybean, which is the latest date considered in this project for herbicide applications, all climate simulations show decreases over 30 years.

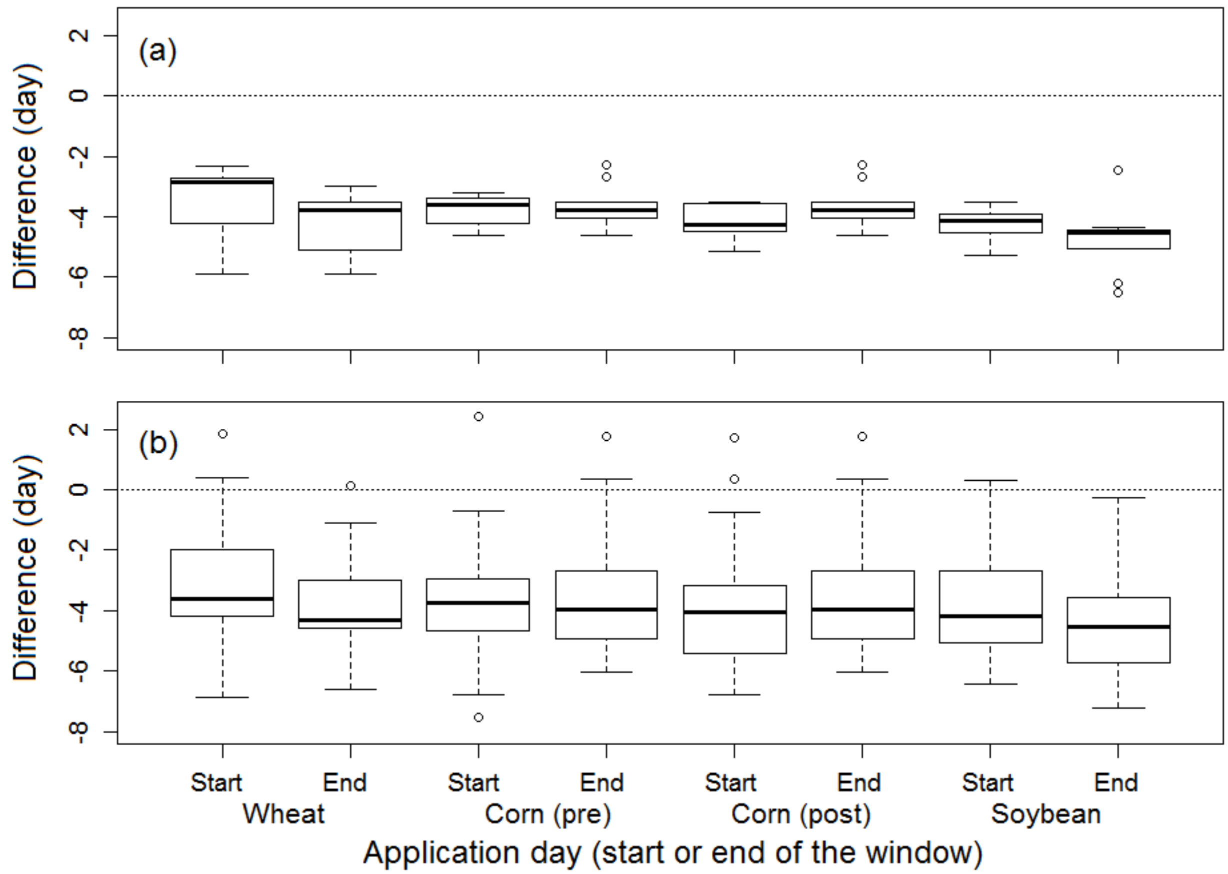

Figure 2. Box plots of the mean differences between the periods 1981-2010 and 2011-2040 for the herbicide application window start and end dates. Each plot is constructed using: (a) 10 data points, namely the median of the mean differences of the 23 climate simulations for each of the 10 sites (variability between sites); (b) 23 data points, namely the median of the mean differences of the 10 sites for each of the 23 climate simulations (variability between climate simulations). Pre = pre-emergent; post = post-emergent.

For the insecticides used on apple, the advance in application dates is even more apparent. The average decreases over 30 years are approximately 3.5 and 8 days for the first application and the end date of the window for the third application, respectively (Figure 3). The average advance over 30 years exceeds 10 days for the end date of the window for the third application for the two orchards furthest from Montreal, namely site 25 located in the Appalachian region near Lake Memphrémagog, in Estrie, and site 26 located on Île d'Orléans (Section 4.3 and Appendix D). The criteria defining the insecticide application windows are presented in Table 4 (Section 4.2.2). As in the case of the herbicide applications, the variability between climate simulations (Figure 3b) is larger than the variability between sites (Figure 3a). It should be noted that in less than 1% of the years, a third application would not be possible since it would occur less than seven days prior to harvest.

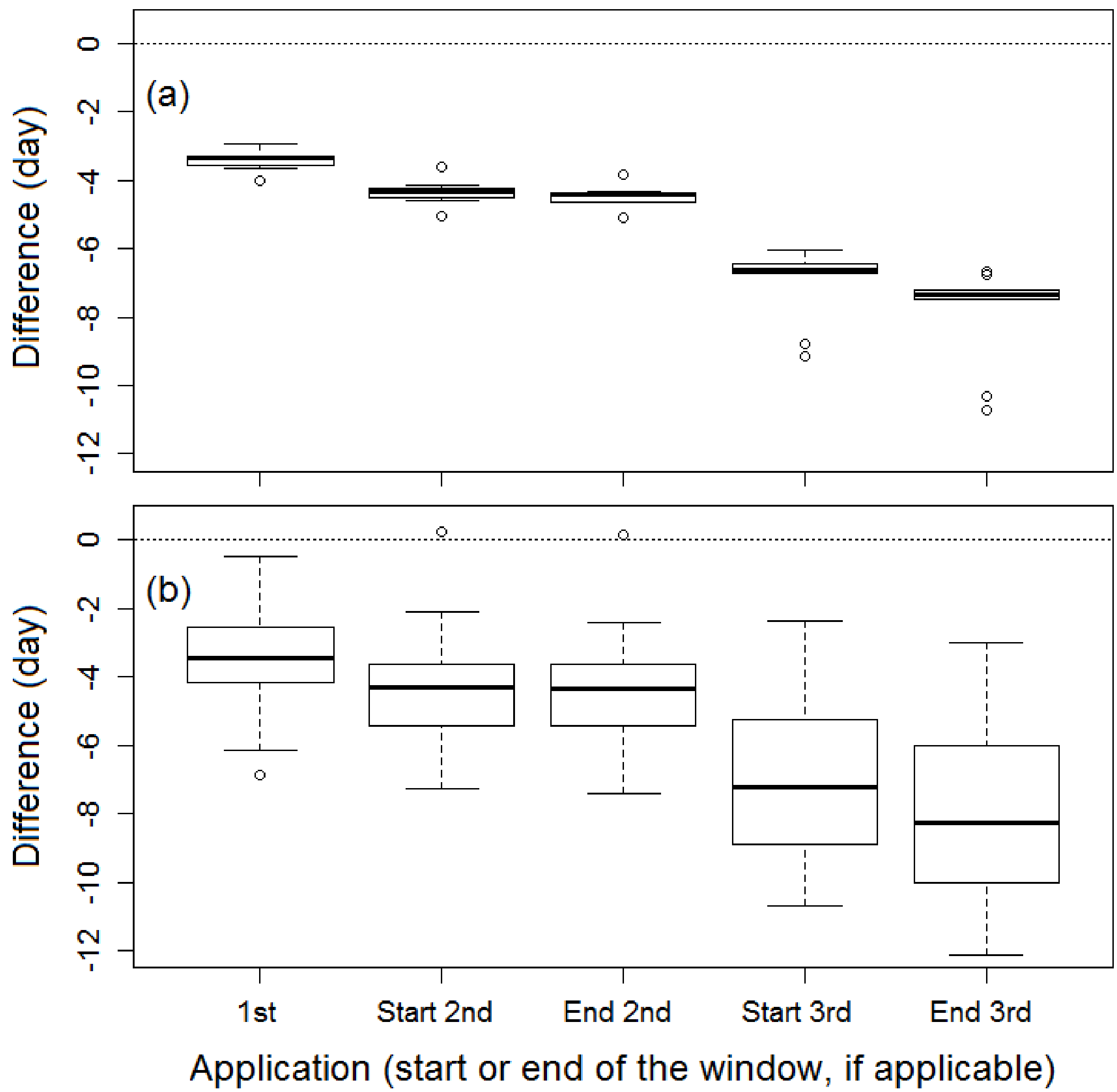

Figure 3. Box plots of the mean differences between the periods 1981-2010 and 2011-2040 for the insecticide application dates for apple. Each plot is constructed using: (a) 9 data points, namely the median of the mean differences of the 23 climate simulations for each of the 9 sites (variability between sites); (b) 23 data points, namely the median of the mean differences of the 9 sites for each of the 23 climate simulations (variability between climate simulations).

Figure 4 illustrates the mean difference over 30 years in the number of days available for the applications. The vast majority of the differences are less than one day. The differences are generally negative, given that the increase in temperature slightly shortens the window (Figures 2 and 3). Moreover, there is no significant change in the proportion of days with more than 1 mm of rain.

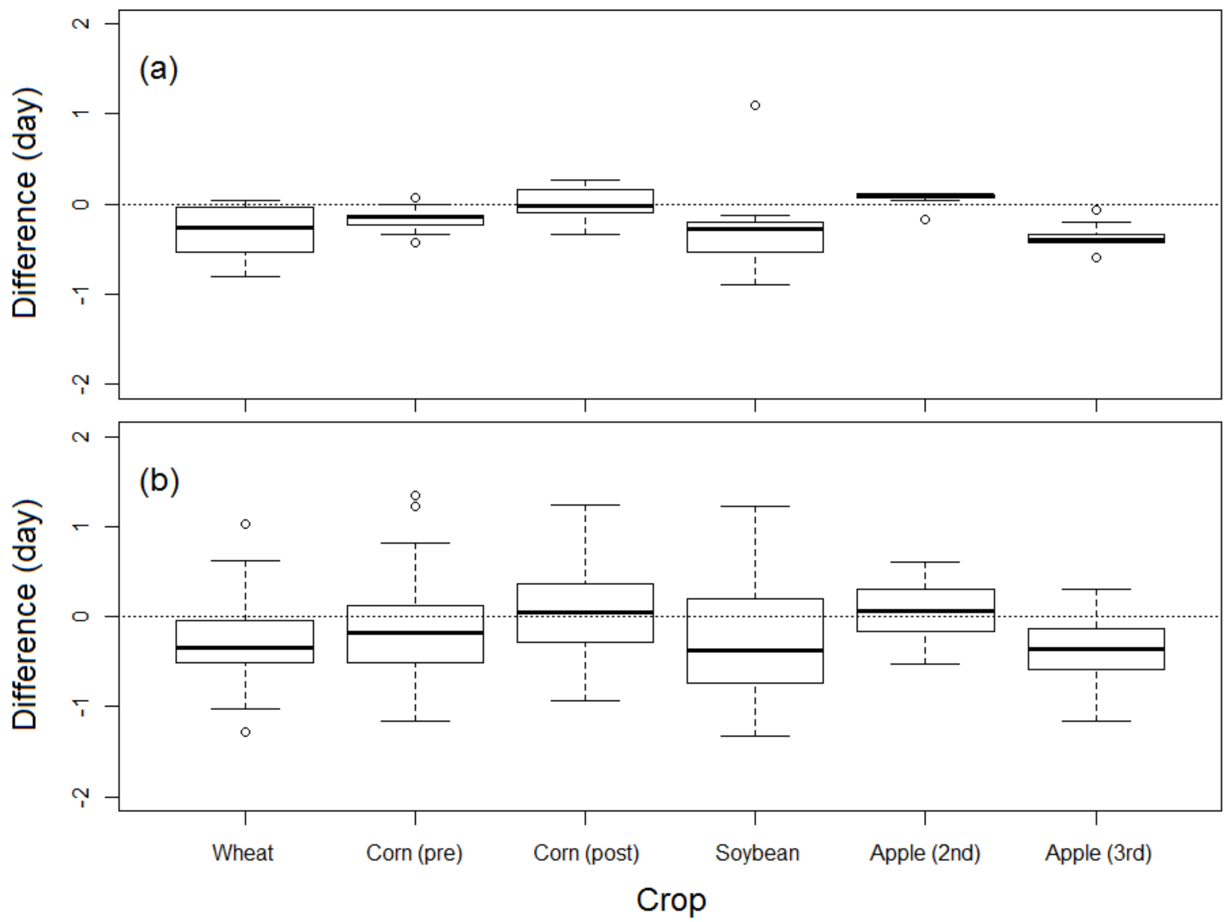

Figure 4. Box plots of the mean differences between the periods 1981-2010 and 2011-2040 for the number of days on which herbicide and insecticide applications are possible. Each plot is constructed using: (a) 9 (apple) or 10 (other) data points, namely the median of the mean differences of the 23 climate simulations for each site (variability between sites); (b) 23 data points, namely the median of the mean differences of the sites for each of the 23 climate simulations (variability between climate simulations). Pre = pre-emergent; post = post-emergent. 2nd, 3rd = 2nd, 3rd application.

In short, the impact of climate change on the herbicide and insecticide application dates for the sites and period (1981-2040) considered is clear. The application dates are directly related to temperature. The later the applications in the season (i.e., the larger the number of accumulated degree days required for application), the greater the impact (Figures 2 and 3). The number of days in the application windows remains stable over the 60-year period (Figure 4), with average decreases of less than one day. The differences in the application dates and length of the application windows would have been larger if the future period had been farther in the future. For example, in Gagnon et al. (2013), the emergence dates for European corn borer are advanced by approximately two weeks between the periods 1970-1999 and 2041-2070, and the treatment periods are shortened by more than one day.

5.1.2 Number of fungicide and bactericide applications

Figure 5 illustrates the average change in the number of fungicide applications for the control of apple scab between the periods 1981-2010 and 2011-2040 as well as the variability between sites and between climate simulations. On average, the number of applications per year increases by approximately 0.1 between the periods 1981-2010 and 2011-2040, but this increase is non-significant. Nonetheless, seven of the nine study sites show an average increase. The two orchards furthest from Montreal (sites 25 and 26, Section 4.3 and Appendix D) can be distinguished from the others in that they show a very slight average decrease in the number of applications. With respect to the 23 climate simulations, the results are mixed. For instance, there are seven climate simulations for which there is an average increase over 30 years for all nine sites, and six for which there is a decrease for all sites. This means that for a given site, there are always climate simulations that generate positive differences and others than generate negative differences.

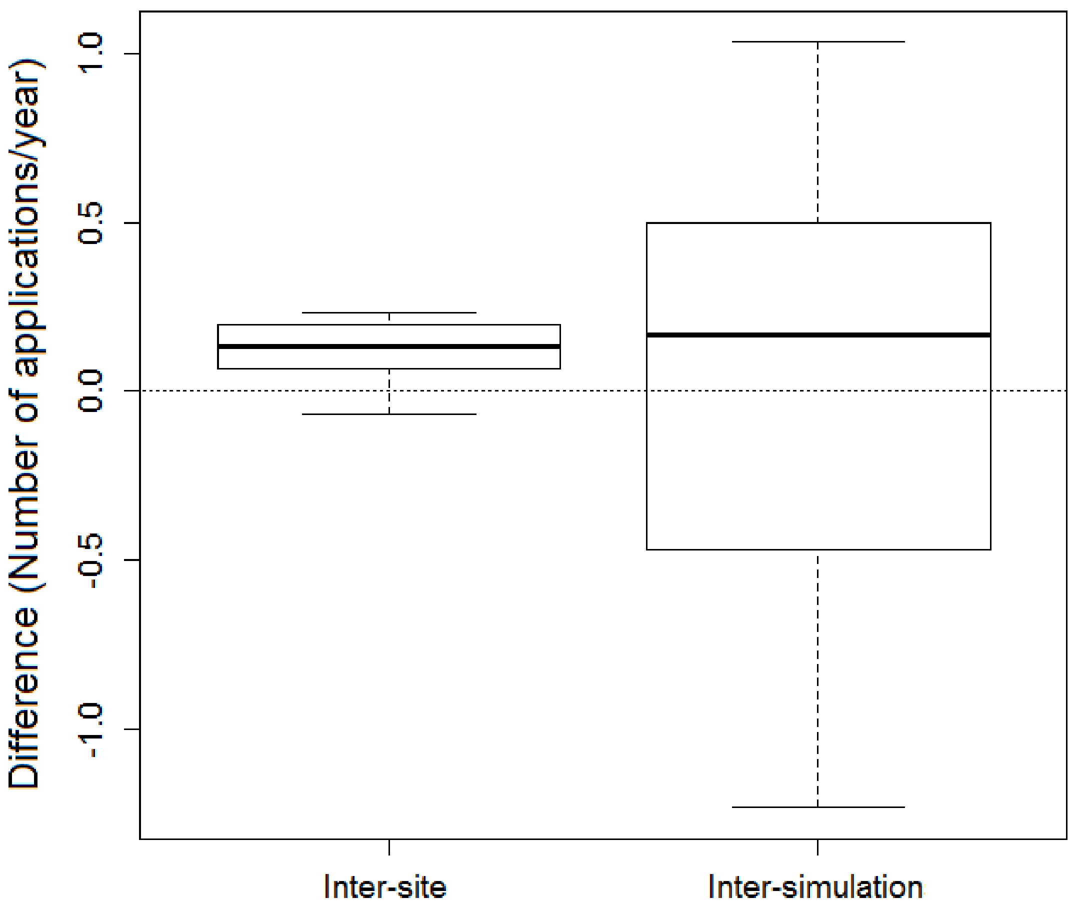

Figure 5. Box plots of the mean differences between the periods 1981-2010 and 2011-2040 for the number of fungicide applications to control apple scab. Each plot is constructed using: (left; "Inter-site") 9 data points, namely the median of the mean differences of the 23 climate simulations for each of the 9 sites; (right; "Inter-simulation") 23 data points, namely the median of the mean differences of the 9 sites for each of the 23 climate simulations.

Figure 6 illustrates the average change in the number of bactericide applications against fire blight (apple) between the periods 1981-2010 and 2011-2040. There is no change, because the main variable limiting the number of applications is the length of the application window, which is relatively short. The advance of the application window has very little impact on its length, since it is early in the season. A similar finding was obtained by Hirschi et al. (2012).

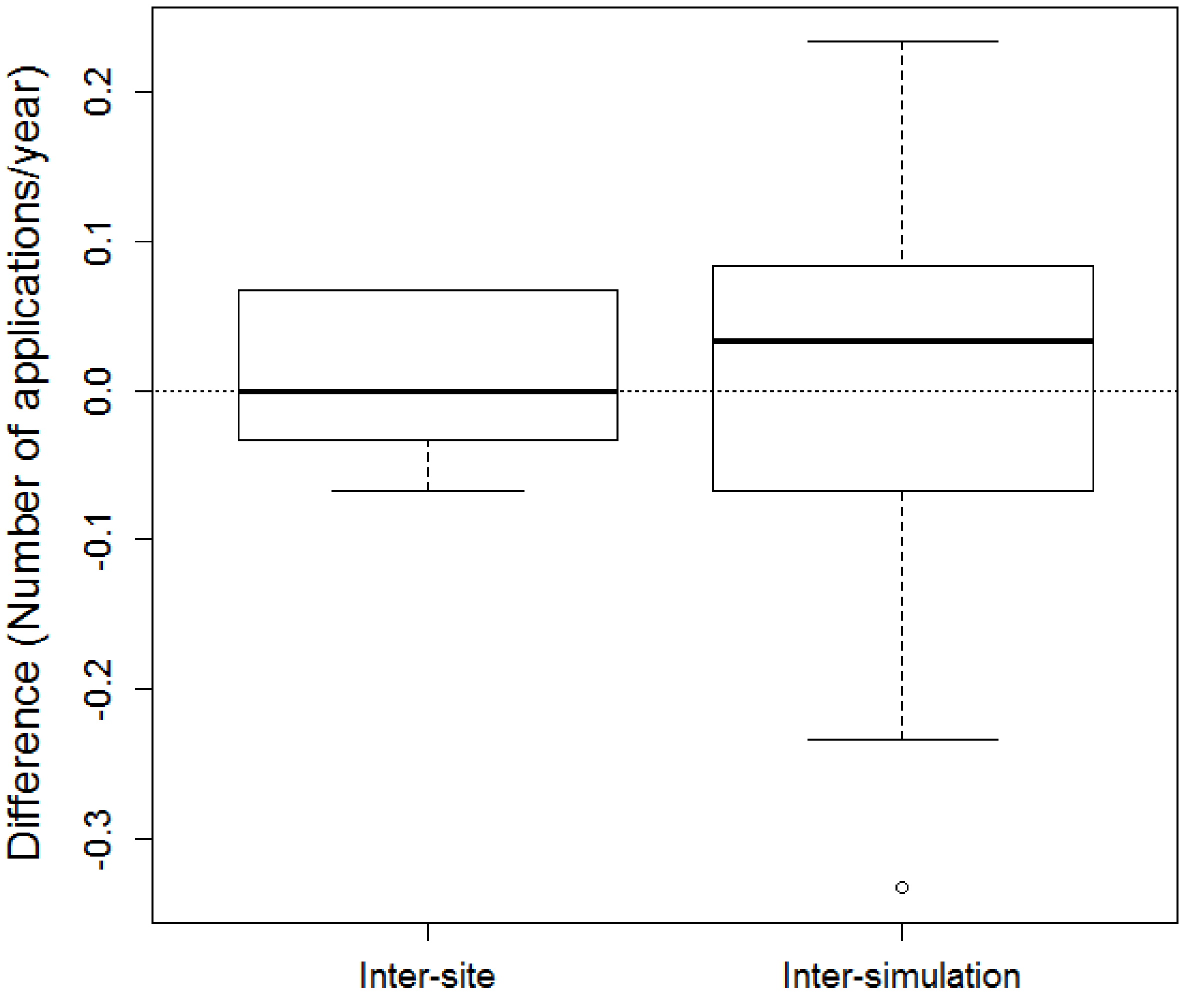

Figure 6. Box plots of the mean differences between the periods 1981-2010 and 2011-2040 for the number of bactericide applications for control of fire blight (apple). Each plot is constructed using: (left; "Inter-site") 9 data points, namely the median of the mean differences of the 23 climate simulations for each of the 9 sites; (right; "Inter-simulation") 23 data points, namely the median of the mean differences of the 9 sites for each of the 23 climate simulations.

5.1.3 Maximum daily rainfall

The most important rainfall events are those that occur shortly after pesticide application. Each year, for each site/crop/climate simulation combination, maximum daily rainfall was extracted from a time window centered on the median herbicide or insecticide application date among the

100 realizations. The term *moving* is used to refer to this window, since its centre varies from year to year. The length of the windows was set at 31 days for herbicide applications and 11 days for insecticide applications, which corresponds approximately to the average duration of the application windows. Table 7 summarizes the results of the Mann-Kendall test for the 60-year trend for maximum daily rainfall during these herbicide (wheat, corn and soybean) and insecticide (apple) application windows. The proportion of positive trends varies from 37.2% (second application of insecticide for apple) to 63.5% (pre-emergent application for corn). Overall, the number of positive trends is slightly higher than the number of negative trends, particularly for applications early in the season, but the proportion of statistically significant trends is less than 5%, except for the pre-emergent application for corn (6.1% positive trends) and for the second and third insecticide applications for apple (7.2 and 6.3% negative trends, respectively). There is therefore no clear trend for maximum daily rainfall during the application window.

Table 7. Results of the Mann-Kendall test on maximum daily rainfall during the moving window for the period 1981-2040, for each crop/site/climate simulation combination. The application scenarios used are presented in Table 3 for wheat, corn and soybean and in Table 4 for apple. The windows are centered on the median application date calculated each year. A trend is considered significant if the observed test threshold is less than 0.05.

Crop	Number of tests	Number of positive trends		Number of negative trends	
		Significant	Total	Significant	Total
Wheat	230	2 (0.9%)	123 (53.5 %)	3 (1.3%)	107 (46.5%)
Corn (pre-emergent)	230	14 (6.1%)	146 (63.5 %)	2 (0.9%)	84 (36.5%)
Corn (post-emergent)	230	6 (2.6%)	111 (48.3 %)	1 (0.4%)	118 (51.3%)
Soybean	230	4 (1.7%)	118 (51.3 %)	5 (2.2%)	111 (48.3%)
Apple (1st application)	207	4 (1.9%)	115 (55.6 %)	5 (2.4%)	91 (44.0%)
Apple (2nd application)	207	6 (2.9%)	77 (37.2 %)	15 (7.2%)	129 (62.3%)
Apple (3rd application)	207	6 (2.9%)	111 (53.6 %)	13 (6.3%)	96 (46.4%)

The application window correlates with the changes in climate. A warmer than average early season will advance the timing of applications, whereas a colder early season will delay the timing of applications. In order to exclude the interannual variation in application dates, the annual maximum daily rainfall was also extracted from a time window centered on the median application date for the entire 60-year period (thus identical from year to year), for each site/crop/climate simulation combination. The term *fixed* is used to refer to this window. The lengths of the windows are still fixed at 31 and 11 days for the herbicide and insecticide applications, respectively. The results of the Mann-Kendall test are presented in Table 8. Overall, there are more upward trends than in Table 7. This is true for all herbicide applications. The tests performed on a fixed window over the 60-year period even indicate an increase of over 10% in the number of positive trends for the post-emergent application for corn compared to the tests performed on the moving window, which varies from year to year as a function of temperature and which more realistically represents the application period. These results suggest that adjusting the application window on the basis of seasonal weather could reduce the impact of climate change to some extent. However, this effect is not statistically significant; the number of significant trends remains low (Table 8).

Table 8. Results of the Mann-Kendall test on maximum daily rain during the fixed application window for the period 1981-2040, for each crop/site/climate simulation combination. The application scenarios used are presented in Table 3 for wheat, corn and soybean and in Table 4 for apple. The windows are centered on the median application date calculated over the entire 60 years. A trend is considered significant if the observed test threshold is less than 0.05.

Crop	Number of tests	Number of positive trends		Number of negative trends	
		Significant	Total	Significant	Total
Wheat	230	3 (1.3%)	137 (59.6%)	1 (0.4%)	92 (40.0%)
Corn (pre-emergent)	230	19 (8.3%)	148 (64.3%)	0 (0%)	82 (35.7%)
Corn (post-emergent)	230	5 (2.2%)	136 (59.1%)	4 (1.7%)	93 (40.4%)
Soybean	230	6 (2.6%)	135 (58.7%)	7 (3.0%)	95 (41.3%)
Apple (1st application)	207	4 (1.9%)	109 (52.7%)	4 (1.9%)	94 (45.4%)
Apple (2nd application)	207	3 (1.5%)	89 (43.0%)	12 (5.8%)	118 (57.0%)
Apple (3rd application)	207	10 (4.8%)	106 (51.2%)	6 (2.9%)	101 (48.8%)

Figure 7 illustrates the mean difference in maximum daily rainfall between the periods 1981-2010 and 2011-2040 during the moving and fixed application windows. The mean difference over 30 years is generally slightly higher for fixed windows (Figure 7b) than for moving windows (Figure 7a), which corroborates the results of Tables 7 and 8. The difference between the moving and fixed windows is greater for the herbicide applications, which are done in the spring. The calculation of the average for all climate simulations at each site gives an average increase between the periods 1981-2010 and 2011-2040 for almost all site/fixed herbicide application window combinations (39/40). For the site/moving application window combinations for herbicides, an average increase is obtained in only 26 of 40 cases. However, increases remain minimal compared to the variability between the site/climate simulation combinations.

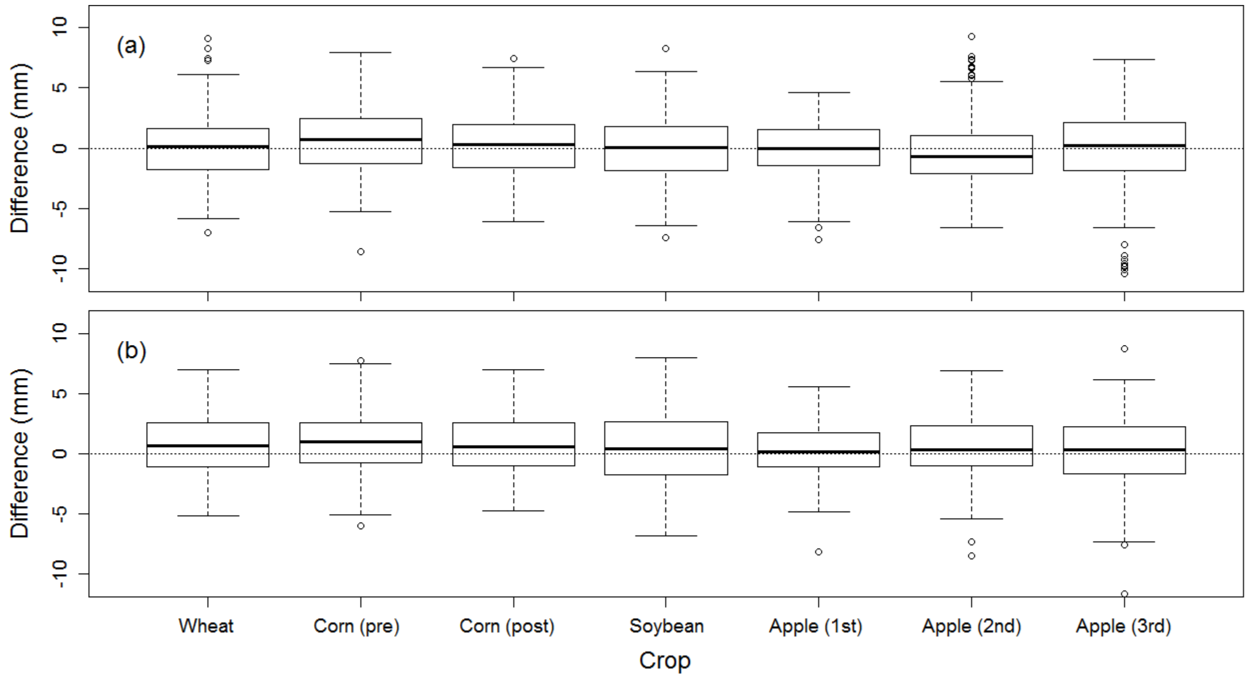

Figure 7. Box plots of the mean differences in maximum daily rainfall between the periods 1981-2010 and 2011-2040 during the (a) moving and (b) fixed application windows. The plots are constructed using all site/climate simulation combinations for a given crop (207 for apple, 230 for the other crops). Pre = pre-emergent; post = post-emergent.

5.1.4 Average daily rainfall

Table 9 summarizes the results of the Mann-Kendall test for the 60-year trend in average daily rainfall during the moving applications windows as calculated in Section 5.1.3. There are fewer upward trends for average rainfall than for maximum daily rainfall (Table 7) and few of them are statistically significant. There is therefore no clear impact of climate change on average daily rainfall during the application window (1981-2040) for the sites considered.

Table 10 presents the results of the Mann-Kendall test performed on average daily rainfall during the period 1981-2040 during the fixed application windows as calculated in Section 5.1.3. As with maximum daily rainfall, there are fewer positive trends in the case of moving application windows, which vary from year to year, than in the case of fixed application windows. However, in absolute terms, the differences over 30 years between past and future average daily rainfall are small relative to the variability between the site/climate simulation combinations, for both the moving and fixed application windows (Figure 8).

Table 9. Results of the Mann-Kendall test performed on average daily rainfall during the moving application window for the period 1981-2040, for each crop/site/climate simulation combination. The application scenarios used are presented in Table 3 for wheat, corn and soybean and in Table 4 for apple. The windows are centered on the median application date calculated each year. A trend is considered significant if the observed test threshold in less than 0.05.

Crop	Number of tests	Number of positive trends		Number of negative trends	
		Significant	Total	Significant	Total
Wheat	230	1 (0.4%)	106 (46.1%)	4 (1.7%)	122 (53.0%)
Corn (pre-emergent)	230	6 (2.6%)	123 (53.5%)	0 (0%)	106 (46.1%)
Corn (post-emergent)	230	3 (1.3%)	97 (42.2%)	3 (1.3%)	132 (57.4%)
Soybean	230	2 (0.9%)	102 (44.3%)	9 (3.9%)	125 (54.3%)
Apple (1st application)	207	4 (1.9%)	132 (63.8%)	2 (1.0%)	75 (36.2%)
Apple (2nd application)	207	2 (1.0%)	75 (36.2%)	17 (8.2%)	131 (63.3%)
Apple (3rd application)	207	11 (5.3%)	109 (52.7%)	10 (4.8%)	97 (46.9%)

Table 10. Results of the Mann-Kendall test performed on average daily rainfall during the fixed application window for the period 1981-2040, for each crop/site/climate simulation combination. The application scenarios used are presented in Table 3 for wheat, corn and soybean and in Table 4 for apple. The windows are centered on the median application date calculated over the entire 60-year period. A trend is considered significant if the observed test threshold is less than 0.05.

Crop	Number of tests	Number of positive trends		Number of negative trends	
		Significant	Total	Significant	Total
Wheat	230	10 (4.3%)	128 (55.7%)	5 (2.2%)	98 (42.6%)
Corn (pre-emergent)	230	17 (7.4%)	132 (57.4%)	2 (0.9%)	98 (42.6%)
Corn (post-emergent)	230	10 (4.3%)	129 (56.1%)	2 (0.9%)	100 (43.5%)
Soybean	230	6 (2.6%)	107 (46.5%)	8 (3.5%)	123 (53.5%)
Apple (1st application)	207	3 (1.4%)	144 (69.6%)	1 (0.5%)	62 (30.0%)
Apple (2nd application)	207	3 (1.4%)	91 (44.0%)	14 (6.8%)	115 (55.6%)
Apple (3rd application)	207	16 (7.7%)	105 (50.7%)	2 (1.0%)	102 (49.3%)

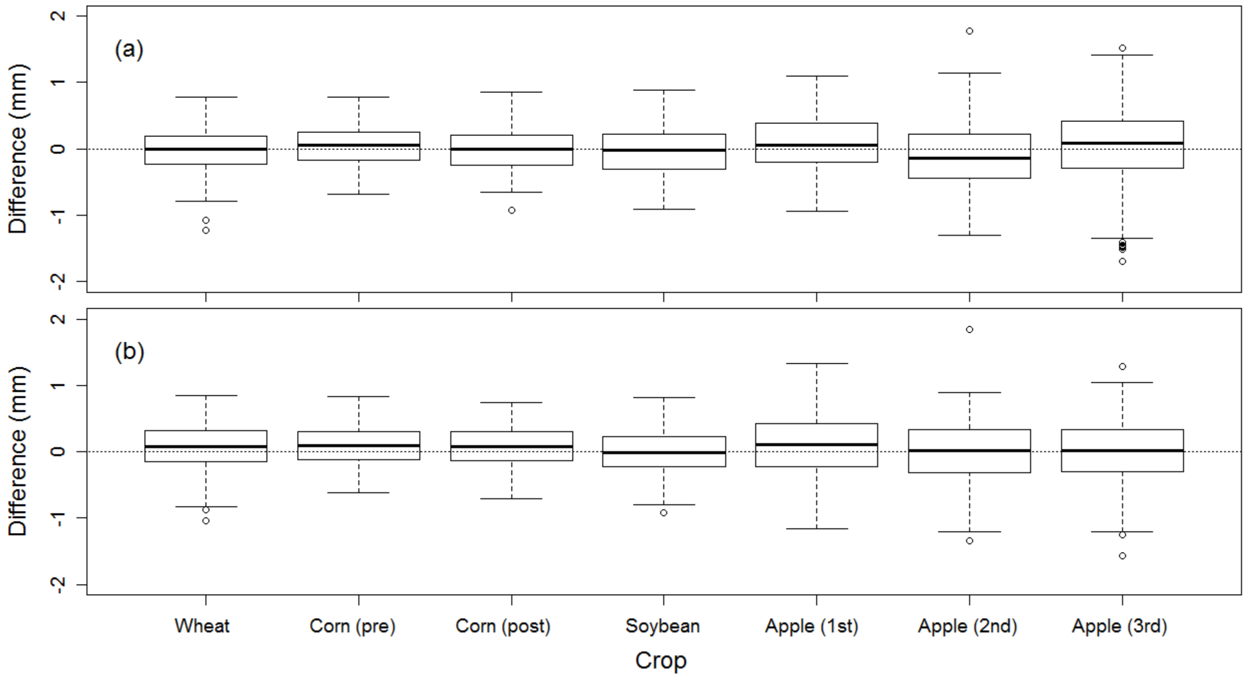

Figure 8. Box plots of mean differences between the periods 1981-2010 and 2011-2040 for average daily rainfall during the (a) moving and (b) fixed application windows. The plots are constructed using all site/climate simulation combinations for a given crop (207 for apple, 230 for the other crops). Pre = pre-emergent; post = post-emergent.

5.2 Pesticide contamination of runoff water

The analyses were conducted separately for dissolved loads and adsorbed loads (transported in eroded soil). The values of interest are the annual maximum daily load and the annual mean load. The correlation between these two variables is very strong. For all site/simulation/crop/active ingredient/realization combinations, the proportion of the total load over the 60-year period coming from the annual maximum daily loads is on average 85% for pesticide loads transported in the dissolved form and 90% for loads transported in the adsorbed form. The annual maximum daily loads account for more than half of the total load simulated over 60 years in 97% and 99% of the cases for the dissolved and adsorbed forms, respectively. That is why only the annual mean loads were analyzed. The average relative loss and the average concentration in runoff water are also presented for each active ingredient.

5.2.1. Changes in the annual load transported in dissolved form

There are a total of 510,600 annual series (site/climate simulation/crop/active ingredient /realization combinations) and as many trends estimated using the Mann-Kendall test. Figure 9 presents box plots illustrating the proportion of positive trends obtained for each site, active ingredient, realization and simulation.

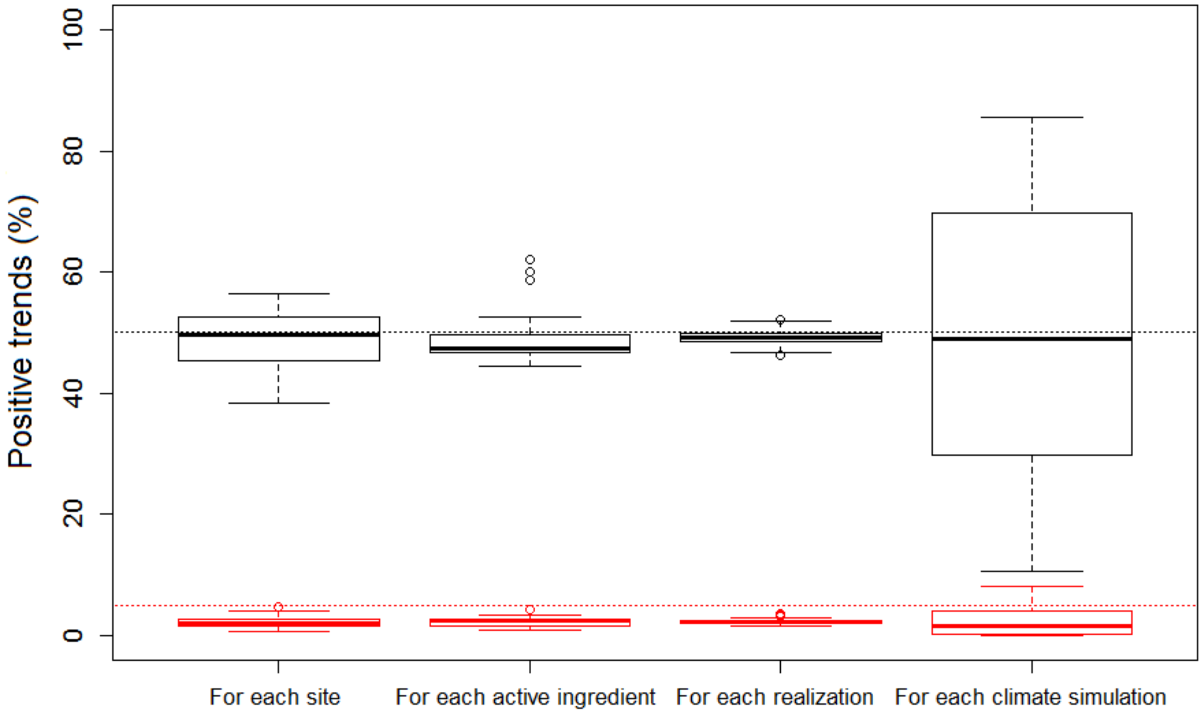

Figure 9. Proportion of positive trends (%) for the annual dissolved load, obtained for each of the 28 sites, 21 active ingredients, 100 realizations and 23 climate simulations. The red box plots illustrate the proportions of positive trends that are significant according to the Mann-Kendall test. The red line represents the test threshold (5%).

On average, approximately half of the trends are positive, and approximately half are negative, but very few of the trends are statistically significant. The impact of climate change on the transported loads is therefore very limited, with the exception of the three fungicides considered for the control of apple scab (captan, mancozeb and metiram). For these three fungicides, roughly 60% of the trends are positive. These positive trends are caused by the slight increase, on average, in the number of annual applications between the periods 1981-2010 and 2011-2040 (Figure 5). In absolute terms, the average load of captan transported annually in dissolved form increased from 1.32 g/ha for the period 1981-2010 to 1.44 g/ha for the period 2011-2040. Given that captan is highly volatile (Appendix A), this load corresponds, on average, to less than 0.01% of the mass applied annually. For mancozeb, which is even more volatile (Appendix A), the average annual runoff load increases from 3.79 x 10^{-3} to 4.15 x 10^{-3} g/ha. For metiram, which is volatile and almost immobile (Appendix A), the average annual runoff load increases from 3.47 x 10^{-3} to 4.7 x 10^{-3} g/ha. In short, the average increase in the load transported in dissolved form between the periods 1981-2010 and 2011-2040 for these three fungicides is 10%, but in absolute terms the values are low. It should be noted that the proportion of upward trends that are statistically significant is low. With longer time series, it would likely have been possible to detect a larger number of significant trends.

There is very large variability among the 23 climate simulations, with the percentage of positive trends varying from 10% to 85%. This indicates that the "natural" variability is greater than the climate change signal. The results of Section 5.1 had already indicated larger inter-simulation variability than inter-site variability for the influent climate variables. Nonetheless, there is some degree of inter-site variability. The site characteristic (Appendix D) most strongly correlated with the proportion of positive trends is the field capacity, with 32%. Except for the three active ingredients used for the control of apple scab, variability between the active ingredients is low.

The impact of climate change on the runoff loads varies very little from realization to realization (Figure 9). Nonetheless, the differences between the realizations, although small, indicate that some parameters of the PRZM can have an impact on the changes in the annual runoff load over time. Table 11 presents, for each parameter, the correlation between the proportion of positive trends for each realization and the pseudo-random value used to generate the parameter (Appendix F). The results indicate that the change in annual load varies significantly as a function of the values chosen for two parameters. Parameter KP, governing field capacity and permanent wilting point, is 47% positively correlated with the proportion of positive trends. This corroborates the results of the analysis of the change in loads for each site. Since soil organic carbon is positively correlated with field capacity, the parameter OC is also positively correlated with the proportion of upward trends for the annual load. It should be noted that the impact of these parameters is statistically significant, but is limited in absolute terms (Figure 9).

Table 11. Pearson's correlation coefficient (%) between the proportion of positive trends for each realization and the pseudo-random value used to generate each parameter (Appendix F). The asterisks indicate whether the correlation is statistically significant (*: < 0.1; **: < 0.05; *: < 0.01). The parameters are defined in Appendix E.**

Parameter	Correlation	Parameter	Correlation	Parameter	Correlation
SFAC	0.05	MNGN	-0.05	UPTKF	0.01
CINTCP	-0.16	CN	0.13	FEXTRC	-0.09
AMXDR	-0.06	DEPI	0.05	KP and BD	0.47***
COVMAX	-0.07	TAPP	-0.07	OC	0.41***
HTMAX	-0.18*				

Changes in the runoff load over 30 years (1981-2010 compared to 2011-2040) were calculated separately for each of the 222 site/crop/active ingredient combinations. For each combination, there are 2,300 differences over 30 years (23 climate simulations x 100 realizations). The variability between simulations can be estimated using, for each climate simulation, the mean difference over the 100 realizations (23 values). Similarly, the variability between realizations can be estimated using, for each realization, the mean difference over the 23 climate simulations (100 values). 90% confidence intervals for variability between simulations and between realizations were then calculated based on the 23 and 100 values, respectively. For all of the 222 site/crop/active ingredient combinations, the 90% confidence interval for the inter-simulation variability of the differences over 30 years contains the value 0. Thus, for the 222 cases, the inter-simulation variability is too large to conclude that there is a significant impact.

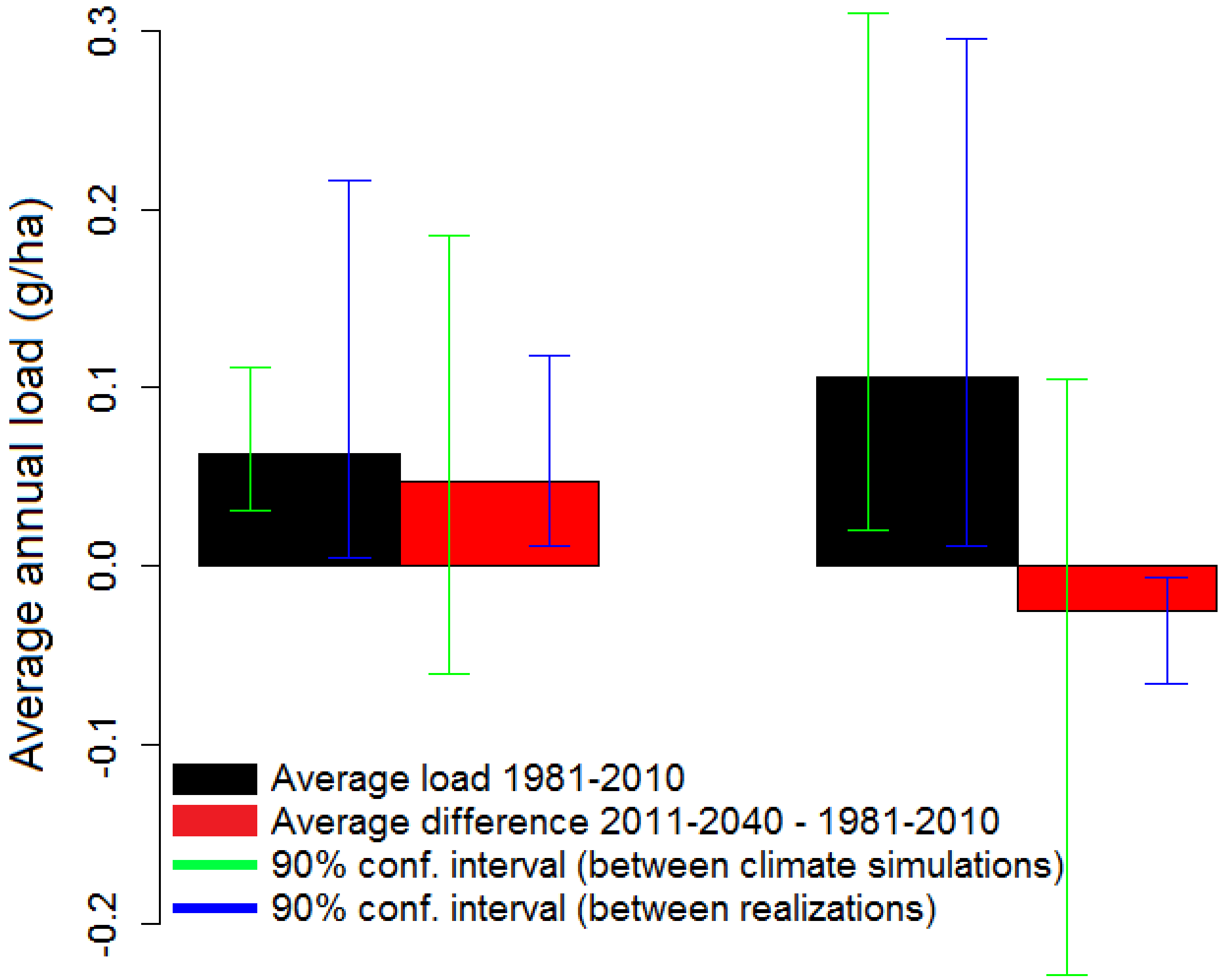

Figure 10. Differences in the average annual load transported in dissolved form between the periods 1981-2010 and 2011-2040 for two site/crop/active ingredient combinations. In both cases, the active ingredient is streptomycin sulphate. Left: site 28; right: site 23.

There are 39 cases in which 0 is outside the range of the 90% confidence interval for inter-realization variability in the differences over 30 years, namely 28 positive mean differences and 11 negative mean differences. Two of these cases, from among the most extreme, are illustrated in Figure 10. For the majority of the 222 runoff loads over 30 years (1981-2010), the inter-realization intervals are larger than the inter-simulation intervals. For most of the 222 load differences over 30 years (1981-2010 compared to 2011-2040), the opposite is true, i.e., inter-simulation intervals are larger than inter-realization intervals. The selected values of the parameters of the transport model have a significant impact on the values of the simulated runoff loads, but the temporal changes in the loads depend more on climate than on the value of the parameters.

5.2.2 Changes in the load transported in adsorbed form

Figure 11 presents box plots illustrating the proportion of positive trends for the annual load transported in adsorbed form, for each site, active ingredient, realization and climate simulation.

The results are very similar to those obtained for the load transported in dissolved form, i.e., overall, the runoff loads do not increase significantly during the period studied (1981-2040). There is no visible impact of climate change, except in the case of the three active ingredients used for the control of apple scab. The correlation between the proportion of positive trends for the annual loads transported in dissolved and adsorbed form is 97.6% for the site averages, 97.2% for the active ingredient averages, 91.9% for the realization averages and 99.7% for the simulation averages.

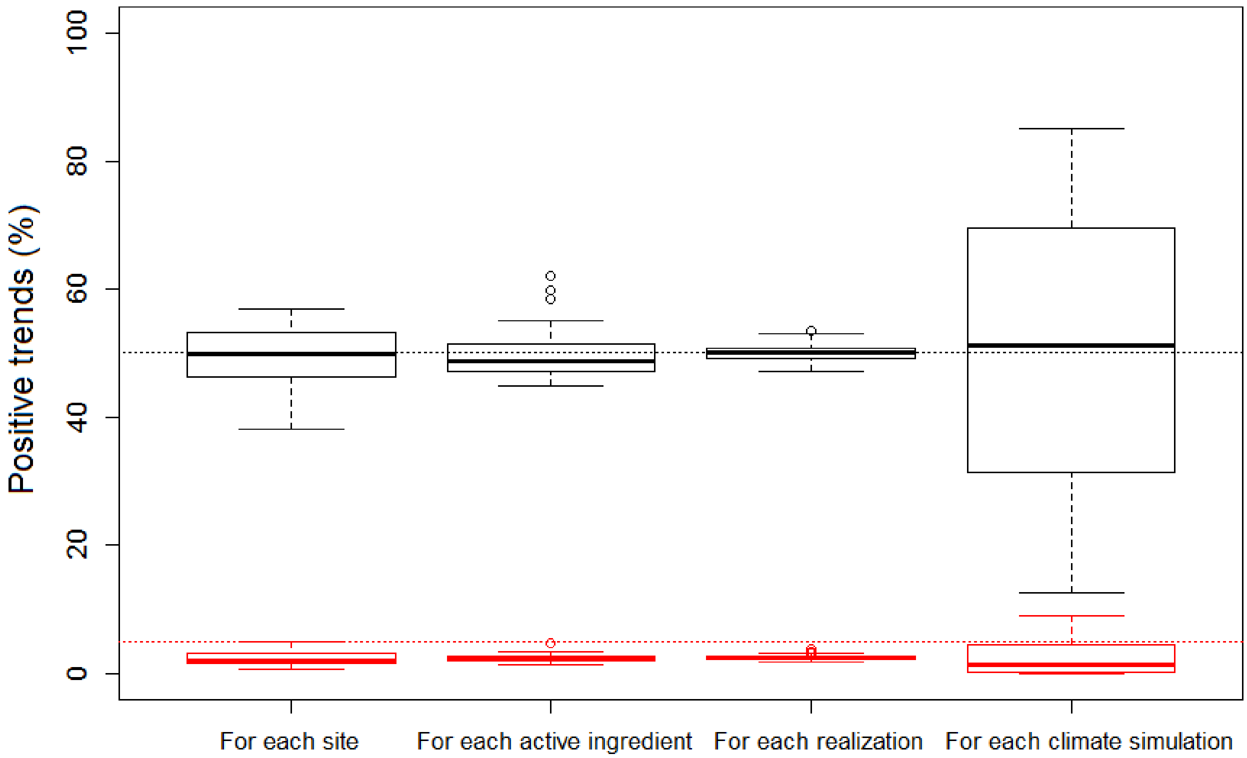

Figure 11. Proportion of positive trends (%) for the annual load transported in adsorbed form, for each of the 28 sites, 21 active ingredients, 100 realizations and 23 climate simulations. The red box plots illustrate the number of positive trends that are significant according to the Mann-Kendall test. The red line represents the test threshold (5%).

The difference in the load transported in adsorbed form over 30 years (1981-2010 compared to 2011-2040) and the 90% inter-simulation and inter-realization confidence intervals are calculated in the same manner as for loads transported in the dissolved form (Section 5.2.1) for the 222 site/crop/active ingredient combinations. Once again, the 90% confidence interval for the variability in differences between simulations over 30 years contains the value 0 for all combinations. There are 29 cases in which 0 is outside the range of the 90% confidence interval for variability in differences between realizations over 30 years, namely 24 positive mean differences and 5 negative mean differences. As in the case of the loads transported in dissolved form, the variability of the load over 30 years (1981-2010) is larger between realizations, whereas the variability of the difference in load over 30 years (1981-2010 compared to 2011-2040) is larger between simulations.

5.2.3 Average relative loss for each active ingredient

Table 12 presents the average proportion of the applied mass that is transported in dissolved and adsorbed forms for each active ingredient. The average losses obtained are all less than 1%, which corroborates the figures reported in the literature (Wauchope, 1978; Bloomfield et al., 2006). At the event scale, the percentage of losses may be larger than 1%. Active ingredients with a long half-life generally show larger losses overall. The proportion of the loss from the adsorbed form increases with the value of the water/organic carbon partitioning coefficient (K_{oc}; Appendix A).

Table 12. Average proportion of the applied mass that is transported in runoff water in dissolved and adsorbed form, by active ingredient

Crop	Active ingredient	Loss in dissolved form (%)	Loss in adsorbed form (%)	Total (%)
Wheat	Bromoxynil	4×10^{-3}	4×10^{-3}	8×10^{-3}
	Fenoxaprop-p-ethyl	3×10^{-5}	1×10^{-3}	1×10^{-3}
	Pyrasulfotole	0.12	0.09	0.22
	Thifensulfuron-methyl	0.05	3×10^{-3}	0.05
	Tribenuron-methyl	0.10	6×10^{-3}	0.11
Corn	Atrazine	0.12	0.01	0.13
	Dicamba	0.03	2×10^{-4}	0.03
	Glyphosate	0.02	0.07	0.09
	Mesotrione	0.10	0.01	0.11
	S-metolachlor	0.07	0.01	0.08
Soybean	Bentazon	0.09	8×10^{-3}	0.10
	Glyphosate	0.02	0.09	0.11
	Imazethapyr	0.15	0.01	0.16
	Quizalofop-p-ethyl	4×10^{-3}	0.01	0.02
	Thifensulfuron-methyl	0.04	3×10^{-3}	0.05
Apple	Acetamiprid	0.01	5×10^{-4}	0.01
	Phosmet	9×10^{-3}	8×10^{-4}	9×10^{-3}
	Spinetoram	8×10^{-3}	0.01	0.02
	Thiacloprid	0.05	3×10^{-3}	0.05
	Captan	0.01	5×10^{-4}	0.01
	Mancozeb	2×10^{-5}	2×10^{-6}	2×10^{-5}
	Metiram	3×10^{-5}	1×10^{-3}	1×10^{-3}
	Streptomycin sulphate	0.04	4×10^{-5}	0.04

5.2.4 Average concentration in water for each active ingredient

Table 13 presents the averages of the annual mean concentration and annual maximum daily concentration for each active ingredient in runoff water (sum of the dissolved and adsorbed forms). The concentrations are accompanied by threshold values for the protection of agricultural activities (livestock watering). The criteria for the protection of aquatic life and drinking water were not taken into account, since pesticide transport was simulated at the field scale. The average annual maximum daily concentration exceeds the toxicity threshold for the protection of agricultural activities (livestock watering) in two of seven cases where a threshold value is available. Atrazine shows one of the highest simulated transported concentrations, and is the most toxic of the six active ingredients for which toxicity criteria exist. The average annual maximum daily concentration of captan also exceeds the threshold value, even though only 0.01% of what is applied is transported in runoff water (Table 12).

5.3 Impact of adaptation measures

Each adaptation measure was tested on a single active ingredient in order to limit the run time (Table 6, Section 4.2.3). For each site, 2,300 (23 climate simulations x 100 realizations) 60-year series (1981-2040) are simulated. The impact of adaptation is assessed on the basis of the difference between the total 30-year loads of the simulations with adaptation and the reference simulations (without adaptation). The impact is compared with the impact of climate change, assessed on the basis of the mean differences over 30 years between the simulations with adaptation and the reference simulations. The confidence level of the impact of adaptation is assessed, for each site, on the basis of the variability between realizations and between simulations. It should be noted that none of the measures tested can be applied for the fungicides and bactericides considered in this project.

5.3.1 No application the day before rainfall

For the reference simulations, the herbicide and insecticide applications could not be carried out if more than 1 mm of rain fell during the target day. This measure consists in adding a constraint, i.e., not to carry out applications if more than 1 mm of rain is forecast for the day after the target day. It must be assumed that producers are willing to shorten their application window, with the risks this may entail. This measure could not necessarily be as strictly applied in practice, given the importance of treating crops at the right time, even in the case of herbicides (D. Bernier, MAPAQ, pers. comm.). It simply could not be implemented for fungicides and bactericides, given that the treatments are often applied under wet conditions. Nonetheless, this measure can be used to assess the impact of the delayed application on pesticide transport in runoff water. It is evaluated here for phosmet, an insecticide used on apple trees.

Table 13. Averages of the annual mean concentration and annual maximum daily concentration for each active ingredient in runoff water (sum of dissolved and adsorbed forms). The values are averages calculated using all site/realization/simulation combinations over 60 years (1981-2040). The threshold value is the value used by the Quebec Department of Sustainable Development, Environment and the Fight Against Climate Change (MDDELCC, 2002) for the protection of agricultural activities (livestock watering). This value is not available for all active ingredients. Averages above the threshold are in bold.

Crop	Active ingredient	Annual mean concentration (µg/L)	Annual maximum daily concentration (µg/L)	Threshold value (µg/L)
Wheat	Bromoxynil	0.02	0.8	11
	Fenoxaprop-p-ethyl	7×10^{-4}	0.03	-
	Pyrasulfotole	0.2	2.8	-
	Thifensulfuron-methyl	8×10^{-3}	0.3	-
	Tribenuron-methyl	8×10^{-3}	0.2	-
Corn	Atrazine	2.4	**55**	5
	Dicamba	0.4	21	122
	Glyphosate	1.9	53	280
	Mesotrione	0.3	7	-
	S-metolachlor	1.6	43	-
Soybean	Bentazon	1.7	44	> 510
	Glyphosate	2.9	78	280
	Imazethapyr	0.3	6	-
	Quizalofop-p-ethyl	0.02	0.7	-
	Thifensulfuron-methyl	4.3	143	-
Apple	Acetamiprid	0.1	1.1	-
	Phosmet	1.3	11	-
	Spinetoram	0.1	0.5	-
	Thiacloprid	0.7	3.3	-
	Captan	3.0	**40**	13
	Mancozeb	0.01	0.1	-
	Metiram	0.3	4.6	-
	Streptomycin sulphate	1.9	44	-

Figure 12 presents the average annual load transported in dissolved form for the past (1981-2010) and the effects of the climate change adaptation measure for the nine simulated sites. These results are accompanied by 90% confidence intervals for variability between simulations and between realizations. It should be noted that the results obtained for each average annual load adsorbed to eroded soil particles follow the same trend, but the values are smaller (results not presented).

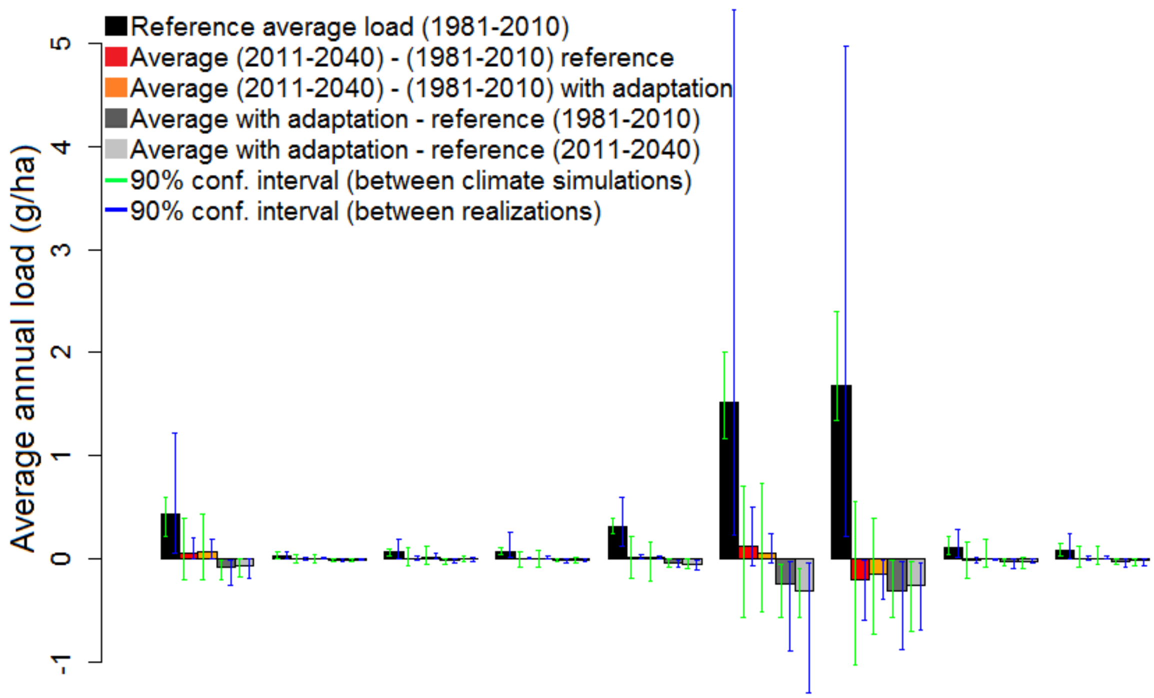

Figure 12. Impact of the adaptation measure (no application the day before rain) and climate change on the runoff load of dissolved phosmet, assessed on the 30-year averages for the nine sites simulated.

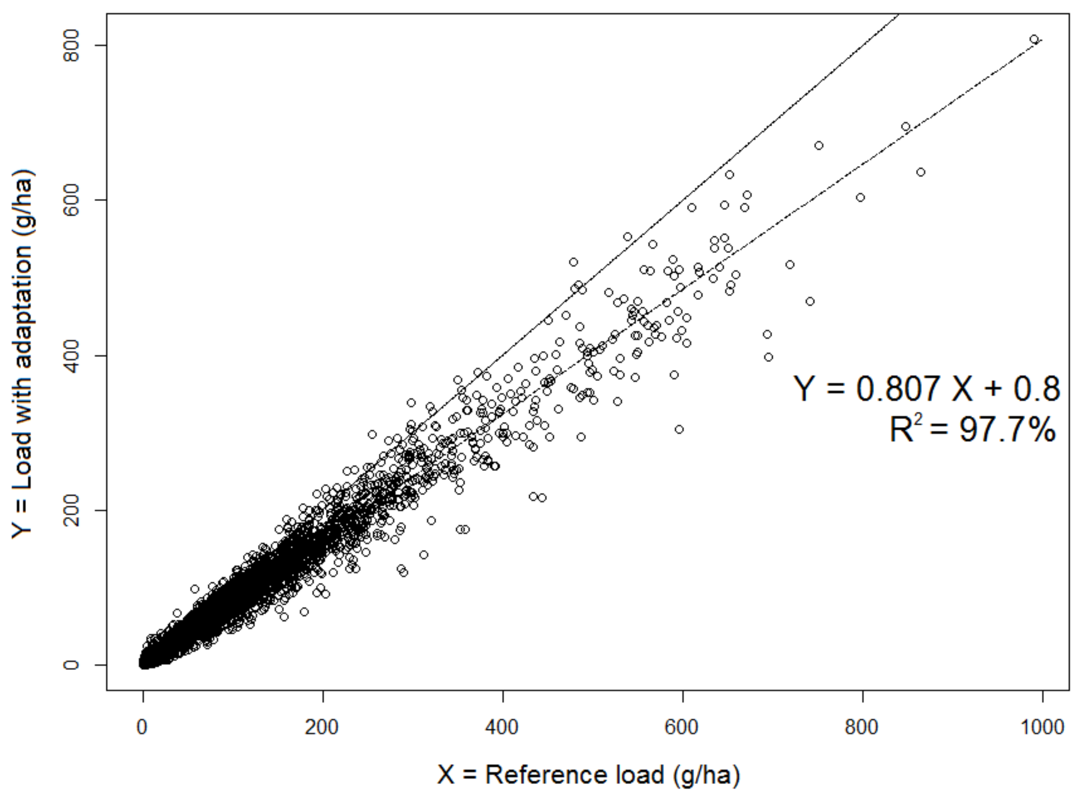

Figure 13. Total phosmet load (1981-2040) transported in dissolved form in runoff water in the simulations and with no adaptation measure for the 20,700 site/simulation/realization combinations. The solid line is the line Y = X and the dashed line is the regression line.

The impact of the adaptation measure is significant for sites with the highest runoff loads. This suggests that for sites having the highest runoff loads for the reference simulations, there was at least one significant rain event the day after an application. A comparison of the total loads over 60 years obtained in simulations with and without adaptation for all site/simulation/realization combinations shows that the load with adaptation is on average approximately 20% lower (Figure 13). This decline roughly corresponds to the daily degradation rate of phosmet used in all simulations, namely ln(2)/half-life = ln(2)/3.1 day = 22%/day (Appendix A).

In cases where the majority of the total runoff load comes from rain events that occur the day after treatment, the decrease caused by this adaptation measure should be approximately equal to ln(2)/long-term half-life. In all likelihood, this should be the case for active ingredients having a relatively short half-life. For active ingredients having a long half-life, the decrease should be smaller, given that intense rainfall events can transport a large pesticide load, even if they occur several days after treatment. In any event, at the daily scale, all things being equal, a one-day increase in the interval between treatment and rainfall will result in a decrease in the transported load approximately equal to the daily degradation rate of the active ingredient. This illustrates the importance of using less persistent products and of having a long time interval between treatment and the next rainfall, where possible. This is true despite climate change.

5.3.2 Variation of rain threshold

This section presents an analysis of the sensitivity of runoff loads to the precipitation threshold value defined for the herbicide and insecticide applications. For the reference simulations, herbicide and insecticide applications are permitted only if the accumulated precipitation during the target day is less than 1 mm. Thresholds of 0.1 and 5 mm were tested for phosmet (apple trees) at nine sites. The value of 0.1 mm essentially corresponds to no precipitation and the value of 5 mm is a value beyond which it is unlikely that a producer would apply a treatment.

Figure 14 indicates that lowering the threshold from 1 to 0.1 mm has virtually no effect on the total pesticide load transported in the dissolved form. The results are similar for the adsorbed form (not presented). It is important to note that the reference threshold (1 mm) is already a constraint, and increasing the threshold to 5 mm has no appreciable effect (Figure 15). This indicates that intense rainfall events are what contribute most to the total load. Producers should try to avoid such events, where possible.

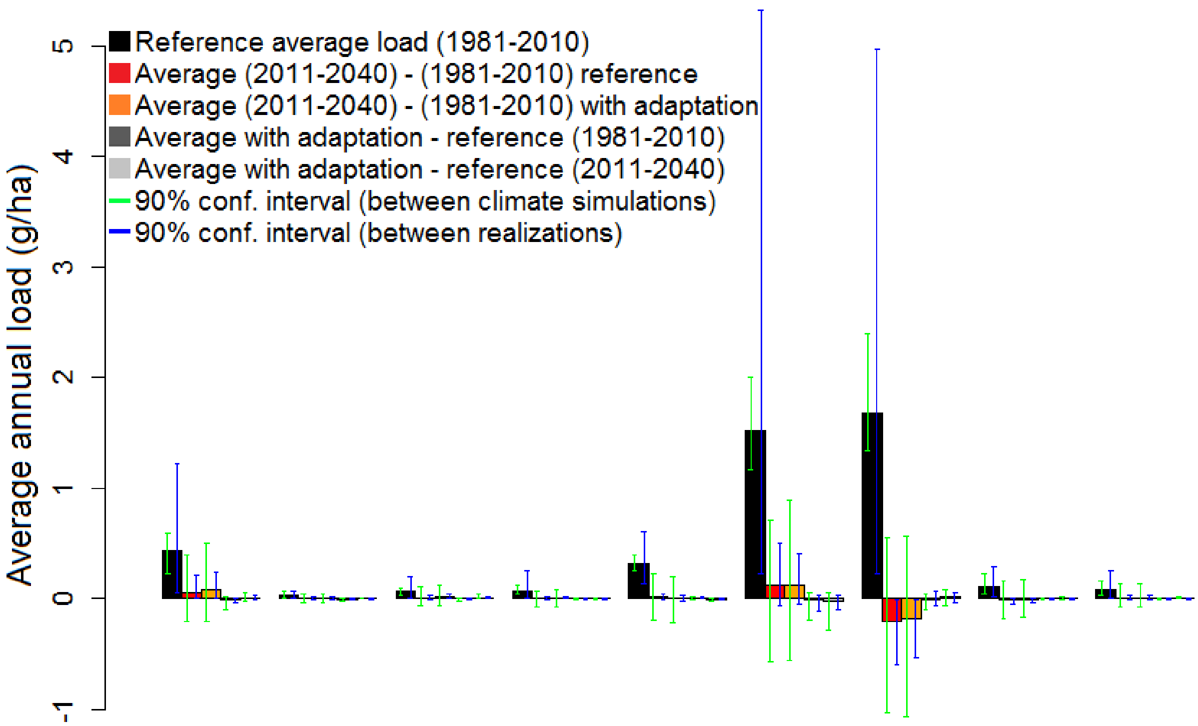

Figure 14. Impact of the adaptation measure (lowering the rainfall threshold from 1 to 0.1 mm) and of climate change on the runoff load of dissolved phosmet, assessed on the basis of the averages over 30 years for the nine sites simulated.

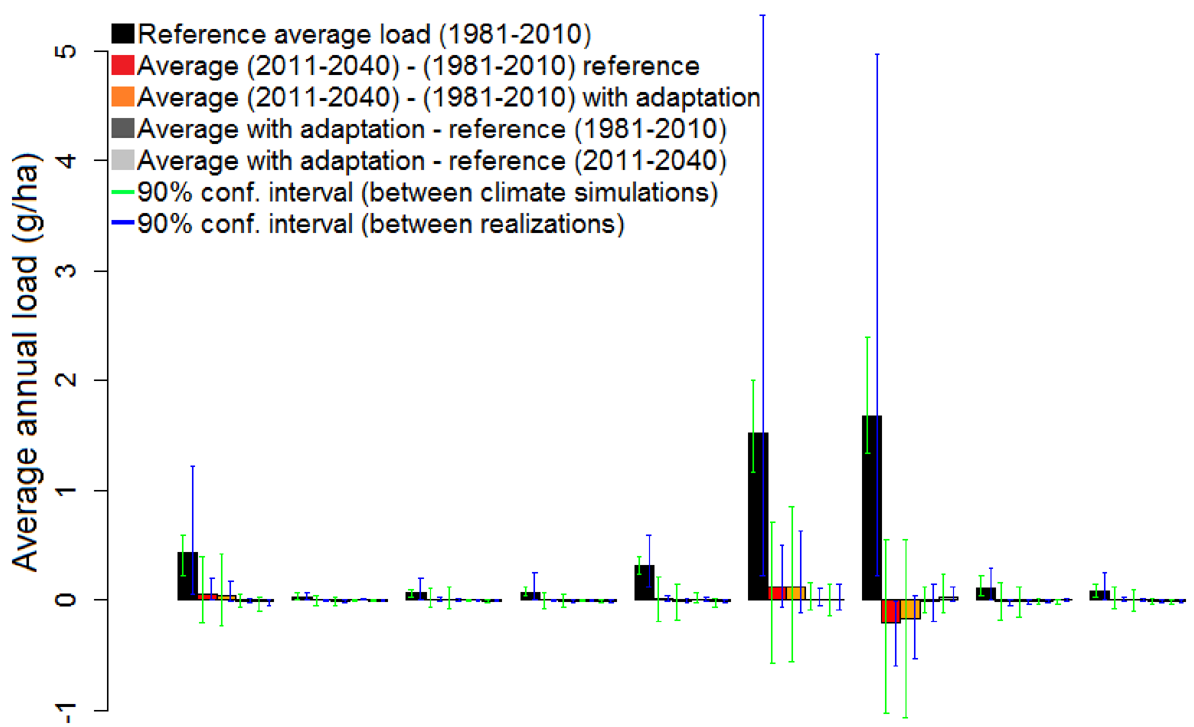

Figure 15. Impact of the adaptation measure (raising of the rainfall threshold from 1 to 5 mm) and of climate change on the runoff load of dissolved phosmet, assessed on the basis of the averages over 30 years for the nine sites simulated.

5.3.3 Reduced tillage

Reduced tillage is a system that involves less tillage than conventional tillage. It is difficult to precisely define the nature and impact of reduced tillage, as it encompasses a wide range of practices and its definition evolves over time, i.e., a practice once considered reduced tillage could now be considered conventional tillage (AAFC, 2014). In this section, reduced tillage was considered to be reflected by a 2% reduction in the curve number (CN; Appendix E) (Table 5.13; Suarez, 2005) over the entire year, a roughly 13% reduction in the C factor of the Universal Soil Loss Equation (USLE; Appendix E) over the entire year (Wall et al., 2002) and a decrease in Manning's roughness coefficient (MNGN; Appendix E; see Table 5.46 of Suarez, 2005). However, because reduced tillage leaves more weed seeds in the top centimetres of soil than conventional tillage (Douville, 2002), this adaptation measure requires an additional preplant application of glyphosate. The rate of application for a corn field ranges from 0.27 to 5.76 kg/ha (SAgE pesticides, 2014), and it was assumed that it took place no more than five days prior to planting. The adaptation was tested for glyphosate-resistant corn. For all simulations, with or without adaptation, a post-emergent glyphosate application was simulated for glyphosate-resistant corn at a rate ranging from 0.9 to 1.8 kg/ha (Table 3, Section 4.2.2), which is generally lower than the preplant rate assumed for the adaptation measure.

Figure 16 presents the average annual load transported in dissolved form in the past (1981-2010) as well as the effects of the adaptation measure and of climate change for the 10 sites simulated, accompanied by 90% confidence intervals for variability between simulations and between realizations.

The results show that average runoff loads for the simulations with reduced tillage are roughly double those obtained for the reference simulations (conventional tillage). This increase is significant. The loads transported in adsorbed form (not presented) vary significantly from site to site, but in the case of the dissolved form, the average runoff load for the simulations with reduced tillage is roughly double that obtained for simulations with conventional tillage.

On average, runoff losses (sum of dissolved and adsorbed forms) are 0.06 and 0.09% of the amount applied under reduced tillage and conventional tillage, respectively. Reduced tillage therefore results in a relative reduction in runoff loss, but because of the requirement for an additional preplant application of glyphosate, the total runoff load increases.

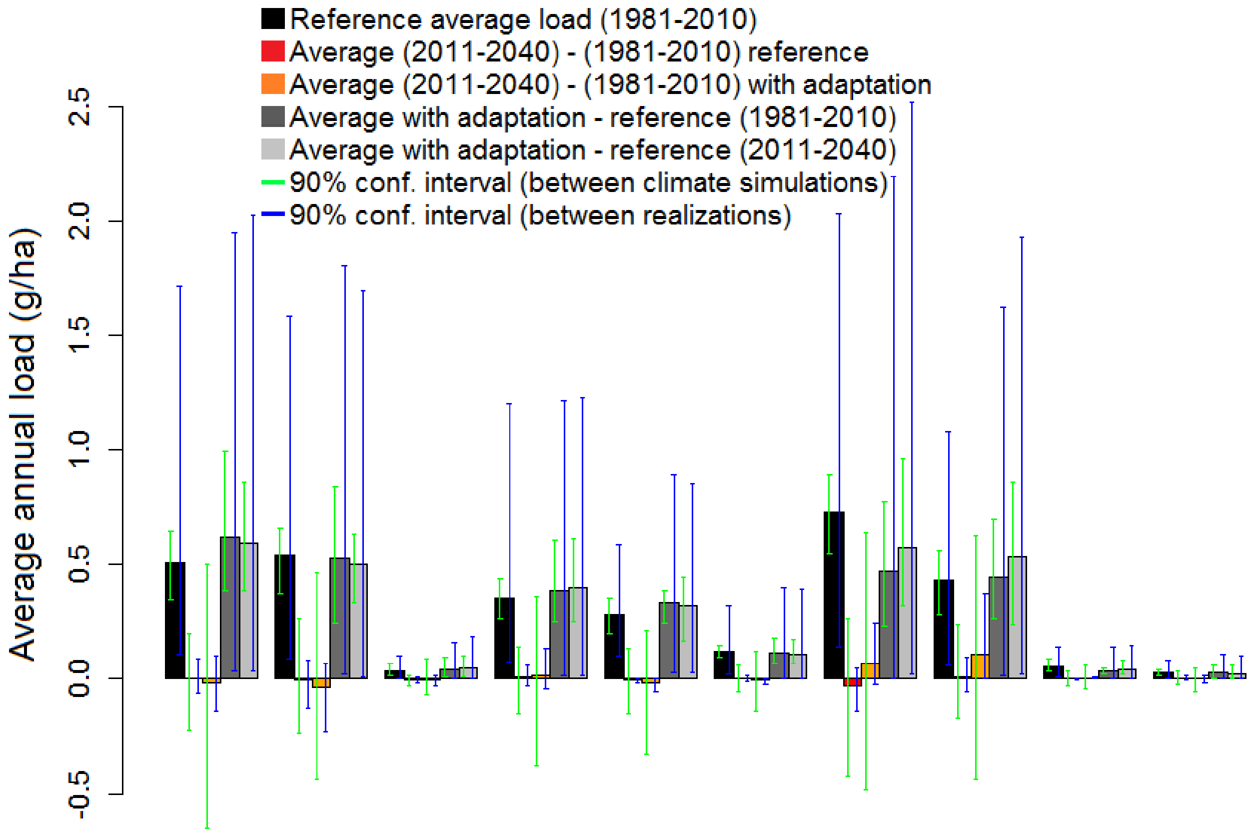

Figure 16. Impact of the adaptation measure (reduced till) and climate change on the runoff load of dissolved glyphosate, assessed on the basis of averages over 30 years for the 10 sites simulated.

5.3.4 No till

This adaptation measure consists in doing no tillage in the fall. In the PRZM parameters, this translates to a 4% reduction in the curve number (CN; Appendix E) (Table 5.13; Suarez, 2005) over the entire year, a reduction in the USLE's C factor value (Appendix E) ranging from approximately 40% for wheat and corn to approximately 60% for soybean over the entire year (Wall et al., 2002) and a decrease in Manning's roughness coefficient (MNGN; Appendix E; see Table 5.46 of Suarez, 2005). As in the case of reduced tillage (Section 5.4.3), it was assumed that this adaptation measure required an additional application of glyphosate no more than five days prior to planting at a rate ranging from 0.27 to 5.76 kg/ha (SAgE pesticides, 2014). Once again, the adaptation was tested for glyphosate-resistant corn, and a post-emergent glyphosate application is assumed to be required for all simulations, with or without adaptation, at a rate of between 0.9 and 1.8 kg/ha (Table 3, Section 4.2.2). The same 10 sites as those considered for reduced tillage (Section 5.3.3) were analyzed.

As with reduced tillage, no till leads to an average increase in total loads transported in dissolved form, but the increase is smaller and is not significant given the variability between realizations (Figure 17). The simulated impact of no till is higher for loads transported in adsorbed form, although the differences between no till and conventional tillage are negligible (not presented).

This is due to the significant decrease in the USLE's C parameter (Appendix E). On average, total runoff losses (in dissolved and adsorbed forms) correspond to 0.03% of what is applied for no till, compared to 0.09% for conventional tillage.

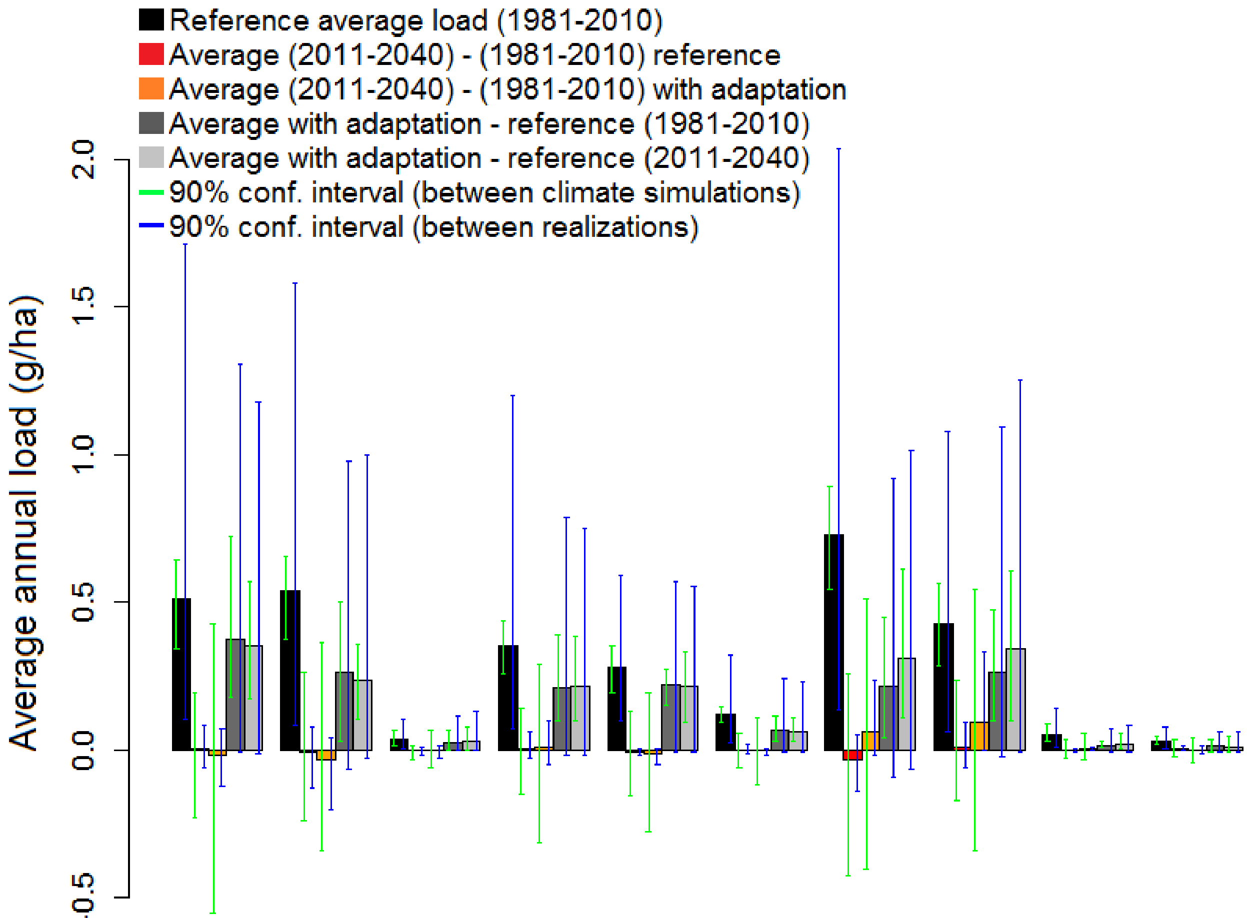

Figure 17. Impact of the adaptation measure (no till) and of climate change on runoff load of dissolved glyphosate, assessed on the basis of averages over 30 years for the 10 sites simulated.

5.3.5 Soil incorporation

For all simulations performed to date, it was assumed that the pesticide was sprayed and that foliar interception was proportional to the area of ground covered by the crop. The mass of pesticide that reaches the soil surface infiltrates the soil, and the soil pesticide concentration decreases linearly to a depth given by the parameter DEPI (Appendix E). For soil incorporation, the concentration is highest at depth DEPI and decreases linearly to the soil surface. Few commercially sold active ingredients can be incorporated. Atrazine is the only active ingredient considered in this project that can be incorporated.

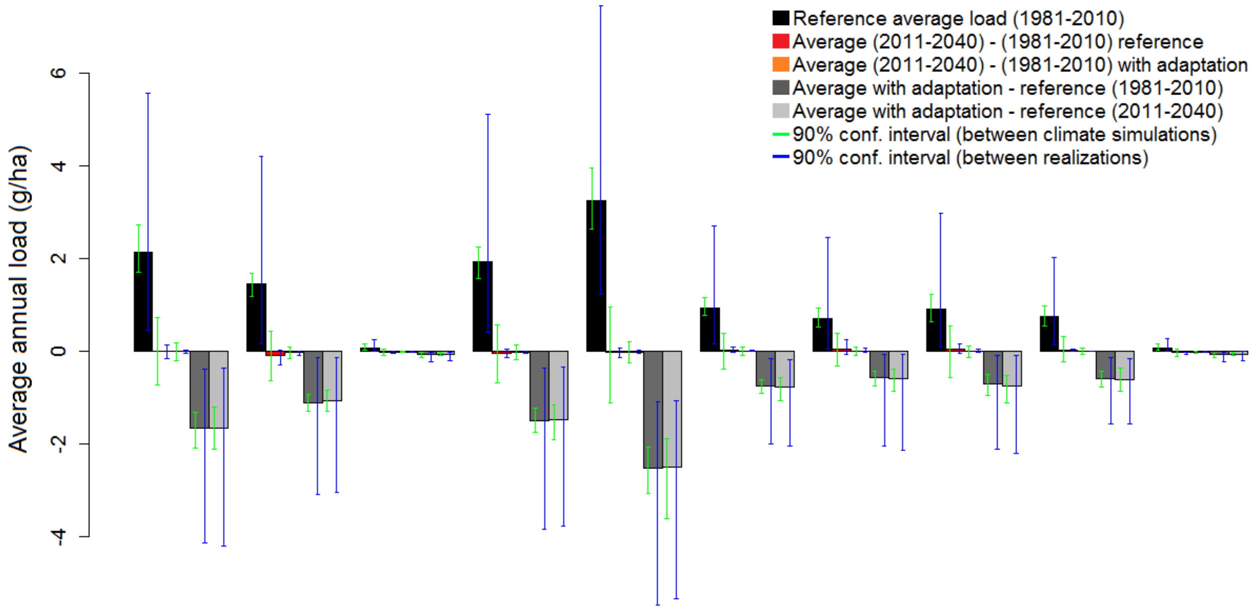

Figure 18. Impact of the adaptation measure (soil incorporation) and of climate change on the runoff load of dissolved atrazine, assessed on the basis of the averages over 30 years for the 10 sites simulated.

With incorporation, the total dissolved load over 60 years is reduced by about 75% on average, regardless of site (Figure 18). Incorporation almost completely reduces the adsorbed load, with an average reduction of 98%. The exact impact varies from realization to realization depending on the DEPI parameter. The distribution chosen for DEPI is a normal distribution with expectation 4 cm and standard deviation 1 cm (Appendix E). The realization with the smallest DEPI value (1.4 cm) gives a 20% reduction in the average load; the realization with the median DEPI value (4.1 cm) gives an 84% reduction, and the realization with the highest DEPI value (6.4 cm) gives a 92% reduction. This non-linear reduction can be explained on the basis of the PRZM equation defining $I(z)$, the fraction of pesticides in soil in the dissolved phase that is available for runoff (Suarez, 2005; p. 200):

$$I(z) = 0.7\left(\frac{1}{2z + 0.9}\right)^2 \tag{1}$$

where z is the soil depth and is less than or equal to 2 cm. This fraction decreases rapidly with depth, and pesticides found at depths below 2 cm are not available for runoff. In short, the exact value of the impact of soil incorporation depends essentially on Equation (1), on the depth of infiltration after spraying and on the depth of application for incorporations. In the simulations, these two depths are assumed to be equivalent to DEPI. Regardless, the fact remains that the runoff load will decrease with the depth of incorporation. It should be noted that atrazine can be applied more deeply (10 cm), which increases the beneficial impact of incorporation on atrazine runoff load.

6 Conclusion

The general objective of the project was to predict the impact of climate change on changes in surface runoff contamination by pesticides used in the control of certain pests of wheat, corn, soybean and apple during the period 1981-2040 (Section 2). A method integrating the interactions and uncertainties associated with the various physical and chemical processes was developed (Section 4). Simulations were carried out on 28 Quebec sites using scaled daily precipitation and temperature data from 23 climate simulations from the CIPRA bioclimatic models (Plouffe et al., 2014) and from the PRZM pesticide transport model, version 3.12.3 (Suarez, 2005). The PRZM parameter values were selected using the Monte Carlo method to take into account the uncertainty associated with their estimate. In total, 21 active ingredients were considered. For each site/active ingredient/climate simulation combination, 100 daily time series of 60 years (1941-2040) were generated.

6.1 Summary of findings

The results obtained were designed to objectively estimate the impact of climate change and the impact of adaptation measures on surface runoff contamination by pesticides during the period 1981-2040 for the selected crop-pest combinations.

6.1.1 Changes in relevant climate variables

Accumulated degree days increase from 1981 to 2040 for all climate simulations used on the study sites, resulting in advances in the simulated herbicide and insecticide application dates. On average, applications during the 2011-2040 period are advanced by approximately three days relative to the 1981-2010 period for early season herbicide applications (Figure 2, Section 5.1.1) and by approximately eight days for late season insecticide applications to apple trees (Figure 3, Section 5.1.1). The average advance in the date of late season insecticide applications is 10 days for the two orchards farthest from Montreal (Figure 1).

No clear impact of climate change on mean or maximum daily precipitation during the application window on the sites and period studied was observed (Tables 7 and 9; sections 5.1.3 and 5.1.4). This can be explained by three important factors. First, the study period (1981-2040) is relatively short from a climate perspective. Longer time series (e.g., 1961-2100, namely the period covered by each climate simulation) would likely have made it possible to detect more changes, since the climate should continue to change until 2100 (especially for the scenario A2; IPCC, 2007). From a statistical viewpoint, a longer time series increases the power of the test, i.e., it can more easily detect a trend, when one exists. Second, the large natural variability in precipitation, especially for extreme events, can mask the impact of climate change (CEHQ, 2013; Gagnon and Rousseau, 2014). Third, the fact that the application window varies from year to year as a function of weather is a form of adaptation to climate change. This factor is the least important of the three, since daily precipitation is stable over the 60-year period for most sites and climate simulations (Tables 7 to 10 and Figures 7 and 8; sections 5.1.3 and 5.1.4).

Precipitation also influences fungicide applications for the control of apple scab as it impacts the number of hours of apple leaf wetness and indirectly affects the number of days without rain. A slight average increase of 0.1 fungicide application per season between the periods 1981-2010 and 2011-2040 was obtained in the simulations. This increase is not statistically significant. The number of seasonal bactericide applications for the control of fire blight (apple trees), which depends essentially on temperature, but over a very short period, remains stable during the period 1981-2040.

6.1.2 Changes in transported loads

Overall, annual loads transported in dissolved and adsorbed form remain stable during the period 1981-2040. The only exception is the three active ingredients used in the control of apple scab, with approximately 60% positive trends, although few of them are statistically significant (Figures 9 and 11; sections 5.2.1 and 5.2.2). In absolute terms, runoff loads of these three ingredients increase, on average, by approximately 10% between the periods 1981-2010 and 2011-2040. Runoff loads of atrazine and mesotrione, two active ingredients applied pre-emergent to corn, are higher in only 52.8 and 52.7% of the cases, respectively, despite an upward trend in maximum daily rainfall in 63.5% of the cases (Table 7; Section 5.1.3). On average, for all active ingredients, more than 85% of the total runoff load over 60 years comes from annual maximum daily loads. These annual maximum loads are generally generated by intense rainfall events occurring shortly after the application of pesticides. As shown by the box plots of the averages for each climate simulation (Figures 9 and 11), the natural variability of these rainfall events is very large, which masks the impact of climate change, if one exists, on runoff load during the period 1981-2040.

For a given pest, the impact of climate on runoff load varies very little as a function of site, active ingredient and realization. In absolute terms, these three factors have a significant effect on runoff load, but in relative terms, they have little or no effect on the impact of climate change on runoff load.

It should be noted that in the proposed application scenarios (Section 4.2.2), the producer applies pesticides in a rational manner and succeeds in effectively eliminating the risks associated with crop pests. If this is not the case—for instance, if several herbicide applications are necessary or if the producer is required to perform several applications to control type II apple scab infections—the impact of climate change could be more pronounced.

6.1.3 Impact of adaptation measures

Measures that can reduce field-scale runoff loads were simulated (Table 6, Section 4.2.3). The first two measures presented, i.e., no application the day before rain and variation of the rain threshold for the applications, illustrated that what should be avoided are essentially intense rain events occurring shortly after pesticide application. The increase in the interval between an application and heavy rain is beneficial, especially in the case of active ingredients of low persistence.

The simulated impact of reduced tillage and no tillage is limited. While the proportion of the total pesticide mass applied that is transported in runoff water declines for the two adaptation measures, the total transported load, in absolute terms, increases. There are two important elements to be considered in the evaluation of the scope of these results. First, it could be that the recommended adjustments in the values of certain parameters of the PRZM model would not make it possible to precisely enough take account of the benefits of the management practices (Miao et al., 2004). For example, no tillage, and to some extent reduced tillage, increases the organic carbon content at the soil surface (Alletto et al., 2010), but this effect is not considered in the model. Second, reduced tillage and no tillage have an impact on surface runoff and on other water quality variables. A complete assessment of these measures should include their impacts on all of these variables.

The incorporation of atrazine into the soil significantly reduces runoff loss compared to surface spraying. There is some degree of variability in the exact value of the decline in the runoff load caused by incorporation. Nonetheless, the average decreases are 75% for the dissolved form and 98% for the adsorbed form, calculated under conservative scenarios (i.e., shallow incorporations).

6.2 Limitations

The findings are valid only for the crop pests considered (Section 2). The phenology of the crops and pests depends on climate, and the pesticide application dates were generated accordingly. In contrast, pest abundance was not considered; the application rate was the same from year to year for a given simulation. The impact of climate change could differ for other diseases or pests that are already problematic in Quebec. Climate change could also result in the arrival of new pests, which were not considered, nor were the possible resistance of the pests to certain active ingredients (Bloomfield et al., 2006; Lethmayer et al., 2009; Hakala et al., 2011), the impact of crop rotation or the effects of temperature and previous year treatments on insect pest abundance (Rafoss and Saethre, 2003; Gagnon et al., 2013).

The analyses were conducted over the period 1981-2040, and it was assumed that agricultural practices not directly related to climate would remain unchanged. The selection of this period was based on the fact that agricultural practices, particularly pesticide use, are rapidly evolving and that an assessment beyond 2040 is unrealistic. The impact of climate change would likely have been more significant if the study period had been longer. In addition, because climate change is not globally uniform, the results cannot be directly transposed to other regions.

Technological advancements associated with crop protection practices could occur in the coming years and decades and could have a significant impact—greater than that of climate change—on water contamination (Boxall et al., 2009; Hakala et al., 2011). For example, new application methods, new pest-resistant cultivars, and new, less toxic, less persistent and less mobile active ingredients could reduce the risk of water contamination associated with pesticide use. On the other hand, the arrival of new cultivars that are resistant to certain active ingredients could increase the application of these active ingredients. The risk of contamination will increase if the active ingredients are more toxic, more persistent or more mobile than those currently used.

It is assumed that all of the 23 climate simulations cover the entire possible spectrum of climate change from 1981 to 2040. The simulations are based on GHG emissions scenarios developed 15 years ago (Nakicenovic and Swart, 2000). New simulations with new scenarios could provide different results. That being said, the choice of GHG emissions scenarios is more important for longer horizons.

The climate data may be sensitive to the scaling method used, in this case, daily translation (Mpelasoka and Chiew, 2009), particularly for extremes (Chen et al., 2012; Sulis et al., 2012). Given that runoff loads are highly dependent on extreme events, the simulated absolute values depend on the scaling method used. However, the test used to evaluate trends in precipitation and runoff loads (Mann, 1945; Kendall, 1970) is non-parametric (i.e., analysis of ranks rather than raw data) and is therefore not sensitive to the scaling method used.

The increase in temperatures could also lead to an increase in the number of extreme convective precipitation events (Gagnon and Rousseau, 2014). This evolution could increase extreme rainfall events at the local scale, but is not considered in the application of the statistical scaling. However, the impact should be quite low, given the relatively short duration of the analysis period (1981-2040).

The three principal sources of uncertainty in modelling are input data, model parameters and the model itself (Dubus et al., 2003). For pesticide transport, the first two sources were considered, but only one model was used (PRZM version 3.12.3; Suarez, 2005). The results depend therefore on the model's representation of the processes. Some phenomena were not simulated, such as drift and atmospheric deposition (Messing et al., 2013). In addition, the time step of the model (daily) does not allow for a precise representation of various important processes. That said, the choice of values of the main model parameters is perhaps more important than the choice of transport model used (Dann et al., 2006). The results showed that the values of the PRZM parameters have very little or no effect on the impact of climate change on runoff load, even though these values have a considerable impact on the runoff loads in absolute terms.

The properties of the active ingredients were considered to be fixed. In reality, the parameter K_{oc} (Farenhorst et al., 2009) and the half-life (Bloomfield et al., 2006; Shymko et al., 2011; Balbus et al., 2013) vary depending on soil properties, but the interactions between microbiological activity and soil are unknown (van den Burg et al., 2012). The half-life can also decrease with an increase in temperature, which could lead to a reduction in the runoff load in the future, unless the more rapid degradation leads to an increase in the number of applications (Bloomfield et al., 2006). The transport of metabolites in water was not considered. Since, for a given crop, the change in simulated runoff loads over time is comparable from one active ingredient to another (sections 5.2.1 and 5.2.2), it can be assumed that the runoff load of a metabolite has the same evolution over time as its parent active ingredient. The transport and toxicity of the adjuvants were not considered.

In short, the interaction between climate and many important factors, such as the pesticide application rates and the degradation rate of the active ingredients, remains difficult to quantify. A better scientific understanding of these interactions would enable a more representative and more comprehensive assessment of the impact of climate change.

Lastly, changes in contamination were assessed at the field scale. For an assessment of contamination of river water, modelling at the watershed scale should be conducted. Such modelling should take into account the impact of changes in land use, which could be more significant than the impact of climate change (Quilbé et al., 2008; Boxall et al., 2009; Poelmans et al., 2011; Balbus et al., 2013).

6.3 Recommendations

Despite the limitations of the study, a number of recommendations designed to limit the risk of water contamination by pesticides can be made. It is important to mention that they do not take into account external factors, such as the costs and financial risks associated with the measures to be adopted.

The main impact of climate change on the simulated runoff load involves applications for the control of apple scab. For the three active ingredients considered (captan, mancozeb, metiram), the very slight average increase in the number of simulated applications could lead to an average increase of 10% in the runoff load of fungicides for the next 30 years. Special attention should be given to regions where applications are already problematic. The three active ingredients considered in this project are not highly persistent, but given that they are often applied in wet conditions, high concentrations exceeding the water quality criteria may occur in runoff water (Table 13).

The results of this project have illustrated the importance of rainfall and high flows on runoff loads. Beneficial management practices (BMPs) can be applied to reduce runoff and erosion during these events. Two measures associated with tillage were analyzed: reduced tillage and no tillage. The results show that these measures reduce the runoff load per application, but do not necessarily reduce the total runoff load, since an additional preplant application is required.

Although there are many uncertainties associated with the impact of the measures obtained from the modelling (Miao et al., 2004), these measures can be beneficial if the active ingredient used in pre-emergence or post-emergence applications is more toxic than that used in preplant applications. Other BMPs exist that do not require additional pesticide applications, such as riparian buffers (Rousseau et al., 2012) and constructed wetlands (Lizotte et al., 2012).

A number of measures can be taken at the field or orchard scale to reduce the concentration and load of pesticides in runoff water during major rainfall events. Where possible, the producers should:

- monitor weather conditions so as to avoid applying products too shortly before a major rain event;

- use less mobile, less persistent products;

- use products that can be incorporated into the soil.

These measures are beneficial, regardless of whether or not climate change is an issue.

References

AAFC, 2010. Soil Landscapes of Canada version 3.2. [Online] http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html (accessed September 4, 2014).

AAFC, 2014. Flexibility of No Till and Reduced Till Systems Ensures Success in the Long Term. [Online] http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/soil-and-land/soil-management/flexibility-of-no-till-and-reduced-till-systems-ensures-success-in-the-long-term/?id=1219778199286 (accessed November 13, 2014).

Alletto, L., Y. Coquet, P. Benoit, D. Heddadj, and E. Barriuso, 2010. Tillage management effects on pesticide fate in soils. A review. *Agronomy for Sustainable Development*, 30, 367-400.

Atlas agroclimatique du Québec, 2012. Atlas agroclimatique du Québec - Un outil d'aide à la décision et de sensibilisation. [Online] http://dev.agrometeo.org/atlas/display_guide/Formules_atlas_agroclim_2012_v8.pdf (accessed February 17, 2014). [in French]

Balbus, J.M., A.B.A. Boxall, R.A. Fenske, T.E. McKone, and L. Zeise, 2013. Implications of global climate change for the assessment and management of human health risks of chemicals in the natural environment. *Environmental Toxicology and Chemistry*, 32(1), 62-78.

Barrette, É., 2006. Pesticides et eau souterraine : Prévenir la contamination en milieu agricole, Direction des politiques en milieu terrestre, ministère du Développement durable, de l'Environnement et des Parcs, Québec (QC), 17 pp. [in French]

Baskerville, G.L., and P. Emin, 1969. Rapid estimation of heat accumulation from maximum and minimum temperatures. *Ecology*, 50(3), 514-517.

Bloomfield, J.P., R.J. Williams, D.C. Gooddy, J.N. Cape, and P. Guha, 2006. Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater—a UK perspective. *Science of the Total Environment*, 369, 163–177.

Bootsma, A., S. Gameda, and D.W. McKenney, 2005. Potential impacts of climate change on corn, soybeans and barley yields in Atlantic Canada. *Canadian Journal of Soil Science*, 85 (2), 345-357.

Bourgeois, G., A. Bourque, and G. Deaudelin, 2004. Modelling the impact of climate change on disease incidence: a bioclimatic challenge. *Canadian Journal of Plant Pathology*, 26, 284-290.

Boxall, A.B.A., A. Hardy, S. Beulke, T. Boucard, L. Burgin, P.D. Falloon, P.M. Haygarth, T. Hutchinson, R.S. Kovats, G. Leonardi, L.S. Levy, G. Nichols, S.A. Parsons, L. Potts, D. Stone,

E. Topp, D.B. Turley, K. Walsh, E.M.H. Wellington, and R.J. Williams, 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. *Environmental Health Perspectives*, 117(4), 508-514.

Burgoa, B., and R.D. Wauchope, 1995. Pesticides in run-off and surface waters. Dans Roberts, T.R., and P.C. Kearney (eds). Environmental Behaviour of Agrochemicals. John Wiley & Sons Chichester, UK, vol. 9, pp. 221-255.

Carbone, J.P., P.L. Havens, and W. Warren-Hicks, 2002. Validation of pesticide root zone model 3.12: Employing uncertainty analysis. *Environmental Toxicology and Chemistry*, 21(8), 1578-1590.

Carisse, O., and T. Jobin, 2006. Apple scab: Improving understanding for better management - Agriculture and Agri-Food Canada. [Online] http://www.agr.gc.ca/eng/science-and-innovation/science-publications-and-resources/technical-factsheets/apple-scab-improving-understanding-for-better-management/?id=1234199585484 (accessed February 13, 2014).

Caya, D., and R. Laprise, 1999. A semi-implicit semi-lagrangian Regional Climate Model: The Canadian RCM. *Monthly Weather Review*, 127, 341-362.

CEHQ, 2013. Atlas hydroclimatique du Québec méridional – Impact des changements climatiques sur les régimes de crue, d’étiage et d’hydraulicité à l’horizon 2050. Québec (QC), 2013, 51 pp. [in French]

Cessna, A.J., C. Sheedy, A. Farenhorst, and D.A.R. McQueen, 2010. Chapter 15 Pesticides. In Eilers, W., R. MacKay, L. Graham, A. Lefebvre (eds). Environmental Sustainability of Canadian Agriculture: Agri-Environmental Indicator Report Series — Report #3. Agriculture and Agri-Food Canada, Ottawa (ON), Canada, pp. 101-107.

Chen, J., F.P. Brissette, and R. Leconte, 2012. Downscaling of weather generator parameters to quantify hydrological impacts of climate change. *Climate Research*, 51, 185-200.

Chidawanyika, F., and J.S. Terblanche, 2011. Rapid thermal responses and thermal tolerance in adult codling moth Cydia pomonella (Lepidoptera: Tortricidae). *Journal of Insect Physiology*, 57, 108-117.

Dann, R.L., M.E. Close, R. Lee, and L. Pang, 2006. Impact of data quality and model complexity on prediction of pesticide leaching. *Journal of Environmental Quality*, 35, 628-640.

Dayyani, S., S.O. Prasher, A. Madani, and C.A. Madramootoo, 2012. Impact of climate change on the hydrology and nitrogen pollution in a tile-drained agricultural watershed in eastern Canada. *Transactions of the ASABE*, 55(2), 389-401.

de Elia, R., and H. Côté, 2010. Climate and climate change sensitivity to model configuration in the Canadian RCM over North America. *Meteorologische Zeitschrift*, 19(4), 325-339.

Diós, N., K. Szenteleki , A. Ferenczy, G. Petrányi, and L. Hufnagel, 2010. A climate profile indicator based comparative analysis of climate change scenarios with regard to maize (Zea mays L.) cultures. *Applied Ecology and Environmental Research*, 7(3), 199-214.

Douville, Y., 2002. Prévention des mauvaises herbes : grandes cultures. Technaflora, Bécancour (QC), 23 pp. [in French]

Dubus, I.G., and P.H.M. Janssen, 2003. Issue of replicability in Monte Carlo modeling: A case study with a pesticide leaching model. *Environmental Toxicology and Chemistry*, 22(12), 3081-3087.

Dubus, I.G., C.D. Brown, and S. Beulke, 2003. Sources of uncertainty in pesticide fate modelling. *Science of the Total Environment*, 317, 53-72.

Duffy, B., B. Schoch, J. Vogelsanger, E. Holliger, and E. Moltmann, 2008. Fire blight forecasting model optimization in a user-friendly online interface. *Acta Horticulturae*, 803, 77-82.

Farenhorst, A., D.A.R. McQueen, I. Saiyed, C. Hilderbrand, S. Li, D.A. Lobb, P. Messing, T.E. Schumacher, S.K. Papiernik, and M.J. Lindstrom, 2009. Variations in soil properties and herbicide sorption coefficients with depth in relation to PRZM (pesticide root zone model) calculations. *Geoderma*, 150, 267-277.

Flato, G.M., G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader, and A.J. Weaver, 2000. The Canadian Centre for Climate Modeling and Analysis Global Coupled Model and its Climate. *Climate Dynamics*, 16, 451-467.

Footprint, 2008. Database containing complete PRZM parameterisation for FOOTPRINT soil, climate and crop scenarios. Project no. 022704 (SSP) [Online] http://www.eu-footprint.org/downloads/FOOTPRINT_DL20.pdf (accessed on September 4, 2014).

Fortin, J.-P., R. Turcotte, S. Massicotte, R. Moussa, J. Fitzback, and J.-P. Villeneuve, 2001a. A distributed watershed model compatible with remote sensing and GIS data. Part I: Description of the model. *Journal of Hydrologic Engineering*, 6(2), 91-99.

Fortin, J.-P., R. Turcotte, S. Massicotte, R. Moussa, and J. Fitzback, 2001b. A distributed watershed model compatible with remote sensing and GIS data. Part 2: Application to the Chaudière watershed. *Journal of Hydrologic Engineering*, 6(2), 100-108.

Foulon, É., 2013. Détection de situations hydrologiques extrêmes à partir de variables météorologiques dans un contexte de changements climatiques. Report done for the class

« EAU901 - Travail dirigé II », Institut National de la Recherche Scientifique, centre Eau Terre Environnement. [in French]

Gagnon, A.-È., G. Arsenault-Labrecque, G. Bourgeois, L. Bourdages, P. Grenier, and M. Roy, 2013. Études de cas pour faciliter une gestion efficace des ennemis des cultures dans le contexte de l'augmentation des risques phytosanitaires liés aux changements climatiques. Ouranos, Final report Project no 550004-PXI. 183 pp. [in French]

Gagnon, P., and A.N. Rousseau, 2014. Stochastic spatial disaggregation of extreme precipitation to validate a Regional Climate Model and to evaluate climate change impacts over a small watershed. *Hydrology and Earth System Sciences*, 18, 1-10.

Gagnon, P., C. Sheedy, A. Farenhorst, D.A.R. McQueen, A.J. Cessna, and N. Newlands, 2014. A coupled stochastic/deterministic model to estimate the evolution of the risk of water contamination by pesticides across Canada. *Integrated Environmental Assessment and Management*, 10(3), 429-436.

Giroux, I., and L. Pelletier, 2012. Présence de pesticides dans l'eau au Québec : bilan dans quatre cours d'eau de zones en culture de maïs et de soya en 2008, 2009 et 2010, Québec, ministère du Développement durable, de l'Environnement et des Parcs, Direction du suivi de l'état de l'environnement, ISBN 978-2-550-64159-9 (PDF), 46 pp. and 3 annexes. [in French]

Gordon, H.B., L.D. Rotstayn, J.L. McGregor, M.R. Dix, E.A. Kowalczyk, S.P. O'Farrell, L.J. Waterman, A.C. Hirst, S.G. Wilson, M.A. Collier, M.A., I.G. Watterson, and T.I. Elliott, 2002. The CSIRO Mk3 Climate System Model. CSIRO Atmospheric Research Technical Paper No. 60.

Gordon, H.B., S.P. O'Farrell, M.A. Collier, M.R. Dix, L. Rotstayn, E.A. Kowalczyk, T. Hirst, and I.G. Watterson, 2010. The CSIRO Mk3.5 Climate Model. Centre for Australian Weather and Climate Research Technical Report No. 021.

Hakala, K., A.O. Hannukkala, E. Huusela-Veistola, M. Jalli, and P. Peltonen-Sainio, 2011. Pests and diseases in a changing climate: a major challenge for Finnish crop production. *Agricultural and food science*, 20, 3-14.

Hirschi, M., S. Stoeckli, M. Dubrovsky, C. Spirig, P. Calanca, M.W. Rotach, A.M. Fischer, B. Duffy, and J. Samietz, 2012. Downscaling climate change scenarios for apple pest and disease modeling in Switzerland. *Earth System Dynamics*, 3, 33-47.

Holt, E., R. Weber, G. Stevenson, and C. Gaus, 2010. Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) impurities in pesticides: A neglected source of contemporary relevance. *Environmental Science & Technology*, 44, 5409-5415.

Hopkinson, R.F., D.W. McKenney, E.J. Milewska, M.F. Hutchinson, P. Papadopol, and L.A. Vincent, 2011. Impact of Aligning Climatological Day on Gridding Daily Maximum-Minimum Temperature and Precipitation over Canada. *Journal of Applied Meteorology and Climatology*, 50, 1654-1665.

Hunsche, M., L. Damerow, M. Schmitz-Eiberger, and G. Noga, 2007. Mancozeb wash-off from apple seedlings by simulated rainfall as affected by drying time of fungicide deposit and rain characteristics. *Crop protection*, 26, 768-774.

Hutchinson, M.F., D.W. McKenney, K. Lawrence, J.H. Pedlar, R.F. Hopkinson, E.J. Milewska, and P. Papadopol, 2009. Development and Testing of Canada-Wide Interpolated Spatial Models of Daily Minimum-Maximum Temperature and Precipitation for 1961-2003. *Journal of Applied Meteorology and Climatology*, 48, 725-741.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the IPCC Fourth Assessment Report. Cambridge University Press, Cambridge, United Kingdom, 996 pp.

IPCC, 2013. Summary for Policymakers. Dans Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 27 pp.

IRDA, 2013. Feuillets cartographiques. [Online] http://www.irda.qc.ca/fr/outils-et-services/informations-sur-les-sols/etudes-pedologiques/feuillets-cartographiques/ (accessed on September 4, 2014). (in French)

Jones, R.A.C., and M.J. Barbetti, 2012. Influence of climate change on plant disease infections and epidemics caused by viruses and bacteria. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, 7, art. no. 022.

Jungclaus, J.H., M. Botzet, H. Haak, N. Keenlyside, J.-J. Luo, M. Latif, J. Marotzke, U. Mikolajewicz, and E. Roeckner, 2006. Ocean circulation and tropical variability in the AOGCM ECHAM5/MPI-OM. *Journal of Climate*, 19(16), 3952-3972.

Juszczak, R., L. Kuchar, J. Leśny, and J. Olejnik, 2013. Climate change impact on development rates of the codling moth (*Cydia pomonella* L.) in the Wielkopolska region, Poland. *International Journal of Biometeorology*, 57, 31-44.

Kattwinkel M., J.-V. Kühne, K. Foit, and M. Liess, 2011. Climate change, agricultural insecticide exposure, and risk for freshwater communities. *Ecol Appl*, 21(6), 2068-2081.

Kendall, M.G., 1970. Rank Correlation Methods, 4th ed., Griffin, London, UK.

Koleva, N.G., and U.A. Schneider, 2010. The impact of climate change on aquatic risk from agricultural pesticides in the US. *Int J Environ Stud*, 67(5), 677-704.

Kondo, K., J. Boulange, T.K. Phong, K. Hiramatsu, T. Inoue, and H. Watanabe, 2012. Probabilistic assessment of herbicide runoff from Japanese rice paddies: The effects of local meteorological conditions and site-specific water management. *Journal of Pesticide Science*, 37(4), 312-322.

Lafrance, P., O. Banton, and F. Bernard Inc., 1996. Évaluation environnementale des pratiques culturales sur maïs pour la réduction des pertes d'herbicides. Research report INRS-Eau n° R-390 for the Direction de l'information environnementale et de la recherche, ministère de l'Environnement et de la Faune du Québec. Final report in five volumes, 919 pp. [in French]

Lafrance, P., O. Banton, and P. Gagné, 1997. Exportation saisonnière d'herbicides vers les cours d'eau mesurée sur six champs agricoles sous quelques pratiques culturales du maïs (Basses-Terres du St-Laurent). *Revue des Sciences de l'Eau*, 10(4), 439-459. [in French]

Lawrence, M.G., 2005. The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications. *Bulletin of the American Meteorological Society*, 86, 225-233.

Lethmayer, C., H. Hausdorf, J. Altenburger, and S. Blümel, 2009. Trials of alternative codling moth (*Cydia pomonella*) control strategies in Austria. *International Journal of Fruit Science*, 9(4), 385-393.

Lizotte Jr., R.E., F.D. Shields Jr., J.N. Murdock, R. Kröger, and S.S. Knight, 2012. Mitigating agrichemicals from an artificial runoff event using a managed riverine wetland. *Science of the Total Environment*, 427-428, 373-381.

Luedeling, E., K.P. Steinmann, M. Zhang, P.H. Brown, J. Grant, and E.H. Girevetz, 2011. Climate change effects on walnut pests in California. *Global Change Biology*, 17, 228-238.

Luo, Y., F. Spurlock, X. Deng, S. Gill, and K. Goh, 2011. Use-Exposure Relationships of Pesticides for Aquatic Risk Assessment. *PLoS ONE*, 6(4), art. no. e18234.

Mailhot, A., I. Beauregard, G. Talbot, D. Caya, and S. Biner, 2012. Future changes in intense precipitation over Canada assessed from multi-model NARCCAP ensemble simulations. *International Journal of Climatology*, 32(8), 1151-1163.

Mann, H.B., 1945. Nonparametric tests against trend, *Econometrica*, 13, 245-259.

McQueen, D.A.R, A. Farenhorst, S. Allaire, and A.J. Cessna, 2007. Automation and evaluation of three pesticide fate models for a national analysis of leaching risk in Canada. *Canadian Journal of Soil Scienc*e, 87(2), 203-212.

MDDELCC, 2002. Critères de qualité de l'eau de surface. [Online] http://www.mddefp.gouv.qc.ca/eau/criteres_eau/index.asp (accessed May 2, 2014). [in French]

Mearns, L.O., et al., 2007. *The North American Regional Climate Change Assessment Program dataset*, National Center for Atmospheric Research Earth System Grid Data Portal, Boulder, Colorado.

Meehl, G.A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J.F.B. Mitchell, R.J. Stouffer, and K.E. Taylor, 2007. The WCRP CMIP3 Multi-Model Dataset: A New Era in Climate Change Research. *Bulletin of the American Meteorological Society*, 88(9), 1383-1394.

Messing, P., A. Farenhorst, D. Waite, and J. Sproull, 2013. Influence of usage and chemical-physical properties on the atmospheric transport and deposition of pesticides to agricultural regions of Manitoba, Canada. *Chemosphere*, 90(6), 1997-2003.

Miao, Z., A. Vicari, E. Capri, F. Ventura, L. Padovani, and M. Trevisan, 2004. Modeling the Effects of Tillage Management Practices on Herbicide Runoff in Northern Italy. *Journal of Environmental Quality*, 33(5), 1720-1732.

Mpelasoka, F.S., and F.H.S. Chiew, 2009. Influence of Rainfall Scenario Construction Methods on Runoff Projections, *Journal of Hydrometeorology*, 10, 1168-1183.

Nakicenovic, N., and R. Swart (eds.), 2000. IPCC special report on emissions scenarios: a special report of Working Group III of the IPCC. Cambridge, UK, 599 pp.

Natural Resources Canada, 2000. Canadian Digital Elevation Data (CDED). [Online] http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/3A537B2D-7058-FCED-8D0B-76452EC9D01F.html (accessed March 30, 2015).

Nolan, B.T., I.G. Dubus, N. Surdyk, H.J. Fowler, A. Burton, J.M. Hollis, S. Reichenberger, and N.J. Jarvis, 2008. Identification of key climatic factors regulating the transport of pesticides in leaching and to tile drains. *Pest Management Science*, 64, 933-944.

OMAFRA, 2011. Apple scab. [Online] http://www.omafra.gov.on.ca/english/crops/facts/apscab.htm (accessed May 22, 2014).

Paquin, D., 2010. Évaluation du MRCC4 en passé récent (1961-1999). Rapport interne No 15: Ouranos, Équipe Simulations climatiques. [in French]

Plouffe, D., G. Bourgeois, N. Beaudry, G. Chouinard, and D. Choquette, 2014. CIPRA - Centre Informatique de Prévision des Ravageurs en Agriculture. Agriculture and Agri-Food Canada, Publication No. 12147F. 138 pp. [Online] http://www.agrireseau.qc.ca/documents/Document_88744.PDF (accessed December 8, 2014). [in French]

Poelmans, L., A.V. Rompaey, V. Ntegeka, and P. Willems, 2011. The relative impact of climate change and urban expansion on peak flows: a case study in central Belgium. *Hydrological Processes*, 25, 2846-2858.

Poirier, S.C., J.K. Whalen, and A.R. Michaud, 2012. Bioavailable phosphorus in fine-sized sediments transported from agricultural fields. *Soil Science Society of America Journal*, 76, 258-267.

Quilbé, R., A.N. Rousseau, J.-S. Moquet, S. Savary, S. Ricard, and M.S. Garbouj, 2008. Hydrological responses of a watershed to historical land use evolution and future land use scenarios under climate change conditions. *Hydrology and Earth System Sciences*, 12, 101-110.

Rafoss, T., and M.-G. Saethre, 2003. Spatial and temporal distribution of bioclimatic potential for the Codling moth and the Colorado potato beetle in Norway: model predictions versus climate and field data from the 1990s. *Agricultural and Forest Entomology*, 5, 75-85.

Rousseau, A.N., P. Lafrance, M.-P. Lavigne, S. Savary, B. Konan, R. Quilbé, P. Jiapizian, and M. Amrani, 2012. A hydrological modeling framework for defining achievable performance standards for pesticides. *Journal of Environmental Quality*, 41, 52-63.

Sabbagh, G.J., R. Muñoz-Carpena, and G.A. Fox, 2013. Distinct influence of filter strips on acute and chronic pesticide aquatic environmental exposure assessments across U.S. EPA scenarios. *Chemosphere*, 90, 195-202.

SAgE pesticides, 2014. SAgE pesticides - Utilisation rationnelle des produits et traitements phytosanitaires contre ravageurs. [Online] http://www.sagepesticides.qc.ca/ (accessed February 17, 2014).

Scinocca, J. F., N.A. McFarlane, M. Lazare, J. Li, and D. Plummer, 2008. Technical Note: The CCCma third generation AGCM and its extension into the middle atmosphere. *Atmospheric Chemistry and Physics*, 8, 7055-7074.

Shymko, J.L., A. Farenhorst, and F. Zvomuya, 2011. Polynomial response of 2,4-D mineralization to temperature in soils at varying soil moisture contents, slope positions and depths. *Journal of Environmental Science and Health Part B*, 46, 301-312.

Singh, P., and R.L. Jones, 2002. Comparison of pesticide root zone model 3.12: runoff predictions with field data. *Environmental Toxicology and Chemistry*, 21(8), 1545-1551.

Smith, T.J., 2010. CougarBlight 2010. Washington State University Extension. [Online]. http://county.wsu.edu/chelan-douglas/agriculture/treefruit/Pages/Cougar_Blight_2010.aspx (accessed February 13, 2014).

Steiner, P., 1990. Predicting Apple Blossom Infections by Erwinia amylovora Using the Maryblyt Model. *Acta Horticulturae*, 273, 139-148.

Steiner, P., and G. Lightner, 1996. Maryblyt 4.3. A predictive program for forecasting fire blight diseases in apples and pears. Gemplers Inc., Mt. Hebron, Wisconsin, 53572, USA.

Stensvand, A., D.M. Gadoury, T. Amundsen, L. Semb, and R.C. Seem, 1997. Ascospore release and infection of apple leaves by conidia and ascospores of *Venturia inaequalis* at low temperatures. Phytopathology, 87(10): 1046-1053.

Stoeckli, S., M. Hirschi, C. Spirig, P. Calanca, M.W. Rotach, and J. Samietz, 2012. Impact of Climate Change on Voltinism and Prospective Diapause Induction of a Global Pest Insect – *Cydia pomonella* (L.). *PLoS ONE*, 7(4), art. no. e35723.

Stratonovitch, P., J. Storkey, and M.A. Semenov, 2012. A process-based approach to modelling impacts of climate change on the damage niche of an agricultural weed. *Global Change Biology*, 18, 2071-2080.

Suarez, L.A., 2005. PRZM-3, A model for predicting pesticide and nitrogen fate in the crop root and unsaturated soil zones: User's manual for release 3.12.2. EPA/600/R-05/111. Athens (GA), USA: U.S. Environmental Protection Agency, National Exposure Research Laboratory, Ecosystems Research Division. [Online] http://www.epa.gov/athens/publications/reports/Suarez600R05111PRZM3.pdf (accessed April 16, 2012).

Sulis, M., C. Paniconi, M. Marrocu, D. Huard, and D. Chaumont, 2012. Hydrologic response to multimodel climate output using a physically based model of groundwater/surface water interactions, *Water Resources Research*, 48, W12510.

Tungate, K.D., D.W. Israel, D.M. Watson, and T.W. Rufty, 2007. Potential changes in weed competitiveness in an agroecological system with elevated temperatures. *Environmental and Experimental Botany*, 60, 42-49.

Turcotte, R., A.N. Rousseau, J.-P. Fortin, and J.-P. Villeneuve, 2003. Development of a process-oriented, multiple-objective, hydrological calibration strategy accounting for model structure. *Advances in Calibration of Watershed Models,* (Water Science & Application: no. 6). In Duan, Q., S. Sorooshian, H. Gupta, A.N. Rousseau, and R. Turcotte (eds). American Geophysical Union (AGU), Washinghton, USA. pp. 153-163.

University of Hertfordshire. 2013. The Pesticide Properties DataBase (PPDB) developed by the Agriculture & Environment Research Unit (AERU), University of Hertfordshire, funded by UK national sources and through EU-funded projects, 2006-2013. [Online] http://sitem.herts.ac.uk/aeru/ppdb/en/index.htm (accessed February 20, 2014).

USDA, Natural Resources Conservation Service (NRCS). 2004. Chapter 9 - Hydrologic Soil-Cover Complexes. Dans National engineering handbook - Part 630, Hydrology. USDA NRCS. Washington (DC), USA. [Online] http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17758.wba (accessed February 17, 2014).

van den Berg, F., A. Tiktak, G.B.M. Heuvelink, S.L.G.E. Burgers, D.J. Brus, F. de Vries, J. Stolte, and J.G. Kroes, 2012. Propagation of uncertainties in soil and pesticide properties to pesticide leaching. *Journal of Environmental Quality*, 41, 253-261.

van der Zwet, T., G. Lightner, J. Walter, and P. Steiner, 1990. Comparison of the Maryblyt predictive model with the billing revised system for blossom blight risk assessment in apple. *Acta Horticulturae*, 273, 171-183.

Wall, G.J., D.R. Coote, E.A. Pringle, and I.J. Shelton (eds), 2002. RUSLEFAC — Revised Universal Soil Loss Equation for Application in Canada: A Handbook for Estimating Soil Loss from Water Erosion in Canada. Research Branch, Agriculture and Agri-Food Canada. Ottawa. Contribution No. AAFC/AAC2244E. 117 pp.

Warren-Hicks, W., J.P. Carbone, and P.L. Havens, 2002. Using Monte Carlo techniques to judge model prediction accuracy: Validation of the Pesticide Root Zoot Model 3.12. *Environmental Toxicology and Chemistry*, 21(8), 1570-1577.

Wauchope, R.D., 1978. The pesticide content of surface water draining from agricultural fields – A review. *Journal of Environmental Quality*, 7(4), 459-472.

Wolfe, D.W., L. Ziska, C. Petzoldt, A. Seaman, L. Chase, and K. Hayhoe, 2008. Projected change in climate thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers. *Mitigation and Adaptation Strategies for Global Change*, 13, 555-575.

Wu, Y., and S. Liu, 2014. Improvement of the R-SWAT-FME framework to support multiple variables and multi-objective functions. *Science of the Total Environment*, 466-467, 455-466.

Ziska, L.H., 2010. Elevated carbon dioxide alters chemical management of Canada thistle in no-till soybean. *Field Crops Research*, 119, 299-303.

Ziska, L.H., 2013. Observed changes in soyabean growth and seed yield from *Abutilon theophrasti* competition as a function of carbon dioxide concentration. *Weed Research*, 53, 140-145.

Appendices

Appendix A. Chemical properties of active ingredients

Table 14. Chemical properties of the active ingredients used. Unless otherwise specified, the values come from the Pesticide Properties Database (PPDB) of the University of Hertfordshire (2013).

Active ingredient (AI)	IUPAC name	Commercial name[a]	Half-life (d)[b]	K_{oc} (mL/g)	Henry constant at 20°C (-)
Acetamiprid	(E)-N1-[(6-chloro-3-pyridyl)methyl]-N2-cyano-N1-methylacetamidine	Assail 70 WP	3	200	$5.36\ 10^{-12}$
Atrazine	6-chloro-N2-ethyl-N4-isopropyl-1,3,5-triazine-2,4-diamine	Atrazine 480	75	100	$1.20\ 10^{-7}$
Bentazone	3-isopropyl-1H-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide	Basagran	13	55.3	$2.00\ 10^{-13}$
Bromoxynil	3,5-dibromo-4-hydroxybenzonitrile	Pardner	1	302	$1.46\ 10^{-7}$
Captan	N-(trichloromethylthio)cyclohex-4-ene-1,2-dicarboximide	Captan 4	0.8	200	$2.85\ 10^{-7}$
Dicamba	3,6-dichloro-o-anisic acid	Banvel	4	3.45	$8.80\ 10^{-8}$
Fenoxaprop-p-ethyl	(R)-2[4-[(6-chloro-2-benzoxazolyl) oxy]-phenoxy]-propanoic acid	Excel Super	0.4	11354	$8.80\ 10^{-9}$
Glyphosate	N-(phosphonomethyl)glycine	Roundup	12	1435	$6.60\ 10^{-19}$
Imazethapyr	5-ethyl-2-[(RS)-4-isopropyl-4-methyl-5-oxo-2-imidazolin-2-yl]nicotinic acid	Pursuit	90	52	$1.13\ 10^{-9}$
Mancozeb	manganese ethylenebis(dithiocarbamate) (polymeric) complex with zinc salt	Manzate DF	0.1	998	$1.76\ 10^{-10}$
Mesotrione	2-(4-mesyl-2-nitrobenzoyl)cyclohexane-1,3-dione	Callisto 480 SC	32	122	$4.99\ 10^{-9}$
Metiram	zinc ammoniate ethylenebis(dithiocarbamate) - poly(ethylenethiuram disulfide)	Polyram DF	1	500000	$1.00\ 10^{-5}$ [c]
Phosmet	O,O-dimethyl S-phthalimidomethyl phosphorodithioate	Imidan 50 WP Instapak	3.1	716 [d]	$6.20\ 10^{-4}$
Pyrasulfotole	(5-hydroxy-1,3-dimethylpyrazol-4-yl)(a,a,a-trifluoro-2-mesyl-p-tolyl)methanone	Tundra (contains other AIs)	55.5	368	$3.92\ 10^{-13}$

continued on next page

Table 14. (continued)

Active ingredient (AI)	IUPAC name	Commercial name[a]	Half-life (d)[b]	K_{oc} (mL/g)	Henry constant at 20°C (-)
Quizalofop-p-ethyl	ethyl (R)-2-[4-(6-chloroquinoxalin-2-yloxy)phenoxy]propionate	Assure II	2	1816	$1.93\ 10^{-5}$
S-metolachlor	mixture of : (aRS,1S)-2-chloro-6'-ethyl-N-(2-methoxy-1-methylethyl)acet-o-toluidide et 20–0% (aRS,1R)-2-chloro-6'-ethyl-N-(2-methoxy-1-methylethyl)acet-o-toluidide	Dual Magnum	15	100 [c]	$8.98\ 10^{-7}$
Spinetoram	Mixture of 50–90% (2R,3aR,5aR,5bS,9S, 13S,14R,16aS,16bR)-2-(6-deoxy-3-O-ethyl-2,4-di-O-methyl-α-L-mannopyranosyloxy)-13-[(2R,5S,6R)-5-(dimethylamino) tetrahydro-6-methylpyran-2-yloxy]-9-ethyl-2,3,3a,4,5,5a,5b,6,9,10,11,12,13,14,16a,16b-hexadecahydro-14-methyl-1H-as-indaceno [3,2-d]oxacyclododecine-7,15-dione et de 50–10% (2S,3aR,5aS,5bS,9S,13S,14R, 16aS,16bS)-2-(6-deoxy-3-O-ethyl-2,4-di-O-methyl-α-L-mannopyranosyloxy)-13-[(2R,5S,6R)-5-(dimethylamino)tetrahydro-6 -methylpyran-2-yloxy]-9-ethyl-2,3,3a,5a,5b, 6,9,10,11,12,13,14,16a,16b-tetradecahydro-4,14-dimethyl-1H-as-indaceno[3,2-d]oxacyclododecine-7,15-dione	Radiant SC	16.1	22836	$6.04\ 10^{-7}$
Streptomycin sulfate	5-(2,4-diguanidino-3,5,6-trihydroxy-cyclohexoxy)-4-[4,5-dihydroxy-6-(hydroxymethyl)-3-methylamino-tetrahydropyran-2-yl]oxy-3-hydroxy-2-methyl-tetrahydrofuran-3-carbaldehyde	Streptomycin 17	18 [d]	10 [c]	$1.00\ 10^{-20}$ [c]
Thiacloprid	(Z)-3-(6-chloro-3-pyridylmethyl)-1,3-thiazolidin-2-ylidenecyanamide	Calypso 480 SC	15.5	359 [d]	$1.68\ 10^{-13}$
Thifensulfuron-methyl	methyl 3-(4-methoxy-6-methyl-1,3,5-triazin-2-ylcarbamoylsulfamoyl) thiophene-2-carboxylate	Pinnacle SG	4	28.3	$2.30\ 10^{-8}$

continued on next page

Table 14. (continued)

Active ingredient (AI)	IUPAC name	Commercial name[a]	Half-life (d)[b]	K_{oc} (mL/g)	Henry constant at 20°C (-)
Tribenuron-methyl	methyl 2-[4-methoxy-6-methyl-1,3,5-triazin-2-yl(methyl) carbamoylsulfamoyl]benzoate	MPower R (contains also thifensulfuron-methyl)	14	35	$4.21\ 10^{-12}$

[a]This list is not exhaustive and is for information purposes only.
[b]Value for aerobic soil (University of Hertfordshire, 2013). Used for all states (solid, liquid, gas).
[c]From a qualitative description of the properties in SAgE pesticides (2014).
[d]From the exact value given in SAgE pesticides (2014).

Appendix B. Risk of apple scab infection

Table 15. Number of leaves (sum of cluster and terminal shoots) as a function of temperature (from Carisse and Jobin, 2006).

Number of leaves	Base 5 °C degree days since April 1 (standard method)	Number of leaves	Base 5 °C degree days since April 1 (standard method)	Number of leaves	Base 5 °C degree days since April 1 (standard method)
1	96	10	166	19	386
2	110	11	178	20	430
3	120	12	184	21	478
4	120	13	206	22	534
5	130	14	230	23	598
6	133	15	254	24	674
7	140	16	282	25	766
8	148	17	314	26	882
9	154	18	348	27	1033

Table 16. Number of hours of leaf wetness required to create a risk of infection as a function of mean temperature during leaf wetness (from Stensvand et al.**, 1997; Carisse and Jobin, 2006). A risk of infection exists if the number of hours required is less than or equal to the estimated number of hours of leaf wetness.***

Mean temperature during leaf wetness (°C)	Number of hours of leaf wetness required	Mean temperature during leaf wetness (°C)	Number of hours of leaf wetness required	Mean temperature during leaf wetness (°C)	Number of hours of leaf wetness required
4 and -	> 24	12	8	20	6
5	21	13	8	21	6
6	18	14	7	22	6
7	15	15	7	23	6
8	13	16	6	24	6
9	12	17	6	25	8
10	11	18	6	26 and +	11
11	9	19	6		

*If the rainfall amount for the given day is less than 1 mm, the infection risk is assumed to be nil. If the rainfall amount for the given day is over 5 mm, it is assumed that the leaves are wet during the day. If the rainfall amount for the given day is between 1 and 5 mm, the dew point temperature T_r (in °C) is established approximately as follows (Lawrence, 2005):

$$T_r = \frac{100 - \rho_s}{b} + T_{\min} \tag{2}$$

where $T_{\min}$ = minimum temperature (°C) for the given day;

ρ_s = relative humidity at which dew will form (set at 90%, as suggested by the Ontario Ministry of Agriculture, Food and Rural Affairs; OMAFRA, 2011);

$b = \dfrac{100\,L}{R\left(T_{\min} + 273.15\right)^2}$;

L = enthalpy of vaporization of water (equal to approximately 2.5 x 10^6 J/kg);

R = gas constant for water vapour = 461.5 J/(kg x K).

If T_r is higher than the maximum temperature (°C) for the given day ($T_{\max}$), the leaves are wet during the entire day. Otherwise, the duration of leaf wetness is determined by assuming that the temperature follows a sine function:

$$24\left\{\frac{\arcsin\left(\dfrac{T_r - T_{moy}}{A}\right)}{\pi} + \frac{1}{2}\right\} \qquad (3)$$

where $T_{moy} = \dfrac{T_{\min} + T_{\max}}{2}$ et $A = \dfrac{T_{\max} - T_{\min}}{2}$.

Appendix C. Fire blight infection risk

Table 17. Risk value for fire blight infection for a given day as a function of the maximum temperature. The values come from the model CougarBlight 2010 (Smith, 2010). For the northeast of North America, infection risk is considered high if the sum of the four previous days is greater than 100 (scenario 2; Smith, 2010).

Maximum temperature (°C)	Risk value	Maximum temperature (°C)	Risk value	Maximum temperature (°C)	Risk value
9.5 et -	0	19.5	11.1	29.5	390
10.0	0.1	20.0	14	30.0	410
10.5	0.15	20.5	20	30.5	425
11.0	0.2	21.0	28	31.0	435
11.5	0.3	21.5	37	31.5	440
12.0	0.5	22.0	43	32.0	470
12.5	0.7	22.5	52	32.5	490
13.0	1.1	23.0	61	33.0	508
13.5	1.4	23.5	70	33.5	525
14.0	1.7	24.0	76	34.0	535
14.5	2.0	24.5	92	34.5	540
15.0	2.8	25.0	111	35.0	535
15.5	3.0	25.5	135	35.5	450
16.0	3.3	26.0	160	36.0	310
16.5	3.8	26.5	194	36.5	120
17.0	4.6	27.0	228	37.0	60
17.5	5.5	27.5	260	37.5	30
18.0	6.5	28.0	295	38.0	15
18.5	7.3	28.5	330	38.5	5
19.0	8.2	29.0	360	39.0 et +	0

Appendix D. Sites properties

Table 18. Properties of the sites studied.

no	Crop(s)	Latitude (°)	Longitude (°)	Altitude (m)	Area (ha)	Average slope (%)	Average curve number[a]	Organic carbon (%)[b]	Field capacity (%)[b]	Bulk density (g/cm^3)[b]
1	corn/soybean	46.00	-73.50	50	26.01	1.5	62	2.6	41	1.20
2	wheat	45.80	-73.75	50	9.4	1.5	62	2.6	41	1.20
3	wheat	46.87	-72.40	150	12.57	1.5	81	45.4	50	0.20
4	corn/soybean	46.40	-72.85	50	21.17	14.0	81	3.8	33	1.30
5	corn/soybean	45.15	-74.00	50	5.78	1.5	81	2.2	34	1.35
6	wheat	45.225	-73.505	50	6.13	1.3	81	2.6	30	1.40
7	corn/soybean	45.80	-73.00	25	8.55	1.5	62	1.8	26	1.35
8	wheat	45.60	-72.95	25	5.71	1.4	62	4.9	39	1.15
9	corn/soybean	46.20	-72.50	50	39.04	1.5	81	4.1	31	1.50
10	wheat	46.15	-72.355	75	12.41	2.0	62	1.8	26	1.35
11	corn/soybean	45.225	-71.85	250	24.21	6.9	81	8.2	26	1.30
12	wheat	45.14	-71.75	450	3.18	8.0	81	8.2	26	1.30
13	corn/soybean	46.52	-71.62	120	9.8	1.5	73	6.8	36	1.35
14	wheat	46.00	-70.78	400	16.03	3.6	81	15.7	33	1.25
15	corn/soybean	46.93	-70.93	75	4.64	1.5	73	0.6	27	1.25
16	wheat	46.96	-71.05	75	4.35	4.6	62	0.6	8	1.60
17	wheat/corn/soybean	47.43	-70.50	5	16.03	1.5	73	2.0	36	1.25
18	corn/soybean	48.40	-71.88	150	8.66	1.5	73	11.8	37	1.30
19	wheat	48.90	-72.54	150	18.6	1.5	81	2.8	33	1.25

continued on next page

Table 18. (continued)

no	Crop(s)	Latitude (°)	Longitude (°)	Altitude (m)	Area (ha)	Average slope (%)	Average curve number[a]	Organic carbon (%)[b]	Field capacity (%)[b]	Bulk density (g/cm^3)[b]
20	apple	45.565	-73.99	75	4.71	3.1	73	2.6	38	1.15
21	apple	45.02	-73.62	100	2.36	1.3	62	6.8	21	1.20
22	apple	45.275	-74.11	50	13.96	1.4	62	2.6	41	1.20
23	apple	45.445	-73.06	75	2.18	5.1	62	4.6	21	1.35
24	apple	45.395	-72.835	100	2.47	1.4	81	9.8	21	1.30
25	apple	45.166	-72.275	275	3.19	9.4	81	3.1	25	1.35
26	apple	46.96	-70.96	100	7.49	4.1	73	0.6	27	1.25
27	apple	45.503	-74.005	50	0.94	8.0	62	2.7	25	1.30
28	apple	45.652	-74.03	75	1.39	1.5	62	3.9	29	1.30

[a]Estimated from the values in Suarez (2005) for each hydraulic soil group (A, B, C or D). Hydraulic soil groups are defined according to the saturated hydraulic conductivity (Appendix E).

[b]Value for the upper soil layer.

Appendix E. PRZM parameters

Table 19. Definition of the most important PRZM parameters with their selected statistical distribution. Selection of emergence, maturation and harvest dates is described in Section 4.2 and is not shown in the table.

Parameter (associated process)	Definition	Value/ Distribution*	Description/Justification
AFIELD (erosion)	Field capacity (ha)	FADQ data	AFIELD is used with the HL parameter to calculate erosion. AFIELD is fixed, but HL varies randomly.
AMXDR (crop growth)	Maximum active rooting depth of crops (cm)	N(x; σ)	The values of x and σ are selected so that the interval $x \pm 3\sigma$ covers the possible values for AMXDR for a given crop (Suarez, 2005; Table 5.9).
APPEFF (pesticides application)	Application efficiency	1	No losses are considered during the application.
BD (soil properties)	Bulk density for each soil layer (g/cm^3)	X_{BD} – (1/6) Z_{THEFC}	X_{BD} = bulk density for the soil at the given site (AAFC, 2010); the 1/6 value is an approximation of the inter-layer variability estimated from the whole soil database (AAFC, 2010); and Z_{THEFC} = (THEFC – X_{THEFC})/0.065 (see THEFC parameter). For a given realization, the same pseudo-random value (Appendix F) is used for BD and THEFC, since they are strongly (negatively) correlated.
BIOFLG (pesticide chemistry)	Biodegradation flag	0	Biodegradation is implicitly accounted for in the decay rates, but is not simulated directly.
CAM (pesticides application)	Chemical application model flag	CAM = 9, except for incorporation (CAM = 5)	CAM = 9: Foliar application, linear extraction by the crop foliage based on the degree of crop canopy development, chemical not intercepted by the foliage incorporated to the user-defined depth DEPI. CAM = 5: Soil incorporation, linearly increasing to a user-defined depth DEPI.

continued on next page

Table 19. (continued)

Parameter (associated process)	**Definition**	**Value/ Distribution***	**Description/Justification**
CINTCP (crop growth)	Maximum interception storage of the crop (cm)	N(x; σ)	The values of x and σ are selected so that the interval $x \pm 3\sigma$ covers the possible values for CINTCP for a given crop (Suarez, 2005; Table 5.4).
CN (hydrology)	*Runoff curve number* (average antecedent moisture condition)	N(x; σ) max = 99	For the hydraulic soil group A: x = 62 et σ = 5; for the hydraulic soil group B: x = 73 et σ = 5; for the hydraulic soil group C: x = 81 et σ = 3.5; and for the hydraulic soil group D: x = 85 et σ = 3. Hydraulic soil group are defined form the smallest saturated hydraulic conductivity value in the first 100 cm of soil (USDA, 2004). The values of x and σ are selected so that the interval $x \pm 3\sigma$ covers the possible values for CN for a given hydraulic soil group (Suarez, 2005; Table 5.10). The value for CN is diminished of 2 et 4% for reduced tillage and no till, respectively.
CORED (soil properties)	Total depth of the soil core (cm)	X	X = value in the soil database for the given site (AAFC, 2010).
COVMAX (crop growth)	Maximum areal crop coverage (%)	N(90,3) max = 99	PRZM user manual (Suarez, 2005) suggests values between 80 and 100 %.
DAIR (pesticides chemistry)	Vapor phase diffusion coefficient (cm^2/day)	4300	Suggested value in the PRZM user manual (Suarez, 2005). Assumed identical for all active ingredients.
DEPI (pesticides application)	Depth of pesticide incorporation (cm)	N(4,1) min = 1	The default value is 4 cm. Standard deviation was defined so that $\mu - 3\sigma$ = 1 cm.
DGRATE (pesticides chemistry)	Vapor phase degradation rate constant (day^{-1})	ln(2)/X	X = Half-life of the active ingredient (Appendix A).

continued on next page

Table 19. (continued)

Parameter (associated process)	Definition	Value/ Distribution*	Description/Justification
DISP (pesticides chemistry/ soil properties)	Hydrodynamic dispersion coefficient for each pesticide and each soil layer.	0	Pesticide diffusion is accounted for, but hydrodynamic dispersion is not explicitly simulated.
DKFLG2 (pesticides chemistry)	Bi-phase degradation flag	0	Bi-phase degradation not simulated.
DPN (programmation parameter)	Thickness of the compartments in the soil layer (cm)	first layer: between 0.1 and 0.5; other layers: between 1 and 5; depend on soil thickness	Suggested in the PRZM user manual (Suarez, 2005).
DRFT (pesticides application)	Spray drift fraction	0	Spray drift not simulated.
DSRATE (pesticides chemistry)	Absorbed phase degradation rate constant (day^{-1})	ln(2)/*X*	*X* = Half-life of the active ingredient (Appendix A).
DWRATE (pesticides chemistry)	Solution phase degradation rate constant (day^{-1})	ln(2)/*X*	*X* = Half-life of the active ingredient (Appendix A).
ENPY (pesticides chemistry)	Enthalpy of vaporization (kcal/mole)	20	Suggested value in the PRZM user manual (Suarez, 2005). Assumed identical for all active ingredients.

continued on next page

Table 19. (continued)

Parameter (associated process)	Definition	Value/ Distribution*	Description/Justification
ERFLAG (erosion)	Erosion model flag	UD(2, 3, 4)	The three available models are used PRZM (2 = MUSLE, 3 = MUST, 4 = MUSS).
FEXTRC (pesticides chemistry)	Foliar washoff extraction coefficient. (per cm of rain)	N(0.3; 0.07) min = 0.01	The values of x (0.3) and σ (0.07) are selected so that the interval $x \pm 3\sigma$ covers the interval (0.1, 0.5). The values 0.1 and 0.5 are suggested in the PRZM user manual (Suarez, 2005) and in the European project FOOTPRINT (2008), respectively.
HENRYK (pesticides chemistry)	Henry's constant of the pesticide (-)	X	X = Henry's constant at 20°C of the active ingredient (Appendix A). Note that volatilisation simulated by PRZM is negligible when $X < 10^{-4}$ (Farenhorst *et al.*, 2009). This is the case for all active ingredients used, except phosmet (Appendix A).
HL (erosion)	Hydraulic length (m)	U(a,b)	The a and b values are respectively the smallest and the largest distances estimated with ArcGIS allowing to cross the given site. For example, if the site is rectangular, a and b are the length of the sides.
HTMAX (crop growth)	Maximum canopy height of the crop at maturation (cm)	N(x; σ)	The values of x and σ are selected so that the interval $x \pm 3\sigma$ covers the possible values for HTMAX for a given crop (Suarez, 2005; Table 5.16). For apple, x = 400 and σ = 30.
IPSCND (pesticides application)	Disposition of foliar pesticide after harvest	= 2 for conventional tillage, = 3 otherwise	For conventional tillage, it is assumed that almost all residues are removed after harvest (IPSCND = 2). In reduced tillage or no till, it is assumed that leaves remain on the field (IPSCND = 3).
IREG (erosion)	SCS rainfall distribution region flag (for time period May 1 to September 15)	= 2, 3 or 4 with probability ¼, ½ and ¼ respectively	A unique value is provided for each region in the United-States (Suarez, 2005; Figure 5.8). For the major part of the US, except the coastal areas, SCS type II rainfall (IREG = 3) are suggested, This explains why IREG = 3 is selected more often. However, due to the high temporal variability of summer rainfall, SCS rainfall of types IA (IREG = 2; US west coast) and III (IREG = 4; US east coast) are also considered.

continued on next page

Table 19. (continued)

Parameter (associated process)	Definition	Value/ Distribution*	Description/Justification
IRFLAG (hydrology)	Irrigation simulation flag	0	Irrigation is not considered.
ITFLAG (soil properties)	Soil temperature simulation flag	0	Soil temperature is not simulated.
KD (pesticides chemistry/ soil properties)	Pesticide soil-water distribution coefficient for each soil layer (cm^3/g)	$K_{oc} \cdot$ OC	The variable K_{oc} is water/organic carbon partitioning coefficient of the pesticide (Appendix A) and OC is the fraction of soil organic carbon.
MNGN (erosion)	Manning's roughness coefficient	N(x; σ)	For apple, x = 0.24 et σ = 0.02 to cover the suggested values for dense grass (Suarez, 2005; Table 5.46). For other crops, from the middle of the growth season to harvest, x = 0.17 et σ = 0.02; otherwise, x and σ are selected so that the interval covers the possible values for MNGN given a type of tillage and the amount of residues (depending on crop) (Suarez, 2005; Table 5.46).
NHORIZ (soil properties)	Total number of soil layers	X	X = value in the soil database for the given site (AAFC, 2010).
OC (soil properties)	Soil organic carbon for each soil layer (%)	N(X_{OC} + $3 \cdot 0.3 \cdot Z_{THEFC}$; $3 \cdot (1 - 0.3^2)^{½}$) min = 0.1 max = 99	X_{OC} = Percent of soil organic for the soil at the given site (AAFC, 2010). The values 3 et 0.3 are estimations of the inter-layer variability for OC and of the correlation between OC and THEFC, respectively. The estimations were made from the whole soil database (AAFC, 2010). Z_{THEFC} = (THEFC – X_{THEFC})/0.065 (see THEFC parameter).
PLDKRT (pesticides chemistry)	Foliage pesticide first-order decay rate (day^{-1})	ln(2)/X	X = Half-life of the active ingredients (Appendix A).

continued on next page

Table 19. (continued)

Parameter (associated process)	**Definition**	**Value/ Distribution***	**Description/Justification**
PLVKRT (pesticides chemistry)	Foliage pesticide first-order volatilization rate (day^{-1})	0	Volatilization is implicitely account for in PLDKRT.
SFAC (hydrology)	Daily snowmelt factor (cm/°C)	N(0.5; 0.1) min = 0.1	The values of x (0.5) and σ (0.1) are selected so that the interval $x \pm 3\sigma$ covers the possible values for SFAC in *open areas* (Suarez, 2005; Table 5.1).
SLP (erosion)	Slope (%)	U(a,b)	The a and b values are respectively the smallest and the largest slope values calculated at the pixel scale with ArcGIS on a given site.
TAPP (pesticides application)	Target application rate for pesticide (kg/ha)	U(a,b)	The a and b values are respectively the smallest and the largest values suggested in SAgE pesticides (2014). Detailed in Section 4.2.2.
THEFC (soil properties)	Field capacity for each soil layer (cm^3 water / cm^3 soil)	N(X_{THEFC}; 0.065) min = 0.01 max = 0.99	X_{THEFC} = field capacity for the soil at the given site (AAFC, 2010); the 0.065 value is an approximation of the inter-layer variability estimated from the whole soil database (AAFC, 2010).
THETO (soil properties)	Initial water content of each soil layer (cm^3 water / cm^3 soil)	THEFC	Simulations start in January; we assumed that field capacity is reached. The impact of this parameter is relatively small.
THEWP (soil properties)	Wilting point for each soil layer (cm^3 water / cm^3 soil)	X_{THEWP} + 0.045 Z_{THEFC} min = 0.01 max = 0.99	X_{THEWP} = wilting point for the soil at the given site (AAFC, 2010); the 0.045 value is an approximation of the inter-layer variability estimated from the whole soil database (AAFC, 2010); and Z_{THEFC} = (THEFC – X_{THEFC})/0.065 (see THEFC parameter). For a given realization, the same pseudo-random value (Appendix F) is used for THEWP and THEFC, since they are strongly (positively) correlated.
THKNS (soil properties)	Thickness of each soil layer (cm)	X	X = value in the soil database for the given site (AAFC, 2010).

continued on next page

Table 19. (continued)

Parameter (associated process)	Definition	Value/ Distribution*	Description/Justification
UPTKF (crop growth)	Plant uptake efficiency factor (fraction of transpiration x dissolved phase concentration)	U(0,1)	Uncertainty is high for this parameter; the suggested values in the PRZM user manual (Suarez, 2005) cover almost entirely the (0,1)-interval.
USLEC (erosion)	Universal soil loss cover management factor (C-factor)	N(x; σ)	x = suggested value from Table C-3b of Wall *et al*. (2002) depending on crop and tillage; σ = mean difference between tillage types for a given crop.
USLEK (erosion)	Universal soil loss equation of soil erodibility (K-factor)	N(x; 0.04) min = 0.02	x = suggested value in the PRZM user manual (Suarez, 2005; Table 5.3) depending on soil texture and organic matter of the first soil layer; σ = mean difference between organic matter threshold for a given soil texture.
USLELS (erosion)	universal soil loss equation topographic factor (LS-factor)	$\begin{pmatrix} 65.41\sin(p)^2 \\ +4.56\sin(p) \\ +0.065 \end{pmatrix} \times \left(\frac{H}{22.13}\right)^m$	Equation given in Wall *et al*. (2002) with H = hydraulic length (HL, in m), p = slope (SLP, in radian) and m = 0.2 if the slope is < 1%, m = 0.3 if the slope is between 1 and 3%, m = 0.4 if the slope is between 3 and 5% and m = 0.5 if the slope is > 5%. No random term is added for USLELS, but its parameters (slope, hydraulic length) vary randomly.
USLEP (erosion)	Universal soil loss equation practice factor (P-factor)	1	Conservation practices accounted for by the USLEP parameter were not simulated.

*Distributions : N(μ; σ) : Normal with expected value μ and standard deviation σ; U(a,b) : Uniform between a and b; UD(Ω) : Discrete uniform on the set Ω.

Appendix F. Pseudo-random values used in the stochastic model

Table 20. Pseudo-random values *u* from a (0,1)-uniform distribution used to select parameter values for each realization. Parameters « crop_days » and « appl_days » defined days linked to crop growth (planting and harvest; Section 4.2.1) and to pesticide applications (Section 4.2.2), respectively. The other parameters and their distribution are described in Appendix E.

Realization	SFAC	ERFLAG[a]	USLEK	USLEP	IREG[b]	SLP	HL	CINTCP	AMXDR	COVMAX	HTMAX	crop_days	USLEC	MNGN	CN	DEPI	TAPP	UPTKF	FEXTRC	THEFC, THEWP, -BD	OC	appl_days
1	1.00	0.61	1.00	0.49	0.03	0.27	0.63	0.56	0.69	0.84	0.33	0.09	0.33	0.23	0.22	0.94	0.05	0.02	1.00	0.61	1.00	0.49
2	0.22	0.04	0.27	0.11	0.07	0.49	0.40	0.81	0.91	0.32	0.96	0.57	0.11	0.39	0.03	0.79	0.48	0.42	0.22	0.04	0.27	0.11
3	0.98	0.56	0.50	0.54	0.95	0.61	0.01	0.95	0.59	0.29	0.56	0.19	0.69	0.12	0.39	0.91	0.21	0.10	0.98	0.56	0.50	0.54
4	0.08	0.06	0.48	0.13	0.51	0.55	0.97	0.94	0.08	0.13	0.88	0.82	0.99	0.69	1.00	0.60	0.34	0.19	0.08	0.06	0.48	0.13
5	0.78	0.55	0.79	0.51	0.40	0.25	0.74	0.79	0.71	0.89	0.44	0.46	0.26	0.61	0.87	0.15	0.61	0.66	0.78	0.55	0.79	0.51
6	0.19	0.15	0.39	0.31	0.87	0.45	0.16	0.58	0.53	0.01	0.91	0.39	0.56	0.73	0.14	0.95	0.83	0.11	0.19	0.15	0.39	0.31
7	0.87	0.28	0.68	0.39	0.59	0.34	0.66	0.68	0.13	0.19	0.51	0.98	0.32	0.30	0.71	0.33	0.32	0.28	0.87	0.28	0.68	0.39
8	0.91	0.73	0.11	0.27	0.37	0.09	0.20	0.08	0.04	0.94	0.39	0.29	0.16	0.20	0.02	0.68	0.04	0.81	0.91	0.73	0.11	0.27
9	0.88	0.91	0.95	0.37	0.68	0.19	0.90	0.79	0.75	0.37	0.48	0.35	0.71	0.86	0.40	0.31	0.22	0.90	0.88	0.91	0.95	0.37
10	0.22	0.71	0.06	0.74	0.71	0.87	0.63	0.04	0.94	0.33	0.75	0.16	0.84	0.35	0.61	0.13	0.84	0.75	0.22	0.71	0.06	0.74
11	0.79	0.91	0.93	0.02	0.98	0.04	0.16	0.22	0.34	0.92	0.41	0.32	0.26	0.20	0.73	0.85	0.71	0.91	0.79	0.91	0.93	0.02
12	0.12	0.01	0.58	0.68	0.30	0.15	0.54	0.73	0.25	0.97	0.45	0.86	0.07	0.06	0.62	0.18	0.40	0.56	0.12	0.01	0.58	0.68
13	0.90	0.92	0.88	0.58	0.99	0.52	0.52	0.64	0.60	0.95	0.51	0.74	0.37	0.71	0.19	0.60	0.77	0.04	0.90	0.92	0.88	0.58
14	0.52	0.44	0.27	0.00	0.58	0.12	0.89	0.29	0.13	0.39	0.91	0.54	0.83	0.47	0.80	0.93	0.69	0.74	0.52	0.44	0.27	0.00
15	0.21	0.52	0.02	0.30	0.74	0.17	0.04	0.63	0.53	0.55	0.64	0.99	0.32	0.82	0.38	0.50	0.56	0.17	0.21	0.52	0.02	0.30
16	0.18	0.42	0.85	0.01	0.67	0.59	0.85	0.99	0.85	0.19	0.47	0.89	0.98	0.70	0.49	0.53	0.90	0.60	0.18	0.42	0.85	0.01
17	0.07	0.84	0.02	0.62	0.37	0.24	0.06	0.17	0.96	0.38	0.84	0.13	0.10	0.49	0.10	0.29	0.84	0.14	0.07	0.84	0.02	0.62
18	0.67	0.26	0.87	0.17	0.60	0.05	0.15	0.24	0.74	0.19	0.98	0.18	0.33	0.52	0.60	0.36	0.21	0.05	0.67	0.26	0.87	0.17
19	0.91	0.05	0.37	0.31	0.83	0.09	0.58	0.58	0.38	0.99	0.44	0.37	0.00	0.65	0.27	0.12	0.74	0.09	0.91	0.05	0.37	0.31
20	0.10	0.40	0.23	0.58	0.73	0.28	0.82	0.69	0.49	0.92	0.43	0.71	0.08	0.27	0.90	0.85	0.41	0.83	0.10	0.40	0.23	0.58

continued on next page

Table 20. (continued)

Realization	SFAC	ERFLAG[a]	USLEK	USLEP	IREG[b]	SLP	HL	CINTCP	AMXDR	COVMAX	HTMAX	crop_days	USLEC	MNGN	CN	DEPI	TAPP	UPTKF	FEXTRC	THEFC, THEWP, -BD	OC	appl_days
21	0.71	0.99	0.03	0.52	0.29	0.61	0.29	0.71	0.82	0.24	0.09	0.92	0.75	0.93	0.05	0.19	0.16	0.32	0.71	0.99	0.03	0.52
22	0.02	0.31	0.36	0.84	0.12	0.51	0.21	0.99	0.42	0.19	0.96	0.99	0.66	0.33	0.06	0.23	0.67	0.95	0.02	0.31	0.36	0.84
23	0.16	0.13	0.27	0.10	0.28	0.70	0.98	0.40	0.29	0.15	0.07	0.50	0.78	0.20	0.03	0.57	0.10	0.42	0.16	0.13	0.27	0.10
24	0.51	0.89	0.55	0.30	0.68	0.72	0.40	0.43	0.56	0.14	0.27	0.26	0.43	0.09	0.34	0.94	0.77	0.32	0.51	0.89	0.55	0.30
25	0.78	0.23	0.40	0.16	0.22	0.94	0.10	0.41	0.70	0.44	0.27	0.99	0.74	0.97	0.49	0.43	0.17	0.46	0.78	0.23	0.40	0.16
26	0.47	0.54	0.31	0.79	0.36	0.91	0.64	0.81	0.29	0.77	0.62	0.18	0.61	0.48	0.93	0.78	0.07	0.95	0.47	0.54	0.31	0.79
27	0.79	0.83	0.85	0.49	0.52	0.99	0.64	0.08	0.58	0.16	0.82	0.00	0.15	0.30	0.90	0.89	0.53	0.20	0.79	0.83	0.85	0.49
28	0.57	0.53	0.40	0.64	0.38	0.99	0.65	0.53	0.75	0.88	0.12	0.06	0.98	0.46	0.85	0.60	0.77	0.68	0.57	0.53	0.40	0.64
29	0.88	0.45	0.04	0.45	0.73	0.02	0.71	0.80	0.69	0.14	0.64	0.54	0.04	0.63	0.83	0.26	0.95	0.35	0.88	0.45	0.04	0.45
30	0.31	0.48	0.82	0.04	0.29	0.05	0.99	0.31	0.32	0.18	0.99	0.56	0.72	0.19	0.90	0.87	1.00	0.67	0.31	0.48	0.82	0.04
31	0.28	0.66	0.96	0.06	0.31	0.20	0.37	0.62	0.42	0.72	0.13	0.64	0.46	0.60	0.70	0.60	0.63	0.18	0.28	0.66	0.96	0.06
32	0.62	0.94	0.67	0.63	0.13	0.95	0.12	0.97	0.39	0.98	0.85	0.13	0.50	0.36	0.66	0.96	0.99	0.42	0.62	0.94	0.67	0.63
33	0.32	0.85	0.52	0.17	0.25	0.10	0.55	0.46	0.67	0.65	0.44	0.77	0.00	0.22	0.97	0.04	0.39	0.39	0.32	0.85	0.52	0.17
34	0.06	0.86	0.10	0.80	0.71	0.36	0.71	0.48	0.37	0.46	0.24	0.60	0.76	0.98	0.39	0.10	0.90	0.57	0.06	0.86	0.10	0.80
35	0.73	0.58	0.47	0.26	0.02	0.00	0.15	0.39	0.76	0.27	0.49	0.69	0.11	0.69	0.88	0.70	0.15	0.08	0.73	0.58	0.47	0.26
36	0.29	0.62	0.65	0.63	0.42	0.51	0.70	0.89	0.17	0.05	0.07	0.69	0.53	0.99	0.10	0.70	0.85	0.32	0.29	0.62	0.65	0.63
37	0.43	0.10	0.05	0.25	0.71	0.15	0.64	0.36	0.31	0.48	0.73	0.61	0.34	0.12	0.67	0.27	0.93	0.37	0.43	0.10	0.05	0.25
38	0.29	0.64	0.90	0.80	0.30	0.76	0.82	0.97	0.66	0.25	0.58	0.67	0.64	0.18	0.66	0.46	0.05	0.04	0.29	0.64	0.90	0.80
39	0.54	0.44	0.13	0.72	0.13	0.71	0.52	0.31	0.95	0.18	0.94	0.93	0.09	0.67	0.67	0.35	0.35	0.74	0.54	0.44	0.13	0.72
40	0.91	0.30	0.12	0.64	0.13	0.19	0.46	0.39	0.34	0.91	0.46	0.93	0.49	0.97	0.64	0.04	0.06	0.03	0.91	0.30	0.12	0.64

continued on next page

Table 20. (continued)

Realization	SFAC	ERFLAG[a]	USLEK	USLEP	IREG[b]	SLP	HL	CINTCP	AMXDR	COVMAX	HTMAX	crop_days	USLEC	MNGN	CN	DEPI	TAPP	UPTKF	FEXTRC	THEFC, THEWP, -BD	OC	appl_days
41	0.83	0.69	0.38	0.60	0.32	0.02	0.65	0.46	0.66	0.67	0.56	0.14	0.25	0.29	0.08	0.00	0.75	0.18	0.83	0.69	0.38	0.60
42	0.70	0.48	0.06	0.59	0.27	0.92	0.24	0.57	0.38	0.12	0.89	0.07	0.07	0.54	0.87	0.23	0.67	0.17	0.70	0.48	0.06	0.59
43	0.15	0.44	0.51	0.33	0.17	0.99	0.86	0.58	0.82	0.78	0.45	0.70	0.07	0.97	0.46	0.70	0.90	0.42	0.15	0.44	0.51	0.33
44	0.58	0.20	0.37	0.76	0.34	0.29	0.59	0.04	0.66	0.65	0.46	0.66	0.96	0.94	0.51	0.77	0.21	0.16	0.58	0.20	0.37	0.76
45	0.11	0.84	0.67	0.16	0.46	0.80	0.74	0.41	0.59	0.06	0.57	0.07	0.61	0.40	0.82	0.63	0.43	0.07	0.11	0.84	0.67	0.16
46	0.21	0.36	0.10	0.37	0.61	0.40	0.40	0.91	0.80	0.76	0.27	0.17	0.35	0.51	0.34	0.88	0.29	0.33	0.21	0.36	0.10	0.37
47	1.00	0.99	0.18	0.77	0.49	0.67	0.07	0.16	0.37	0.48	0.08	0.20	0.30	0.79	0.28	0.17	0.88	0.84	1.00	0.99	0.18	0.77
48	0.33	0.57	0.20	0.78	0.47	0.78	0.99	0.50	0.18	0.86	0.29	0.28	0.77	0.65	0.21	0.51	0.99	0.52	0.33	0.57	0.20	0.78
49	0.40	0.89	0.12	0.93	0.11	0.38	0.57	0.21	0.02	0.35	0.90	0.03	0.02	0.74	0.52	0.25	0.81	0.45	0.40	0.89	0.12	0.93
50	0.31	0.95	0.30	0.62	0.89	0.19	0.20	0.65	0.18	0.36	0.08	0.12	0.07	0.31	0.87	0.78	0.08	0.87	0.31	0.95	0.30	0.62
51	0.03	0.25	0.23	0.45	0.00	0.94	0.55	0.04	0.89	0.70	0.24	0.23	0.09	0.80	0.20	0.82	0.62	0.67	0.03	0.25	0.23	0.45
52	1.00	0.39	0.09	0.56	0.86	0.08	0.42	0.87	0.40	0.33	0.01	0.34	0.69	0.51	0.56	0.11	0.65	0.92	1.00	0.39	0.09	0.56
53	0.19	0.01	0.15	0.89	0.67	0.72	0.50	0.85	0.62	0.19	0.48	0.16	0.33	0.56	0.42	0.43	0.56	0.93	0.19	0.01	0.15	0.89
54	0.71	0.03	0.30	0.04	0.05	0.21	0.88	0.56	0.81	0.27	0.86	0.70	0.19	0.78	0.14	0.58	0.06	0.87	0.71	0.03	0.30	0.04
55	0.72	0.92	0.51	0.81	0.61	0.89	0.12	0.10	0.79	0.71	0.20	0.44	0.81	0.58	0.36	0.03	0.96	0.97	0.72	0.92	0.51	0.81
56	0.77	0.11	0.73	0.22	0.57	0.81	0.95	0.23	0.09	0.21	0.25	0.05	0.20	0.44	0.30	0.43	0.68	0.04	0.77	0.11	0.73	0.22
57	0.67	0.82	0.23	0.25	0.68	0.34	0.52	0.75	0.16	0.45	0.05	0.87	0.19	0.57	0.02	0.98	0.63	0.13	0.67	0.82	0.23	0.25
58	0.62	0.18	0.93	0.92	0.78	0.33	0.20	0.05	0.32	0.59	0.12	0.61	0.69	0.69	0.30	0.98	0.38	0.38	0.62	0.18	0.93	0.92
59	0.97	0.72	0.60	0.09	0.19	0.35	0.28	0.06	0.05	0.24	0.82	0.03	0.76	0.24	0.30	0.83	0.47	0.39	0.97	0.72	0.60	0.09
60	0.97	0.06	0.36	0.16	0.13	0.16	0.92	0.65	0.91	0.34	0.51	0.67	0.24	0.49	0.75	0.18	0.80	0.75	0.97	0.06	0.36	0.16

continued on next page

Table 20. (continued)

Realization	SFAC	ERFLAG[a]	USLEK	USLEP	IREG[b]	SLP	HL	CINTCP	AMXDR	COVMAX	HTMAX	crop_days	USLEC	MNGN	CN	DEPI	TAPP	UPTKF	FEXTRC	THEFC, THEWP, -BD	OC	appl_days
61	0.34	0.16	0.12	0.88	0.10	0.73	0.24	0.34	0.07	0.49	0.49	0.91	0.29	0.72	0.34	0.47	0.19	0.25	0.34	0.16	0.12	0.88
62	0.84	0.44	0.84	0.15	0.65	0.28	0.49	0.21	0.92	0.07	0.59	0.71	0.77	0.56	0.50	0.57	0.43	0.92	0.84	0.44	0.84	0.15
63	0.08	0.61	0.62	0.14	0.83	0.38	0.44	0.79	0.93	0.88	0.73	0.60	0.39	0.76	0.21	0.97	0.53	0.24	0.08	0.61	0.62	0.14
64	0.55	0.48	0.74	0.99	0.37	0.67	0.91	0.86	0.56	0.95	0.35	0.31	0.88	0.53	0.45	0.61	1.00	0.54	0.55	0.48	0.74	0.99
65	0.06	0.59	0.75	0.75	0.78	0.02	0.12	0.38	0.94	0.38	0.80	0.80	0.19	0.32	0.48	0.30	0.27	0.45	0.06	0.59	0.75	0.75
66	0.82	0.66	0.30	0.37	0.63	0.56	0.52	0.11	0.62	0.81	0.90	0.38	0.79	0.70	0.76	0.82	0.31	0.28	0.82	0.66	0.30	0.37
67	0.33	0.27	0.56	0.83	0.69	0.02	0.54	0.58	0.99	0.08	0.29	0.59	0.01	0.44	0.11	0.37	0.95	0.13	0.33	0.27	0.56	0.83
68	0.97	0.47	0.49	0.29	0.07	0.68	0.66	0.21	0.34	0.96	0.38	0.46	0.22	0.20	0.48	0.76	0.81	0.42	0.97	0.47	0.49	0.29
69	0.83	0.76	0.02	0.15	0.93	0.33	0.97	0.81	0.71	0.80	0.83	0.65	0.99	0.52	0.16	0.70	0.88	0.61	0.83	0.76	0.02	0.15
70	0.51	0.76	0.34	0.98	0.81	0.10	0.75	0.90	0.92	0.23	0.95	0.86	0.18	0.81	0.52	0.33	0.93	0.68	0.51	0.76	0.34	0.98
71	0.32	0.56	0.21	0.14	0.37	0.31	0.10	0.60	0.79	0.54	0.28	0.67	0.15	0.49	0.25	0.65	0.37	0.82	0.32	0.56	0.21	0.14
72	0.49	0.71	0.57	0.01	0.98	0.45	0.76	0.10	0.35	0.91	0.28	0.87	0.00	0.36	0.31	0.12	0.97	0.96	0.49	0.71	0.57	0.01
73	0.21	0.95	0.88	0.58	0.76	0.82	0.55	0.10	0.32	0.74	0.80	0.92	0.33	0.07	0.50	0.55	0.26	0.15	0.21	0.95	0.88	0.58
74	0.34	0.79	0.41	0.88	0.18	0.47	0.83	0.88	0.44	0.83	0.07	0.64	0.74	0.64	0.66	0.66	0.13	0.36	0.34	0.79	0.41	0.88
75	0.63	0.17	0.79	0.72	0.02	0.17	0.80	0.77	0.51	0.52	0.40	0.56	0.79	0.72	0.41	0.07	0.55	0.95	0.63	0.17	0.79	0.72
76	0.97	0.82	0.60	0.52	0.73	0.99	0.33	0.46	0.54	0.41	0.63	0.52	0.79	0.22	0.13	0.72	0.84	0.11	0.97	0.82	0.60	0.52
77	0.67	0.32	0.62	0.29	0.28	0.74	0.90	0.70	0.59	0.52	0.21	0.02	0.11	0.39	0.14	0.02	0.42	1.00	0.67	0.32	0.62	0.29
78	0.37	0.88	0.29	0.45	0.89	0.12	0.96	0.86	0.86	0.18	0.31	0.31	0.96	0.19	0.02	0.22	0.98	0.44	0.37	0.88	0.29	0.45
79	0.33	0.17	0.74	0.79	0.55	0.95	0.48	0.75	0.38	0.77	0.76	0.08	0.69	0.47	0.84	0.41	0.93	0.84	0.33	0.17	0.74	0.79
80	0.14	0.69	0.54	0.06	0.43	0.22	0.34	0.50	0.84	0.96	0.51	0.31	0.35	0.37	0.18	0.98	0.76	0.04	0.14	0.69	0.54	0.06

continued on next page

Table 20. (continued)

Realization	SFAC	ERFLAG[a]	USLEK	USLEP	IREG[b]	SLP	HL	CINTCP	AMXDR	COVMAX	HTMAX	crop_days	USLEC	MNGN	CN	DEPI	TAPP	UPTKF	FEXTRC	THEFC, THEWP, -BD	OC	appl_days
81	0.95	0.56	0.65	0.37	0.66	0.29	0.20	0.61	0.95	0.27	0.40	0.88	0.88	0.15	0.15	0.46	0.40	0.54	0.95	0.56	0.65	0.37
82	0.52	0.54	0.19	0.98	0.89	0.90	0.87	0.97	0.15	0.01	0.88	0.39	0.19	0.86	0.54	0.17	0.20	0.10	0.52	0.54	0.19	0.98
83	0.16	0.75	0.89	0.85	0.58	0.12	0.85	0.73	0.29	0.63	0.29	0.23	0.90	0.83	0.60	0.63	0.91	0.96	0.16	0.75	0.89	0.85
84	0.86	0.11	0.40	0.39	0.65	0.78	0.01	0.90	0.82	0.88	0.52	0.83	0.34	0.47	0.33	0.11	0.15	0.55	0.86	0.11	0.40	0.39
85	0.90	0.94	0.91	0.38	0.21	0.48	0.33	0.10	0.77	0.05	0.76	0.20	0.46	0.43	0.34	0.15	0.17	0.18	0.90	0.94	0.91	0.38
86	0.14	0.33	0.34	0.31	0.42	0.39	0.25	0.95	0.41	0.54	0.59	0.58	0.05	0.01	0.92	0.78	0.14	0.11	0.14	0.33	0.34	0.31
87	0.94	0.46	0.33	0.13	0.43	0.21	0.72	0.10	0.04	0.29	0.76	0.78	0.10	0.40	0.66	0.29	0.55	0.14	0.94	0.46	0.33	0.13
88	0.59	0.08	0.07	0.41	0.60	0.98	0.48	0.64	0.03	0.96	0.81	0.51	0.03	0.95	0.52	0.62	0.33	0.54	0.59	0.08	0.07	0.41
89	0.82	0.46	0.28	0.47	0.01	0.96	0.82	0.95	0.59	0.23	0.13	0.68	0.83	0.90	0.63	0.27	0.36	0.78	0.82	0.46	0.28	0.47
90	0.07	0.07	0.67	0.48	0.59	0.59	0.47	0.22	0.15	0.94	0.61	0.93	0.66	0.24	0.24	0.99	0.35	0.72	0.07	0.07	0.67	0.48
91	0.94	0.52	0.41	0.77	0.57	0.01	0.59	0.36	0.95	0.39	0.90	0.64	0.75	0.50	0.28	0.54	0.39	0.11	0.94	0.52	0.41	0.77
92	0.47	0.03	0.43	0.15	0.69	0.18	0.71	0.21	0.11	0.26	0.24	0.12	0.26	0.73	0.55	0.05	0.31	0.61	0.47	0.03	0.43	0.15
93	0.57	0.85	0.01	0.22	0.02	0.39	0.33	0.53	0.69	0.48	0.14	0.84	0.45	0.66	0.20	0.36	0.73	0.26	0.57	0.85	0.01	0.22
94	0.13	0.72	0.64	0.21	0.31	0.01	0.86	0.00	0.27	0.22	0.98	0.87	0.69	0.77	0.11	0.98	0.27	0.47	0.13	0.72	0.64	0.21
95	0.49	0.69	0.87	0.02	0.69	0.04	0.28	0.82	0.42	0.92	0.08	0.65	0.98	0.32	0.68	0.99	0.27	0.78	0.49	0.69	0.87	0.02
96	0.16	0.62	0.37	0.60	0.84	0.32	0.20	0.67	0.86	0.09	0.97	0.46	0.22	0.65	0.65	0.02	0.33	0.54	0.16	0.62	0.37	0.60
97	0.94	0.98	0.62	0.48	0.44	0.93	0.56	0.86	0.35	0.47	0.19	0.47	0.81	0.43	0.98	0.73	0.41	0.94	0.94	0.98	0.62	0.48
98	0.91	0.37	0.09	0.06	0.99	0.10	0.05	0.21	0.57	0.28	0.77	0.26	0.23	0.58	0.06	0.76	0.44	0.49	0.91	0.37	0.09	0.06
99	0.14	0.93	0.07	0.70	0.51	0.13	0.13	0.02	0.68	0.13	0.47	0.07	0.33	0.36	0.72	0.82	0.82	0.64	0.14	0.93	0.07	0.70
100	0.27	0.20	0.52	0.15	0.03	0.92	0.78	0.53	0.74	0.58	0.55	0.83	0.47	0.60	0.38	0.72	0.41	0.14	0.27	0.20	0.52	0.15

[a]ERFLAG = 2 if $u < 1/3$, ERFLAG = 3 if $u > 1/3$ and $u < 2/3$, and ERFLAG = 4 if $u > 2/3$.

[b]IREG = 3 if $u < 1/2$, IREG = 2 if $u > 1/2$ and $u < 3/4$, and IREG = 4 if $u > 3/4$.

Acknowledgements

This project was funded by Agriculture and Agri-Food Canada (AAFC). Climate model data were scaled and provided by Consortium Ouranos. We thank Jean-François Martineau (Financière agricole du Québec, FADQ) for providing the agricultural data used to select the sites, Isabelle Beaudin (IRDA) for providing soil data on the sites selected, and Roland Joannin (Agropomme) and Vincent Philion (IRDA) for their constructive comments.