Impact of climate change on risk of winter damage to agricultural perennial plants

[Impact des changements climatiques sur les risques de dommages hivernaux aux plantes agricoles pérennes]

Climate Change Action Fund
Project A084

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Final report
June 2001

EXECUTIVE SUMMARY

Harsh winter climatic conditions are a major constraint for perennial crops which are grown on more than 2.1 million hectares in eastern Canada. The predicted increase of 2 to 6°C in average winter temperature by 2050 in eastern Canada will likely affect the climatic factors responsible for winter survival of agricultural perennial plants. To assess the impact of climate change on winter injury to perennial forage crops and deciduous fruit trees, we 1) identified causes of damage during fall, winter and spring specific to each crop type and, 2) developed agro-climatic indices expressing the relative intensity of each cause. Fall indices reflect the effects of temperature and precipitation during cold hardening. Winter indices integrate the interactions between cold intensity, cold duration and the protective role of snow cover, assess the loss of cold hardiness due to warm temperatures, and estimate the potential damage to roots by soil heaving and ice encasement. Spring indices express the risk of damage to floral buds associated with a late spring frost.

Sixty-nine climate stations were selected within the agricultural regions of eastern Canada. Temperatures and precipitations for the periods 2010–2039 and 2040–2069 were estimated for each station by adjusting daily weather data from the 1961–1990 period with climate change data from the first generation Canadian Global Coupled General Circulation Model. Estimated mean indices of the future periods were compared to current values.

Perennial forage crops in eastern Canada are likely to be under a greater risk of winter damage with climate change because of: 1) a more rapid cooling of temperatures during fall which will result in a lower degree of cold hardiness at the onset of winter; 2) a greater occurrence of above-freezing temperatures during winter and associated loss of hardiness; and 3) a loss of snow cover which will likely increase exposure of plants to freezing temperatures, ice, and soil heaving.

Risks of winter damage to deciduous fruit trees in eastern Canada are likely to decrease because of: 1) a shorter photoperiod and consequently deeper cold acclimation at the time of the first frosts; 2) milder winter temperatures reducing the cold stress; and 3) a modified spring temperature regime lowering the risks of damage to floral buds by late frosts, except for the currently warmer regions of southern Ontario. On the other hand, more frequent winter thaw events will result in a loss of hardiness and increase vulnerability to late winter sub-freezing temperatures.

To alleviate the negative effects of climate change on perennial forage crops in eastern Canada, we could envisage: 1) the development and judicious use of species and cultivars adapted to the different climatic conditions, and 2) appropriate harvest and field management.

Furthermore, the expected climate change will also offer opportunities to the fruit tree sector in eastern Canada. For example we may expect the introduction of new species and cultivars and the extension further north of the limits of commercial production of deciduous fruit trees.

INTRODUCTION

Context

Agricultural perennial crops are grown on more than 2.1 million hectares, which represents about 40 % of cultivated land in eastern Canada and an annual value of $1.7 billion (Statistics Canada, 1996). Harsh winter climatic conditions are a major constraint for perennial crops. For example, the Québec Crops Insurance Program, which covers about 1.4 % of cultivated forage land, pays yearly compensations of $1 200 000 (average from 1985 to 1999) because of winter damage to forage legumes (pers. comm.). Each year from 1990 to 1999, approximately 30% of insured forage areas incurred losses due to winter damage.

Meteorological models predict that the mean minimum temperature of the cold season in eastern Canada will increase from 2 to 6°C by 2050 (Canadian Institute for Climate Studies, 2001). This warming will be accompanied by greater fluctuations of temperature and precipitation during fall, winter, and spring. These factors are responsible for frequent winter damage to perennial crops in eastern Canada. Exceptionally warm temperatures observed in recent years have revealed the vulnerability of perennial crops to climate irregularities. A succession of winter frosts and thaws in 1980–1981 killed more than 350 000 apple trees in Québec (Rousselle, 1983), Ontario and the Maritime provinces (Embree, 1984) and caused losses of several million dollars. The 1998 ice storm also caused significant damage to perennial crops.

The objectives of this study were : 1) to evaluate the impact of climate change on the risk of damage to agricultural perennial crops during the cold period; 2) to identify the impact on production systems; and 3) to formulate strategies more suitable for future climatic conditions under a changed climate.

Approach

Agricultural perennial crops are either woody like deciduous fruit trees or herbaceous like forage crops. Physiological and morphological differences between these two types of perennial plants explain their different response to climatic conditions. The main physiological difference between woody and herbaceous perennial plants is their growth rhythm. Woody plants stop their growth in late summer or early fall in response to the shortening of day length even though temperatures are still warm, whereas growth of herbaceous plants is mainly controlled by decreasing temperatures. Woody plants over-winter with their root system deep in the ground (except during their first years) while their stems, branches and buds are aerial. Herbaceous plants have a root system generally located in the uppermost layers of soil, and their crowns and leaf buds are located either immediately below or at the soil surface; above ground stems and leaves die during winter. Because of these fundamental differences and for the purpose of publication of the results, we divided the agricultural perennial plants into two groups: forage crops and deciduous fruit trees.

The impact of climate change on the risk of winter damage to forage crops and deciduous fruit trees was assessed by: 1) identifying respective causes of winter damage, 2) developing specific agro-climatic indices expressing the risk associated to each cause, and 3) calculating indices under climate change scenarios for sixty-nine climate stations within representative agricultural regions of eastern Canada. The values of the indices were then averaged across 22 agricultural regions of eastern Canada and the values for the current 30-year period were compared with those predicted for the 2010–2039 and 2040–2069 periods.

The project was divided into two phases. In the first phase, the methodology was developed and validated for the agricultural regions of Québec; a preliminary report was produced (April 2000). In the second phase, this methodology was used to extend the study to all agricultural regions of eastern Canada (from Ontario to Newfoundland).

Two research papers, prepared as part of this study, are presented in this report. The first research paper (Bélanger *et al.*) presents the impact of climate change on winter survival of perennial forage crops (Section 1). The second research paper (Rochette *et al.*) presents the impact of climate change on winter damage to deciduous fruit trees (Section 2). In Section 3, results are briefly summarised and recommendations are presented. The list of agro-climatic indices is presented in Appendix A, the list of climatic variables is presented in Appendix B, figures illustrating current and predicted values of each index for each of the 22 regions of eastern Canada are presented in Appendix C, and a list of communications related to this study is presented in Appendix D.

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SECTION 1

Potential impact of climate change on winter survival of perennial forage crops in eastern Canada

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ABSTRACT

The possible impact of climate change on overwintering of perennial forage crops in eastern Canada was assessed using indices reflecting risks associated with known causes of winter injury and describing climatic conditions related to cold hardening, cold intensity and duration, snow cover, loss of cold hardiness, and damage due to soil heaving and ice encasement. Climatic indices were calculated for 22 agricultural regions in eastern Canada for current climate (1961–1990) and future climate scenarios (2010–2039 and 2040–2069). Scenario data were extracted from the First Generation Coupled Canadian General Circulation Model. Averaged across all agricultural regions, the hardening period in 2040–2069 would be shorter by 4.0 d and warmer by 17.6 cumulative cold degree days. The annual minimum temperature would increase by 4.8°C, the cold period ($T < -15°C$) would be reduced by 23.8 d and the number of days with snow cover of at least 0.1 m would be reduced by 39.4 d. Consequently, the number of days with a protective snow cover during the cold period was reduced by 15.7 d. Under predicted future climate, risks of winter injury to perennial crops in eastern Canada is likely to increase because of inadequate cold hardening during fall and because of insufficient protective snow cover during the cold period.

Key Words: Climate change, forage crops, winter survival, winter, hardening

RÉSUMÉ

L'impact possible des changements climatiques sur la survie à l’hiver des plantes fourragères pérennes dans l'est du Canada a été évalué en utilisant des indices exprimant les risques associés à des causes connues de destruction par l'hiver et décrivant les conditions climatiques associées à l'acquisition et le maintien de l'endurcissement, à l'intensité et la durée du froid, à la couverture nivale et à l'englacement et le déchaussement des racines. Les indices ont été calculés pour 22 régions agricoles de l'est du Canada pour des conditions actuelles (1961–1990) et futures (2010–2039 et 2040–2069). Les scénarios de changements climatiques furent obtenus du Modèle Couplé de Circulation Générale de Première Génération. D'ici 2040–2069 en moyenne, la période d'endurcissement serait plus courte de 4,0 j et plus chaude de 17,6 degrés-froids. La température minimale annuelle augmenterait de 4,8°C, la période froide ($T < -15°C$) raccourcirait de 23,8 j et le nombre de jours où le couvert de neige est d'au moins 0,1 m serait réduit de 39,4. En conséquence, la durée de protection par la neige au moment où des froids intenses peuvent sévir diminuerait de 15,7 j. Selon le scénario climatique prédit, les risques de dommages par l'hiver aux plantes fourragères pérennes augmenteraient à cause de conditions sous-optimales d'endurcissement automnal et principalement à cause d'une protection inadéquate par la neige durant la saison froide.

Mots clés: Changement climatique, plantes fourragères, survie hivernale, hiver, endurcissement

Perennial forage crops are grown on more than 2.1 million hectares in eastern Canada, which represent about 40% of cultivated land (Statistics Canada, 1996) with an annual estimated farm gate value of $1.3 billion. Winter killing is frequently observed and is one of the most common causes of the loss of stands and yield of perennial forage crops in many forage-growing areas of eastern Canada. These crops are directly dependent on the weather and climate for their winter survival, and any change in fall and winter climate or climate variability may have a significant impact on survival and hence suitability of these crops.

Meteorological models predict that the mean minimum temperature of the cold season will increase from 2 to 6°C by 2050 in eastern Canada (Canadian Institute for Climate Studies 2001). This warming will potentially affect winter survival of perennial forage crops.

Rochette and Dubé (1993a; 1993b) developed agro-climatic indices to assess the risk of winter damage for a broader group of perennial plants. Their indices were based on current knowledge of plant-environment relationships during the cold period using readily available climate variables such as temperatures and precipitation and they were used to express relative spatial differences in the intensity of the causes of damage in the province of Québec, Canada.

Our objective was to develop agro-climatic indices specific to the risk of winter damage to perennial forage crops and to use these indices to assess the impact of climate change on perennial forage crops in eastern Canada. Our approach does not predict winter damage expected in any given year in the future. Instead, relative comparisons are made between present day and future climatic scenarios for forage-producing areas of eastern Canada in relation with winter survival of perennial forage crops.

DEVELOPMENT OF AGRO-CLIMATIC INDICES

Agro-climatic indices are frequently used to characterize particular climatic parameters related to specific plant requirements. In this study, the five indices used are an extension of those previously reported for broader groups of perennial plants by Rochette and Dubé (1993a; 1993b). The indices were thus developed to reflect the risks associated to the most probable climatic causes of damage to perennial forage crops during fall and winter. Fall indices express the influence of temperature and precipitations on the acquisition of cold hardiness. Winter indices assess : 1) the net impact of cold intensity and duration, and the protective role of snow cover, 2) the loss of cold hardiness due to warm temperatures, and 3) the potential damage to the root system by soil heaving and ice encasement. The justification for the selection of each of these indices follows.

Table 1. Agro-climatic indices expressing the risks associated to the most probable causes of damage to perennial forage crops during winter, climatic variables used for the calculation of the indices, and additionnal variables used for the development of the snow cover model. Units and calculations are enclosed in parentheses.

Indices/Variables	Description
Agro-climatic indices	
FH-COLD	Accumulated CDD5 during hardening (CDD5) (V5)
FH-RAIN	Rate of rainfall accumulation during hardening (mm d^{-1}) (V6 / V4)
W-THAW	Rate of DD0 accumulation during cold period (DD0 d^{-1}) (V13)
W-RAIN	Rate of rainfall accumulation during cold period (mm d^{-1}) (V14)
W-COLD	Difference between days of snow cover and cold period (d) (V16)
Variables used for the calculation of the agro–climatic indices	
V1	Date of first occurrence of minimum air temperature ≤ –10°C
V2	Sum of cold degree-days < 5°C - sum of degree-days > 5°C from 1 Aug. to day V1 - 1
V3	Date following last day when V2 = 0
V4	Length of hardening period (d) (V1 - V3)
V5	Sum of cold degree-days < 5°C from day V3 to day V1 - 1
V6	Sum of daily precipitations from day V3 to V1 - 1 (mm)
V7	Date of first occurrence of minimum air temperature ≤ –15°C
V8	Date of last occurrence of minimum air temperature ≤ –15°C
V9	Length of cold period (V8 - V7) (d)
V10	Sum of cold degree-days < –15°C from 1 Aug. to 31 July
V11	Sum of degree-days > 0°C from day V7 to day V8 - 1
V12	Sum of daily rainfall from day V7 to day V8 - 1 (mm)
V13	Rate of accumulation of degree-days > 0°C during cold period (DD0 d^{-1}) (V11/V9)
V14	Rate of rainfall accumulation during cold period (mm d^{-1}) (V12 / V9)
V15	Number of days with a snow cover of at least 0.1 m (d)
V16	Difference between the number of days with a snow cover and the cold period (d) (V15 - V9)
Additionnal variables used for the development of the snow cover model	
V17	Sum of cold degree-days < 5°C from 1 Aug. to day V1 - 1
V18	Sum of degree-days > 5°C from day V3 to day V1 - 1
V19	Rate of accumulation of V2 (V2 / V4)
V20	Date of first fall frost (≤ 0°C)
V21	Photoperiod or daylength on day V20 (hrs)
V22	Mean daily minimum temperature of the coldest month (°C)
V23	Lowest daily minimum temperature from 1 Aug. to 31 July (°C)
V24	Sum of degree-days > 0°C from 1 Jan. to day V8 - 1 (DD0)
V25	Sum of degree-days > 0°C from 1 Jan. to day V26 - 1 (DD0)
V26	Date of last occurrence of minimum temperature ≤ 0°C
V27	Sum of degree-days > 5°C from 1 Jan. to day V28 - 1 (DD5)
V28	Date of last occurrence of minimum temperature ≤ –2°C
V29	Sum of snowfall from 1 Aug. to 31 July (cm)
V30	Length of the period in which minimum temperature ≤ 0°C may occur (d) (V26 - (V20 + 1))
V31	Average mean daily temperature from 1 Nov. to 30 Apr. (°C)
V32	Average mean daily temperature from 1 Aug. to 31 July (°C)
V33	Sum of daily rainfall from 1 Nov. to 30 Apr. (mm)

Fall indices

Conditions favourable for fall growth of perennial forage crops delay the development of cold hardiness (Smith, 1961; McKenzie and McLean, 1980). Warm and rainy days promote growth, slow down the storage of reserves and prevent plants from attaining their maximum level of winter hardiness.

Fall hardening – Temperature

Hardening of perennial herbaceous species in fall is initiated by declining temperatures that trigger storage of assimilates in roots. As a result, plants hardens properly before potentially harmful frosts occur. In northern regions, hardening of forage crops accelerates when mean air temperature decreases below 5°C (Paquin and Pelletier, 1980). Fall hardening is therefore the period ranging from the date when there is a net accumulation of cold degree days below 5°C (CDD5; see Table 1 under V2 for details on net accumulation of CDD5) to the date of first occurrence of a minimum air temperature of –10 °C or less at which above ground foliage should be killed. The cumulative CDD5 that accumulated during the fall hardening period, hereafter called FH-COLD, were used to reflect fall temperature conditions and to express the hardening potential of forage crops.

Fall hardening – Rainfall

Plants fail to harden properly under wet soil moisture conditions (Calder et al., 1965; Paquin and Mehuys, 1980). Evaporation and transpiration are low during fall and soil moisture is closely related to rainfall. The rate of rainfall accumulation during the hardening period was used as an index (FH-RAIN) reflecting fall moisture conditions during acquisition of cold hardiness (Table 1).

Winter indices

Winter survival of cold-hardened plants may be affected by harsh winter climatic conditions. Causes of winter damage to forage crops can be grouped into three main categories related to : cold intensity and duration, loss of cold hardiness by exposure to warm temperatures, and soil heaving and ice encasement.

Cold intensity and duration

Winter temperatures frequently drop to potentially damaging levels even for fully acclimated plants. Perennial forage crops will be injured if the temperature at crown and root level drops below the limit of their tolerance to cold temperatures attained during the preceding fall.

Herbaceous plants of northern regions survive low temperatures by initiating and limiting freezing to extra-cellular spaces. Extra-cellular freezing creates a gradient in vapour pressure between intra and extra-cellular compartments that brings water outside of the cell and thus lowers the freezing point of the cytosol. The extent and duration of freezing can lead to extensive cell dessication, alteration of membrane lipids, and mechanical stresses to cell walls as a result of reduction in cell volume (Sakai and Larcher, 1987). The tolerance to these physiological stresses differs among species and is dependent on both the intensity and the duration of the exposure to cold temperature. Cold-acclimated alfalfa (*Medicago sativa* L.) can withstand temperatures of –20 to –26°C for a brief period (few hours) but is damaged by exposure to temperatures of –8 and –10°C for a few days (Paquin, 1984). Accordingly, maximum cold tolerance, as expressed by LT_{50} or the temperature at which 50% of plants are killed, of alfalfa under field conditions in three different climatic zones in Québec rarely goes below –14 to –15°C and in some cases only to –11 and –12°C (Paquin and Mehuys, 1980).

In our study, –15°C was chosen as the temperature threshold below which plants that tolerate extra-cellular freezing and experience cell dessication are expected to undergo freezing damages. We defined the cold period as the duration in days between the first and the last occurrence of air temperature equal to or less than –15°C (see V9 in Table 1). In eastern Canada, air temperature drops below this threshold every year.

The winter survival of perennial forage crops depends on the protection of their roots and crown buds by adequate snow cover. Soil temperature at the crown level often increases at the onset of permanent snow cover (Andrews and Pomeroy, 1977). When snow cover is absent or inadequate, temperature at the crown level can decrease to potentially damaging levels and stress of dessication may also increase. In this study, the difference between the number of days with a snow cover above or equal to 0.1 m and the length of the cold period was used as an index, hereafter referred as W-COLD, that combines the threat related to sub-freezing temperatures with the protective effect of the snow cover (Table 1). A positive difference indicates that the duration of the period when perennial plants are protected by the snow exceeds that when low killing temperatures may occur. Conversely, a negative difference express the number of days when perennial plants are potentially exposed to freezing temperatures. It was assumed that a minimum snow depth of 0.1 m is required to provide uniform insulating snow coverage over a field. It was also assumed that both the snow cover period and the cold period are centred on a single date.

De-hardening

Fully-acclimated perennial forage plants can maintain a high level of cold hardiness, provided crown temperatures remain below freezing and the plants have adequate energy supply (McKenzie and McLean, 1980). Prolonged exposure to temperature above the 0°C threshold in winter results in a gradual loss of cold hardiness (Sakai and Larcher, 1987) and increases susceptibility to injury by subsequent low temperatures. Thus, in our study, the rate of accumulation of degree-days above 0°C during the cold period was used to express the potential loss of hardiness; this index is hereafter referred as W-THAW (Table 1).

Soil heaving and ice encasement

Heavy winter rainfall along with freezing temperatures may induce ice-sheet formation at the soil surface, leading to the smothering of plants by anoxia and accumulation of CO_2, ethanol, lactic acid and ethylene. These conditions may also result in damage to roots due to soil heaving. Forage plants whith their crown parts close to the soil surface are most affected by these conditions. The presence of an ice sheet at the surface of a humid soil also favours deeper frost penetration. The rate of rainfall accumulation during the cold period, hereafter referred as W-RAIN, was used as an index to express the risk of winter damage associated to ice encasement and soil heaving (Table 1).

MATERIALS AND METHODS

Climatic data

Weather stations

Sixty-nine weather stations within agricultural areas of eastern Canada (42°2'N to 49°24'N, and 52°47'W to 89°20'W) were selected for this study, based on their representativeness of agricultural regions and on data availability (Fig. 1). Stations were required to have daily maximum and minimum air temperatures, rainfall, snowfall and total precipitation available for at least 26 continuous years within the 1961–1990 period. Data were originally obtained from Environment Canada (1999) and reformatted into daily records with missing data estimated. Data were stored in a Daily Climate Archive maintained at Agriculture and Agri-Food Canada, Eastern Cereals and Oilseeds Research Centre, Ottawa.

Climate change scenario and its application to current climatic data

Climate change scenarios for two future time periods (2010–2039 and 2040–2069) were based on a 2001-year "transient" simulation by the first generation coupled Canadian General Circulation Model (CGCMI) that included the effects of aerosols (Boer et al., 2000). This simulation used an effective greenhouse gases (GHG) forcing corresponding to that observed from 1900 to the present and a 1% increase after that until year 2100. Scenarios based on the average results of an ensemble of three simulations were extracted from the Intergovernmental Panel on Climate Change, Data Distribution Centre CD-Rom (IPCC, 1999). Data based on 30-year averages for each of 12 months were extracted for 33 grid points covering all of eastern Canada, ranging from 38°58'N to 50°06'N in latitude and from 52°30'W to 90°00'W in longitude (Fig. 1). Grid spacing for the Canadian GCM is approximately 3.75E lat. x 3.75E long. For temperature, we extracted the changes in monthly mean average daily maximum and minimum air temperature (*d*T) for the two future time periods with respect to the 1961–1990 period. For precipitation, we extracted the mean average daily precipitation rate (mm d^{-1}) for each month based on the 1961–1990 period and the change in the precipitation rate for each of the two future time periods. Monthly precipitation ratios (R) were computed by dividing the rates for each of the future time periods by the rate for the 1961–1990 period. The values for *d*T and R were interpolated to each of the 69 climate stations by weighting values from the four nearest grid points, using an inverse distance weighting procedure (Tabios and Salas, 1985). Daily weather data for the 1961-1990 period at each station were then adjusted to the 2010-2039 and 2040-2069 periods by applying the monthly values for *d*T and R to the daily maximum and minimum air temperatures and precipitation in each of the respective months. If the minimum temperature exceeded the maximum, which occurred infrequently, the two were simply reversed.

Partitioning into rainfall and snowfall for future scenarios

Daily precipitation for the two future time periods was partitioned into rainfall and snowfall using the following formula:

$$F_r = (T_r - T_{max})/(T_r - T_s); \quad \text{if } T_{max} > T_r,\ F_r = 1.0; \quad \text{if } T_{max} < T_s,\ F_r = 0.0$$

in which F_r is the fraction of total daily precipitation falling as rain, T_r and T_s are threshold temperatures for rain and snow, respectively, and T_{max} is the daily maximum temperature. Optimum threshold temperatures were determined for each station using all available observed data for which there was measurable precipitation for November to March period, 1961–1990. An iterative approach was used to determine values for T_r and T_s that resulted in the lowest sum of the difference between estimated and observed daily rainfall. These values generally also had the lowest variance in the daily differences. Optimum T_r and T_s values for each station were then used to partition daily precipitation into rainfall and snowfall for the 2010–2039 and 2040–2069 period. A water equivalent ratio of 10:1 was assumed for snowfall.

Calculation of climatic indices and variables

The 69 weather stations were grouped into 22 agricultural regions (Table 1) based on their climate and the predominant crops. Indices were calculated yearly for the 1961–1990, 2010–2039 and 2040–2069 periods and at each selected weather station. Values of the indices were averaged for each period across agricultural regions and across stations within each of the 22 agricultural regions.

A total of 33 variables including the five indices already described, were calculated yearly from daily climate data for 1961–1990, 2010–2039 and 2040–2069 (Table 1) for each weather station. Variables were computed over a two-calendar year period ranging from 1 August to 31 July . The start of the hardening phase (V4; Table 1) was defined as the date when accumulated daily differences between CDD5 and degree-days above 5EC (DD5) beginning from August 1 (V2; Table 1) always remain above zero, with the condition that negative accumulated values were set to zero. The hardening phase ended on the day before the first occurrence of a minimum temperature of #–10EC (V1; Table 1). If a minimum temperature of #–10°C was not reached during winter, V1 was set as the latest date of the first occurrence of a minimum temperature #–10°C within the years in which such temperatures did occur. If a temperature of #–15EC was not reached, V9 and V10 (Table 1) were set to zero and V11 to V14 and V24 (Table 1) were not computed. V9 was set to 1 if there was only one occurrence of a temperature #–15°C. Since variables V15 and V16 (Table 1) were not available for the two future time periods, it was necessary to develop a snow cover model to estimate these variables.

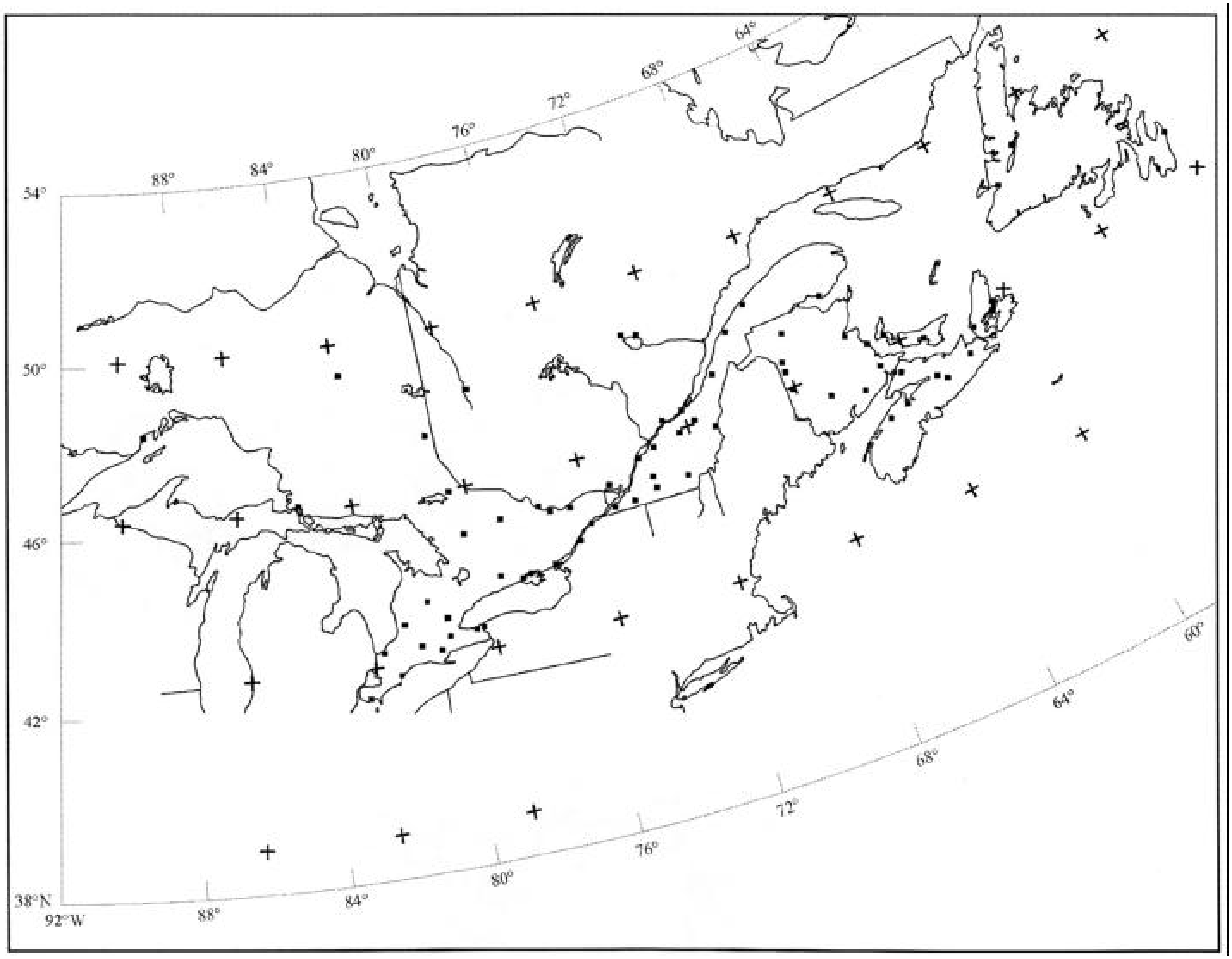

Figure 1. Distribution of weather stations used for the study on the impact of climate change on the winter survival of perennial forage crops in eastern Canada. Grid points (+) of the Canadian General Circulation Model are also presented.

Table 2. Description of the agricultural areas included in the study.

Agricultural region (province)	Weather station	Elevation† (m)	Latitude (N)	Longitude (W)
Harrow (ON)	Harrow CDA, Ridgetown, Sarnia A	193	42°2' – 43°0'	81°53' – 82°54'
Guelph (ON)	Brucefield, Guelph, London A, Mount Forest	322	43°2' – 43°59'	80°14' – 81°33'
Delhi (ON)	Brantford MOE, Delhi CDA	214	43°8' – 45°52'	80°14' – 80°33'
Vineland (ON)	St. Catharines A, Vineland Station	89	43°12' – 43°12'	79°10' – 79°24'
North Bay-Huntsville (ON)	Huntsville WPCP, Madawaska, North Bay A	320	45°21' – 46°22'	77°59' – 79°25'
Kingston (ON)	Belleville, Kingston A, Peterborough A, Smithfield CDA	120	44°5' – 44°14'	76°36' – 78°22'
Eastern Ontario-St. Lawrence Riv. (ON, QC)	Brockville PCC, Morrisburg, Saint-Anicet	75	44°36' – 45°8'	74°21' – 75°40'
Ottawa Valley (ON)	Arnprior Grandon, Chenaux, Ottawa CDA	90	45°23' – 45°35'	75°43' – 76°41'
Continental North (ON, QC)	Earlton A, Kapuskasing CDA, Amos, Normandin CDA, Péribonka	202	47°42' – 49°24'	72°2' – 82°26'
South Québec (QC)	Berthierville, Farnham, Lachute, Lennoxville CDA, Sainte-Clothilde CDA, Saint-Hyacinthe 2	70	45°10' – 46°3'	71°49' – 74°20'
Central Québec (QC)	Laurierville, Nicolet, Québec A, Scott, Saint-Alban, Saint-Prosper	126	46°12' – 46°48'	70°30' – 72°37'
Lower St. Lawrence-Gaspé Peninsula (QC)	Caplan, La Pocatière CDA, Mont-Joli A, Trois-Pistoles	40	47°21' – 48°36'	65°41' – 70°2'
West New Brunswick (NB)	Aroostook, Centreville, Grand Falls-Drummond, Kedgwick	179	46°23' – 47°39'	67°21' – 67°43'
East Coast (NB)	Chatham A, Rexton	20	46°40' – 47°1'	64°52' – 65°28'
Moncton (NB)	Fredericton CDA, Moncton, Sussex, Nappan CDA	23	45°43' – 46°6'	64°15' – 66°37'
Annapolis Valley (NS)	Clarence, Kentville CDA	51	44°55' – 45°4'	64°29' – 65°10'
Truro (NS)	Truro, Upper Stewiacke	32	45°13' – 45°22'	63°0' – 63°16'
Cape Breton (NS)	Baddeck, Collegeville, Port Hood	37	45°29' – 46°6'	60°45' – 62°1'
Prince Edward Island	Charlottetown CDA, O'Leary	31	46°15' – 46°42'	63°8' – 64°16'
Newfoundland (NF)	Deer Lake, St. John's West CDA, Stephenville A	44	47°31' – 49°10'	52°47' – 58°33'
Thunder Bay (ON)	Thunder Bay A	199	48°22'	89°20'
Sault Ste Marie (ON)	Sault Ste. Marie 2	212	46°32'	84°20'

† Averaged elevation of the weather stations used in each region

Snow cover model

Variables V1 to V14 and V17 toV33 (Table 1) were calculated yearly from historic climatic data (1961–1990 period) for 60 weather stations in eastern Canada and six stations in the United States (Baltimore, Concord, Indianapolis, Lexington, Nashville and Newark). Stations from the United States were added to include a wider range of snow cover regimes that may be experienced under future climates in eastern Canada. Daily snow cover data were not available for all years at some locations and only years with some measurable snow cover were used in the analyses. Therefore, the number of years ranged from 1 to 30 per station for a total of 1348 station-years.

Bootstrap techniques were combined with regression model building techniques to determine the best regression model for estimating V15, the number of days where the depth of the snow cover is equal or greater than 0.1 m. First, a random sample of years and observations were selected with replacement from the original data set, and those observations not chosen were retained as a calibration data set. This will be referred to as a bootstrap sample. The best model with 1, 2, up to 30 components was estimated for each bootstrap sample along with the corresponding Mallows CP statistic (Draper and Smith, 1998). The best overall model was chosen based upon Mallows CP and the coefficients of the variables included in the model were retained. This was repeated 2000 times and the final model consisted of coefficients that were included in at least 40% of the bootstrap samples. For each of the 2000 bootstrap samples, the correlation between the predicted values based upon the best overall model and the bootstrap calibration data sets were calculated. The correlation coefficient of the validation data set with the predicted values ranged from 88 to 92%. To eliminate biased estimates of the snow cover for the various locations, stations effects were added to the model. Coefficients accounting for stations effects were calculated as least square estimates from the GLM procedure in the Statistical Analysis System (SAS 1990). Parameters and coefficients of the resulting model are presented in Table 3. Based upon this final model, 87% of the variability in the model was accounted for in the ANOVA and the model could be used confidently for the purpose of this study.

Variable V15 was estimated yearly by the mean of the regression model for each of the 60 Canadian sites for the three periods. Historic climatic data of snow on the ground were not available for nine sites (Ridgetown, Brucefield, Brockville PCC, Morrisburg, Chenaux, Kedgwick, Grand Falls Drummond, Centreville and Sault Ste. Marie 2). For these locations, the average coefficient of the area where they belong or the average of all coefficients (Sault Ste. Marie 2) was used as coefficient for the station effect.

Table 3. Estimates of the linear coefficients for each of the variables and station effect of the model predicting the number of days with a snow cover of at least 0.1 m (V15). †

		Station effect							
Variable	Coefficient	Station	Adjustment term	Station	Adjustment term	Station	Adjustment term	Station	Adjustment term
Intercept	26.38	Harrow CDA	–24.09	Ottawa CDA	–11.25	Saint-Prosper	9.42	Collegeville	–18.49
V4	–0.39	Sarnia A	–21.89	Amos	–10.80	Caplan	–14.78	Port Hood	–27.69
V5	0.27	Guelph	–26.74	Earlton A	–27.70	La Pocatière CDA	–6.56	Charlottetown CDA	–19.01
V6	0.03	London A	–31.30	Kapuskasing CDA	–12.87	Mont-Joli A	–25.92	O'Leary	–14.78
V9	0.38	Mount Forest	–32.74	Normandin CDA	–29.38	Trois-Pistoles	–12.51	Deer Lake	8.68
V11	–0.28	Brantford MOE	–11.84	Péribonka	–23.98	Aroostook	–14.35	St. John's West CDA	–4.02
V12	–0.05	Delhi CDA	–20.73	Berthierville	7.34	Chatham A	–14.69	Stephenville A	–15.50
V13	6.40	St. Catharines A	–32.12	Farnham	–29.03	Rexton	–16.83	Thunder Bay A	–31.42
V17	–0.20	Vineland Station	–22.54	Lachute	1.40	Fredericton CDA	–17.92	Ridgetown‡	–22.99
V23	–0.58	Huntsville WPCP	–7.96	Lennoxville CDA	–16.68	Moncton	–26.03	Brucefield‡	–30.26
V24	0.02	Madawaska	–2.92	Saint-Hyacinthe 2	–3.79	Nappan CDA	–26.47	Brockville PCC‡	1.07
V27	0.02	North Bay A	–14.77	Sainte-Clothilde CDA	–22.48	Sussex	–45.98	Morrisburg‡	1.07
V28	–0.08	Belleville	–15.97	Laurierville	–6.83	Clarence	–19.43	Chenaux‡	–9.02
V29	0.18	Kingston A	–29.05	Nicolet	–17.83	Kentville CDA	–7.36	Kedgwick‡	–14.35
V31	–4.52	Peterborough A	–18.83	Québec A	–8.47	Truro	–28.29	Grand Falls Drummond‡	–14.35
V33	–0.02	Smithfield CDA	–22.55	Scott	–10.90	Upper Stewiacke	–23.18	Centreville‡	–14.35
		Saint-Anicet	1.07	Saint-Alban	–2.39	Baddeck	–6.42	Sault Ste. Marie 2§	–14.91
		Arnprior Grandon	–6.79						

† Prediction model has the following general form for station i: $V15_i = 26.38 - 0.39V4_i + \ldots.. - 0.02V33_i$ + Adjustment term for station i.

‡ Stations for which coefficients were derived from the average coefficients of the area where they belong.

§ Coefficient was derived from the average of all station effect coefficients.

RESULTS AND DISCUSSION

Mean, maximum and minimum values of indices are presented for 22 agricultural regions of eastern Canada areas based on the current climate and climate change scenarios for two future periods (Table 4). For brevity, results are also presented in detail for only five forage-producting regions of eastern Canada: Guelph, Continental North, South Québec, Lower St. Lawrence and Gaspé Peninsula and, Moncton.

Fall indices

The hardening period in eastern Canada currently starts on 1 November and ends on 25 November (Table 4). By 2040–2069, the average starting date of the hardening period would be delayed to 11 November and the ending date, to 1 December. Accordingly, the current length of the hardening period of 24.3 d may decrease to 20.3 d by 2040–2069 (Table 4).

Fall hardening – Temperature

FH-COLD was chosen to express the relative effect of temperature on the degree of hardiness reached by perennial forage crops before the occurrence of potentially damaging sub-freezing temperatures. The value of FH-COLD is expected to decrease by 17.6 CDD5 by 2040–2069 in agricultural regions of eastern Canada and to be 20% of the current value, indicating that the hardening period would be warmer. All the selected forage-producing regions are expexted to experience a decrease in FH-COLD ranging from in Guelph to –7.9 CDD5 in Moncton (Fig. 2).

The predicted lower decrease in FH-COLD in the Moncton region is due partly to the length of the hardening period, which is expected to be shorter by only 1d by 2040–2069 compared to a decrease of 4 d in the Lower St. Lawrence and Gaspé Peninsula and 6 d in Guelph, Continental North and South Québec (Table 5). In addition, the higher decrease in FH-COLD predicted for Guelph, Continental North and South Québec is associated with a greater increase in mean temperature during the hardening period (more than 2°C) than in the Lower St. Lawrence and Gaspé Peninsula (1.85°C) and Moncton (1.7°C).

Hardening of perennial plants is closely associated to the coolness of the climate. Under natural conditions, fall temperatures may vary during the hardening period, but there is a strong correlation between air temperature and hardening of forage crops (Paquin and Pelletier 1980). Under controlled conditions, alfalfa reached a maximum frost tolerance of –21.5°C (TL_{50}) after four weeks of hardening under constant temperature of 1.0°C (Paquin 1977), and timothy reached a maximum frost tolerance of –19°C after four weeks of constant exposure to temperature of 1.5°C (Paquin and Saint-Pierre 1980). This represents a total of 98 to 112 CDD5.

Table 4. Values of agroclimatic indices and other variables of interest averaged across 22 agricultural regions in eastern Canada for the current 30-year period (1961–1990) and the two future periods (2010–2039 and 2040–2069) under climate change scenario.

	Current and future periods								
	1961–1990			2010–2039			2040–2069		
Index or variable (units)	**Mean**	Min.†	Max.†	**Mean**	Min.	Max.	**Mean**	Min.	Max.
Fall indices									
FH-COLD (CDD5)	**86.4**	55.6	132.5	**77.3**	49.3	143.1	**68.8**	43.5	138.9
FH-RAIN (mm d^{-1})	**2.97**	1.89	4.57	**2.83**	1.81	4.49	**2.75**	1.54	4.64
Winter indices									
W-THAW (DD0 d^{-1})	**0.27**	0.09	0.44	**0.47**	0.19	0.80	**0.59**	0.19	0.97
W-RAIN (mm d^{-1})	**0.86**	0.19	1.91	**0.92**	0.11	2.00	**0.98**	0.06	2.40
W-COLD (d)	**–12.1**	–40.3	28.1	**–23.7**	–55.4	14.0	**–27.8**	–62.9	7.3
Other variables of interest									
Beginning of the hardening period (day-month)	**1-11**	15-10	16-11	**6-11**	22-10	22-11	**11-11**	25-10	27-11
Ending of the hardening period (day-month)	**25-11**	6-11	13-12	**29-11**	8-11	20-12	**1-12**	10-11	20-12
Length of the hardening period (d)	**24.3**	16.5	36.7	**22.5**	15.3	38.0	**20.3**	12.8	37.3
Length of the cold period (d)	**94.5**	44.9	138.7	**80.0**	5.3	134.2	**70.7**	1.8	131.2
Number of days with a snow cover of at least 0.1 m (d)	**82.3**	14.7	137.0	**56.4**	0.2	115.3	**42.9**	0.0	99.1

† Maximum and minimum values are based on averaged data for each agricultural region

Because of the moderating effect of the St. Lawrence River on prevailing fall temperatures, the Lower St. Lawrence and the Gaspé Peninsula currently enjoy a longer (Table 5) and cooler hardening period (117.7 CDD5) than the other four forage-producing regions. Alfalfa would fully harden before minimum temperature reaches –10°C in the Lower St. Lawrence and Gaspé Peninsula but not in the other regions under current conditions. Hence, the Lower St. Lawrence and the Gaspé Peninsula could be taken as the reference region for FH-COLD. Current FH-COLD at the other four regions is 67% of that at the reference region, ranging from 60% (70.2 CDD5) in Moncton to 73% (85.9 CDD5) in Guelph. As a result of the warming of fall temperatures by 2040–2069, FH-COLD is predicted to decrease to 102.0 CDD5 in the Lower St. Lawrence and the Gaspé Peninsula, which is 87% of its current value. FH-COLD in the other regions is expected to decrease to an average of 50% of current FH-COLD in the reference region; future values would range from 53.3 CDD5 (45% of reference) in South Québec to 62.3 CDD5 (53%) in Moncton.

Fall hardening – Rainfall

FH-RAIN is expected to increase from the current average of 2.97 mm d^{-1} to 2.75 mm d^{-1} for the 2040–2069 period scenario. This indicates that fall hardening conditions across agricultural regions of eastern Canada may be slightly dryer by 2040–2069 (Table 4). The largest decrease in FH-RAIN among the forage-producing regions is likely to be experienced in South Québec (0.34 mm d^{-1}) whereas the lowest decrease is predicted to occur in Moncton (0.05 mm d^{-1}) (Fig. 2).

During fall, plants fail to harden properly under high soil moisture conditions which are, in turn, affected by rainfall. FH-RAIN is currently 2.47 mm d^{-1} in Continental North, 2.62 mm d^{-1} in the Lower St. Lawrence and Gaspé Peninsula, 2.77 mm d^{-1} in Moncton, 3.04 mm d^{-1} in South Québec, and 3.32 mm d^{-1} in Guelph. Assuming that soil moisture is the same in each region at the onset of the hardening period, FH-RAIN suggests that hardening of forage crops would proceed under more favourable conditions in the Continental North than in the other forage-producing regions. Expected changes in FH-RAIN in forage-producing regions of eastern Canada are expected to be less than 7% of the current values and we believe that changes of this magnitude would not have significant effects on fall hardening of forage plants.

Winter indices

Climate change is predicted to modify considerably winter conditions in eastern Canada. The coldest daily minimum temperature during winter is likely to increase by 4.8°C by 2040–2069; the highest increases (more than 6°C) are expected predominantly in regions located in southern Ontario while the lowest increases (less than 4°C) will likely occur in regions located in the southern part of the Maritime provinces. The mean daily temperature for the period between 1 November and 30 April is expected to increase by 1.9°C by 2010–2039 and by 3.3°C by 2040–2069. Compared to current conditions, total rainfall in the same period will likely increase by 43.9 mm by the 2010–2039 period and by 83.0 mm (32 % increase from current) by 2040–2069.

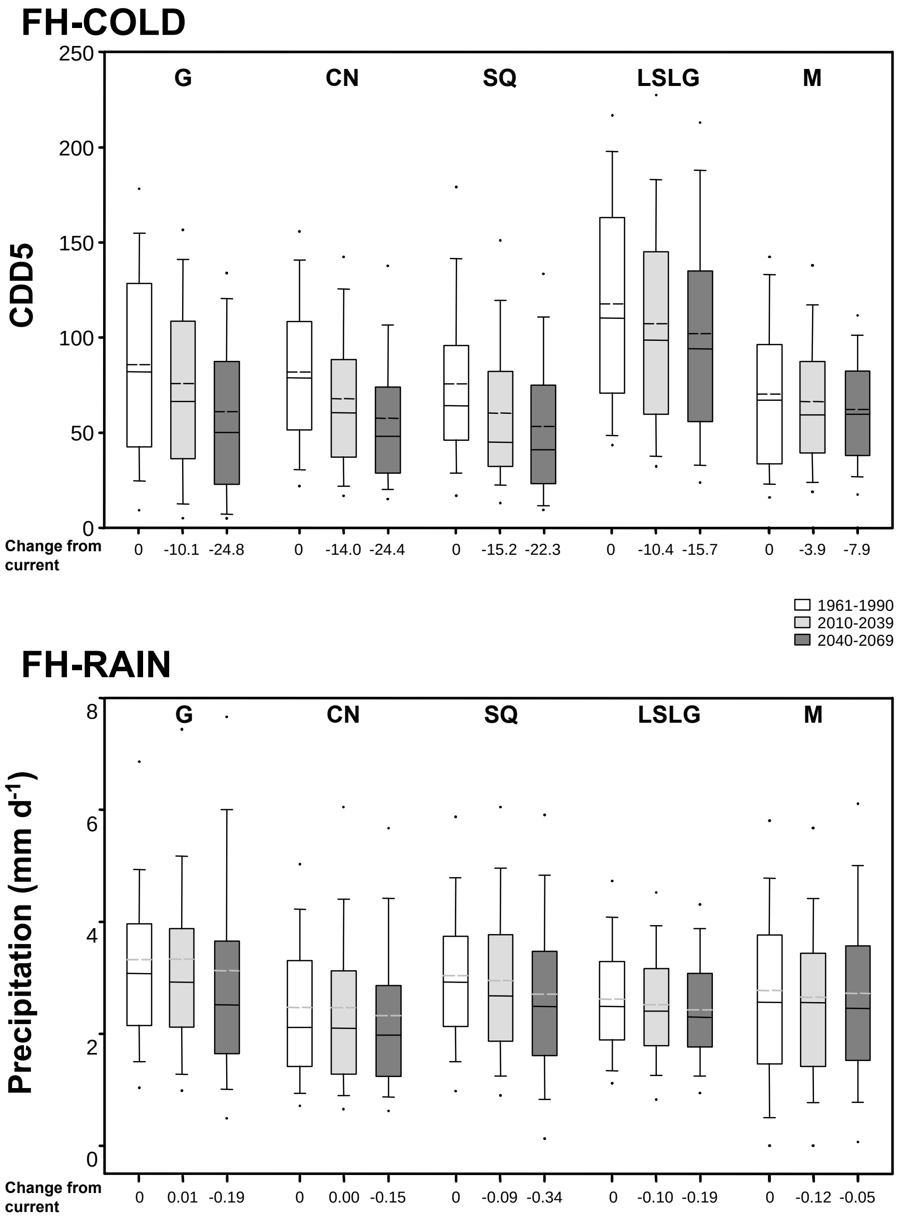

Figure 2. Fall indices in five forage-producing regions in eastern Canada based on current climate and future climate scenarios. G, Guelph; CN, Continental North; SQ, South Québec; LSLG, Lower St. Lawrence and Gaspé Peninsula; and M, Moncton. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

The current average length of the cold period of 94.5 d is expected to decrease by 23.8 d in eastern Canada (Table 4). The average snowfall is predicted to decrease from the current 232 cm to179 cm by 2010–2039, and to 157 cm by 2040–2069 (not shown). Accordingly, the number of days with a snow cover equal or greater than 0.1 m may decrease from the current 82.3 d in eastern Canada to 56.4 by 2010–2039 and to 42.9 d and 2040–2069 (Table 4).

Cold intensity and duration

The threat related to sub-freezing temperatures in the absence of a protective snow cover was expressed by W-COLD. In eastern Canada, there are currently areas where the number of days with a snow cover exceeds the period of prevailing sub-freezing temperatures as it is the case for the Lower St. Lawrence and Gaspé Peninsula, and areas where plants are mostly exposed to potentially harmful temperatures during the cold period. Under climate change W-COLD will likely decrease from the current average of –12.1 d to –23.7 by 2010–2039 and to –27.8 d and 2040–2069 (Table 4), thus likely leading to increased risk of winter damage because plants will be more likely to be exposed to sub-freezing temperatures in the absence of snow cover.

Under climate change scenario, the value of W-COLD in Continental North and South Québec is expected to decrease to reach levels that are similar to those currently experienced in Guelph (Fig. 3). W-COLD in the Moncton region will possibly decrease from the current –27.6 to –54.2 d. In the Lower St. Lawrence and Gaspé Peninsula, the current value of W-COLD (12.2 d) is expected to decrease to –4.3 d. W-COLD will likely remain almost unchanged in the Guelph region (current –32.0 d and –32.6 d by 2040–2069); this is because both the length of the cold period (V9) and the number of days with a snow cover equal or greater than 0.1 m (V15) will likely decrease at the same rate in this region (Table 5).

The value of W-COLD is determined from V9 and V15. V8 could be, in turn, markedly affected by warming of winter temperatures as it is the case in Guelph where V9 is expected to decrease on average by as much as 50 d by 2040–2069, compared to a decrease of 21.6 d in the Lower St. Lawrence and Gaspé Peninsula, 16 d in South Québec, 12.7 d in Moncton, and 7.5 d in Continental North (Table 5). This marked decrease of V9 in the Guelph area is correlated to a shift of the mean daily minimum temperature of the coldest month (V22) from the current -13.2°C, which is close to the –15°C threshold, to an expected –6.4°C (not shown). In the other regions, V22 is predicted to increase from –25.1 to –19.0°C in Continental North, from –17.6 to –12.5°C in South Québec, from –16.5 to –11.6°C in the Lower St. Lawrence and Gaspé Peninsula, and from –15.4 to –11.8°C in Moncton (not shown). On the other hand, since the snow cover is dependent on ambient temperature for establishment and maintenance, increased air temperatures to levels above 0°C would result in reduced duration of snow cover (V15). The average mean daily temperature from the 1 November to the 30 April (V31) in the Guelph region is expected to increase from the current –2.0°C to 2.4°C by 2040–2069 (not shown). This indicates that above 0°C temperatures may be more frequent under climate change scenario, and might explain the noticeable decrease of V15 by 50.6 d in the Guelph region (Table 5).

Table 5. Variables describing the hardening and the cold period of five forage-producing areas of eastern Canada for the current 30-year period (1961–1990) and the two future periods (2010–2039 and 2040–2069) under climate change scenario.

	Current and future periods								
	1961–1990			2010–2039			2040–2069		
Parameter for each forage-producing region (units)	**Mean**	Min.	Max.	**Mean**	Min.	Max.	**Mean**	Min.	Max.
Guelph									
Beginning of the hardening period (day-month)	**4-11**	13-10	24-11	**10-11**	16-10	6-12	**17-11**	17-10	7-12
Ending of the hardening period (day-month)	**28-11**	23-10	21-12	**2-12**	23-10	5-1	**4-12**	29-10	20-1
Length of the hardening period (d)	**23.5**	1	52	**21.6**	1	53	**17.5**	1	56
Length of the cold period (d)	**87.6**	39	131	**55.7**	0	130	**37.5**	0	129
Number of days with a snow cover of at least 0.1 m (d)	**55.6**	0	116	**16.8**	0	60	**5.0**	0	39
Continental North									
Beginning of the hardening period (day-month)	**15-10**	23-9	11-11	**22-10**	26-9	12-11	**25-10**	30-9	12-11
Ending of the hardening period (day-month)	**7-11**	15-10	27-11	**10-11**	18-10	1-12	**11-11**	19-10	9-12
Length of the hardening period (d)	**23.5**	1	53	**19.3**	1	53	**17.3**	2	53
Length of the cold period (d)	**138.7**	99	177	**134.2**	98	166	**131.2**	89	166
Number of days with a snow cover of at least 0.1 m (d)	**137.0**	73	189	**115.3**	63	168	**99.1**	42	147
South Québec									
Beginning of the hardening period (day-month)	**31-10**	8-10	24-11	**6-11**	13-10	29-11	**10-11**	17-10	30-11
Ending of the hardening period (day-month)	**22-11**	20-10	18-12	**23-11**	29-10	18-12	**26-11**	5-11	18-12
Length of the hardening period (d)	**21.8**	1	60	**17.5**	1	48	**16.0**	1	48
Length of the cold period (d)	**104.7**	67	130	**96.8**	48	129	**88.7**	42	129
Number of days with a snow cover of at least 0.1 m (d)	**93.5**	19	163	**66.8**	0	127	**51.0**	0	110
Lower St. Lawrence and Gaspé Peninsula									
Beginning of the hardening period (day-month)	**24-10**	4-10	12-11	**29-10**	7-10	14-11	**3-11**	13-10	20-11
Ending of the hardening period (day-month)	**24-11**	3-11	21-12	**26-11**	8-11	21-12	**29-11**	11-11	23-12
Length of the hardening period (d)	**30.3**	4	62	**28.4**	2	60	**26.4**	3	65
Length of the cold period (d)	**100.7**	59	131	**90.5**	54	121	**79.1**	4	121
Number of days with a snow cover of at least 0.1 m (d)	**112.9**	55	168	**90.0**	30	146	**74.8**	19	134
Moncton									
Beginning of the hardening period (day-month)	**3-11**	8-10	18-11	**7-11**	17-10	19-11	**10-11**	19-10	30-11
Ending of the hardening period (day-month)	**23-11**	20-10	16-12	**26-11**	22-10	21-12	**29-11**	22-10	21-12
Length of the hardening period (d)	**20.1**	2	49	**19.3**	3	48	**19.1**	2	40
Length of the cold period (d)	**98.5**	65	148	**89.7**	49	123	**85.8**	49	119
Number of days with a snow cover of at least 0.1 m (d)	**70.9**	10	129	**45.1**	0	103	**31.6**	0	87

De-hardening

As expected, warmer winter temperatures under climate change will result in an increase of W-THAW from the current 0.27 to 0.62 DD0 d^{-1} by 2040–2069 (Table 4). Currently, W-THAW ranges from 0.09 DD0 d^{-1} in the Lower St. Lawrence and Gaspé Peninsula to 0.33 DD0 d^{-1} in the Moncton region. By 2040–2069, substantial increases in W-THAW are expected in each of the forage-producing regions, with increases ranging from 0.22 to 0.47 DD0 d^{-1} (Fig. 3). The Lower St. Lawrence and Gaspé Peninsula and the Continental North will be at the low end of this range. By 2040–2069, predicted levels of W-THAW in these regions will be similar to the highest rates currently experienced in the other three forage-producing regions. W-THAW may reach 0.70 DD0 d^{-1} in Moncton, 0.74 DD0 d^{-1} in South Québec and 0.78 DD0 d^{-1} in Guelph. It is expected that, under climate change, there will be an increased risk of damage due to the loss of the hardiness during winter, particularly as the snow coverage is expected to diminish and may be no longer adequate to isolate forage plants from the freeze-thaw cycles.

Soil heaving and ice encasement

In eastern Canada, the value of W-RAIN will increase from the current 0.84 mm d^{-1} to expected 1.01 mm d^{-1} (Table 4); this indicates that risks of winter damage due to ice will likely increase under climate change scenario. Among the forage-producing regions, W-RAIN ranges from 0.28 mm d^{-1} in the Continental North to 1.23 mm d^{-1} in Moncton. Under current climate conditions, damage due to ice is rather infrequent in Continental North and in the Lower St. Lawrence and Gaspé Peninsula. By 2040–2069, W-RAIN may increase to reach 0.49 mm d^{-1} in Continental North, 0.53 mm d^{-1} in Lower St. Lawrence and Gaspé peninsula, 0.66 mm d^{-1} in Guelph, 1.08 mm d^{-1} in the South Québec and 1.56 mm d^{-1} in Moncton. The relatively low decrease (0.15 mm d^{-1}) expected for the Guelph area is due to the noticeable decrease in the length of the cold period (Table 5) rather than a decrease in rainfall. The sum of rainfall from 1 November to 30 April is expected to increase by 37% by 2040–2069 in that area (not shown).

Sufficient snow cover can protect plants from ice damage in the same way that it can prevent perennial forage plants from damage by sub-freezing temperatures. Warming of winter temperatures is expected to significantly affect the snow coverage across eastern Canada and this is likely to contribute to increase the damage due to ice on the root system of perennial forage plants.

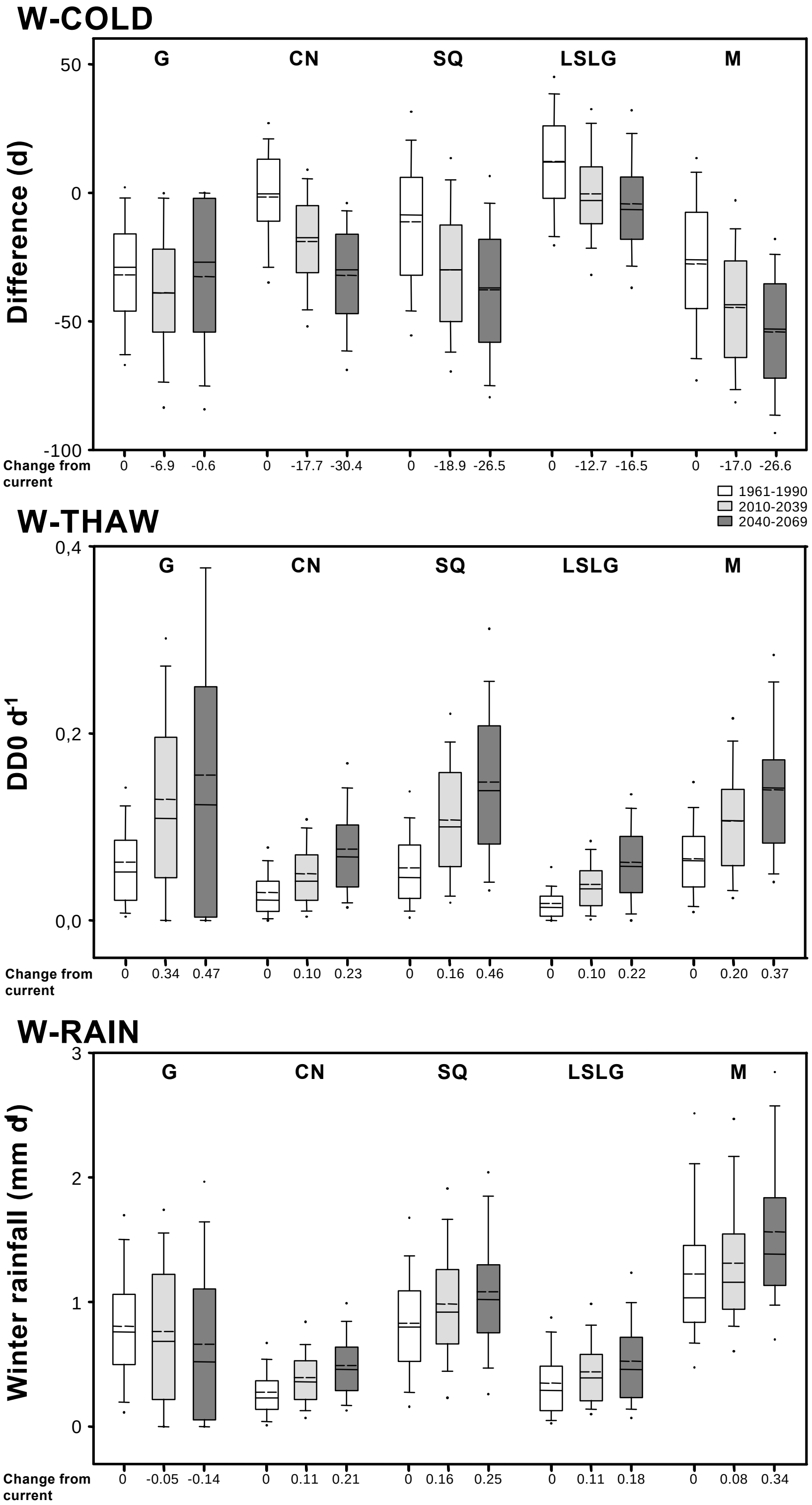

Figure 3. Winter indices in five forage-producing areas in eastern Canada for current climate and for future climate scenarios. G, Guelph area; CN, Continental North; SQ, South Québec; LSLG, Lower St. Lawrence and Gaspé Peninsula; and M, Moncton area. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

CONCLUSIONS

Under the climate change scenarios used in this study, all parts of eastern Canada will likely experience substantial modification in agro-climatic conditions that will possibly have an incidence on winter survival of perennial forage crops. The overall effects are predicted to be warmer fall conditions and a warmer winter characterized by a shift in winter precipitations from snow to rain. The expected milder winter temperature would be beneficial to winter survival of perennial forage crops, but this effect may be largely negated by i) warmer fall temperatures, which would prevent adequate fall hardening, ii) loss of hardiness during winter, and iii) significant loss of snow cover protection which will likely increase risks of damage due to ice and freezing temperatures.

ACKNOWLEDGMENTS

The assistance of D. Anderson (AAFC, Ottawa) in data processing and A. Jones (AAFC, Ottawa) in writing computer programs to compute the variables used is gratefully acknowledged. Thanks are also due to Dr K. McRae (Kentville) for statistical advice. This project was funded in part by the Canadian Climate Change Action Fund.

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SECTION 2

Potential impact of climate change on winter damage to deciduous fruit trees in eastern Canada

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Short Title: Climate change and winter damage to fruit trees

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ABSTRACT

Low temperatures represent a major constraint to fruit production and distribution in eastern Canada. The possible impact of climate change on overwintering of deciduous fruit trees in eastern Canada was assessed using indices expressing the risks associated with known causes of damage during fall, winter, and spring. These indices describe climatic conditions related to the induction of cold acclimation, cold intensity and duration, loss of cold hardiness, and spring development of flower buds. Climatic indices were calculated for 22 agricultural regions in eastern Canada for the current climate (1961–1990) and future climate scenarios (2010–2039 and 2040–2069). Scenario data were extracted from the first generation Canadian Global Coupled Canadian General Circulation Model. Averaged across all agricultural regions of eastern Canada, the first fall frost in 2040–2069 would be delayed by 17 d and the last spring frost would be 20 d earlier. The annual minimum temperature would increase by 4.8°C. The risks of winter damage to deciduous fruit trees in eastern Canada are likely to decrease because of: 1) a shorter photoperiod at the time of first freezing fall temperatures resulting in an early induction of cold hardening, 2) milder winter temperatures reducing the cold stress, and 3) modified spring temperature regime reducing damage to floral buds by late frosts, except for the currently warmer regions. On the other hand, more frequent winter thaw events will likely result in a loss of hardiness and increase vulnerability to late winter low temperatures.

Key Words: Climate change, deciduous fruit trees, winter damage, winter, spring frost

RÉSUMÉ

Les basses températures représentent une contrainte importante pour la production et la distribution des cultures fruitière dans l’est du Canada. L'impact possible des changements climatiques sur la survie à l’hiver des arbres fruitiers dans l'est du Canada a été évalué en utilisant des indices exprimant les risques associés à des causes connues de dommages durant l’automne, l'hiver et le printemps. Ces indices décrivent les conditions climatiques associées à l’induction de l'endurcissement, l'intensité et la durée du froid, et le développement printanier des bourgeons floraux. Les indices ont été calculés pour 22 régions agricoles de l'est du Canada pour des conditions actuelles (1961–1990) et futures (2010–2039 et 2040–2069). Les scénarios de changements climatiques furent obtenus du Modèle canadien Couplé de Circulation Générale de première génération. D'ici 2040–2069 en moyenne, le premier gel automnal serait retardé de 17 j et le dernier gel printanier serait devancé de 20 j. La température minimale annuelle augmenterait de 4,8°C. D’ici 2040–2069, les risques de dommage par le froid aux arbres fruitiers dans l’est du Canada diminueraient à cause : 1) d’une photopériode plus courte au moment du premier gel automnal résultant en une induction hâtive de l’endurcissement automnal, 2) des températures hivernales plus douces diminuant le stress dû au froid, et 3) d’un régime de températures printanières moins propice aux dommages aux bourgeons floraux par les gels tardifs, sauf pour les régions étant actuellement déjà plus chaudes. Par ailleurs, l'augmentation de la fréquence des dégels hivernaux résulterait en une plus grande vulnérabilité aux températures gélives en fin d'hiver.

Mots clés: Changement climatique, arbres fruitiers, dommage par le froid, hiver, gel printanier

Meteorological models predict that the mean minimum temperature of the cold season will increase from 2 to 6°C by 2050 in eastern Canada (Canadian Institute for Climate Studies 2001). The climatic conditions during late fall, winter, and early spring affect the survival and productivity of deciduous fruit trees and contribute to the annual variability in the commercial production of fruits. Hence, the expected warming may have a significant impact on winter damage to deciduous fruit trees in eastern Canada.

The occurrence of low temperatures is the most important factor determining the distribution of plant species (Parker, 1963) and can limit both the yield and the distribution of deciduous fruit trees (Ashworth, 1992). Freezing injury is a serious constraint to fruit production in eastern Canada since several deciduous fruit tree species are either exotics or have arisen from crosses of species or cultivars that are not indigenous to the fruit-producing regions. In eastern Canada, the commercial production of apple (*Malus domestica* Borkh.) and pear (*Pyrus communis* L.) is limited to small areas along the Great Lakes in Ontario, near Lake Champlain in Québec and near the Bay of Fundy region of Nova Scotia. Furthermore, because of their even greater susceptibility to winter injury, commercial production of peach (*Prunus persica* (L.) Batsch.), apricot (*P. armeniaca* L.), cherry (*P. cerasus* L. and *P. avium* L.), plum (*Prunus* spp.), and grape (*Vitis* spp.) is limited to the Niagara region below the escarpment and the northern shore of Lake Erie.

The freezing injury to deciduous fruit trees may result from untimely frosts in fall and spring, or from low temperatures in winter. For these species, freezing injury can be particularly harmful for two reasons: a long period of time is required to replace adult trees and the injury to reproductive organs causes dramatic crop losses because no new flowers are produced during that season.

Within each of the fruit-growing regions of eastern Canada, the risks of winter injury are high. In the apple-growing areas of Ontario and Québec, the frequency of killing freezes is about once every10 years (Rousselle, 1983). Temperatures below –25°C, which are severe enough to injure grapes, peaches, and apricots, occur about 1 year in 30 in the Niagara region in Ontario (Krueger, 1983). In Québec, 300 000 apple trees (15%) were killed during the 1980–1981 winter (Rousselle, 1983). During the same winter, 28 000 trees were killed in eastern Ontario, 26 000 in New Brunswick, and 4 000 in Nova Scotia (Embree, 1984).

Rochette and Dubé (1993a; 1993b) developed agro-climatic indices to assess the risk of winter damage for broad groups of perennial plants. These indices were based on current knowledge of plant-environment relationships during the cold period and required readily available climate variables such as air temperature and precipitation. Rochette and Dubé (1993a; 1993b) used their indices to express relative spatial differences in the intensity of the causes of damage in Québec, Canada. Bélanger et al., (in preparation) used a similar approach to develop agro-climatic indices specific to perennial forage crops and used their indices to assess the impact of climate change on winter survival of perennial forage crops in eastern Canada.

Our objective was to develop agro-climatic indices specific to the causes of winter damage to deciduous fruit trees and to use these indices to assess the impact of climate change on deciduous fruit trees in eastern Canada. Our approach does not predict winter damage expected in any given year in the future. Instead, relative comparisons of risks of winter damage to deciduous fruit trees are made between present day climatic conditions and future climatic scenarios.

DEVELOPMENT OF AGRO-CLIMATIC INDICES

Agro-climatic indices are frequently used to characterize climatic parameters related to specific plant requirements. In our study, six indices were developed to express the risk associated to causes of damage during the overwintering of deciduous fruit trees (Table 1). These indices, which are an extension of those previously reported by Rochette and Dubé (1993a; 1993b), were used to assess the risks associated to climatic causes of damage to deciduous fruit trees during fall, winter and spring. A fall index expresses the risks of damage to acclimating fruit trees from untimely frosts. Winter indices reflect the impact of cold intensity and duration, and assess the loss of cold hardiness due to warm temperatures. Spring indices express the risk of damage to flower buds associated to a late spring frost. The justification of each of these indices follows.

Table 1. Agro-climatic indices expressing the risks associated to the most probable causes of damage to deciduous fruit trees during the cold season and climatic variables used for the calculation of the indices. Units are enclosed in parentheses.

Indices/Variables	Description
Agro-climatic indices	
PHOTO	Photoperiod or daylength on date of first fall frost (hrs)
CDD–15	Sum of cold degree-days < –15°C from 1 Aug. to 31 July (CDD–15)
AMT	Lowest daily minimum temperature from 1 Aug. to 31 July (°C)
W-THAW	Sum of degree-days > 0°C from 1 Jan. to day (L–15) - 1 (DD0)
S-FROST1	Sum of degree-days > 0°C from 1 Jan. to day LSF0 (DD0)
S-FROST2	Sum of degree-days > 5°C from 1 Jan. to day LSF–2 (DD5)
Variables used for the calculation of the agro-climatic indices	
FFF	Date of first fall frost ≤ 0°C
L–15	Date of last occurrence of minimum air temperature ≤ –15°C
LSF0	Date of last spring frost ≤ 0°C
LSF–2	Date of last spring frost ≤ –2°C

Fall index

For most woody species of temperate regions, the progressive decrease in day length induces the end of the growth period and the transition to fall hardening (Larcher, 1980). In nature, seasonal photoperiod and seasonal thermoperiod are necessarily coupled. During fall, the decreasing day length induces the hardening of woody plants and the subsequent declining temperatures allow the completion of the process (Larcher, 1980). The hardening may be inadequate and the overwintering more risky if the frost-free period is too short with respect to the time of cessation of growth. Frost injury to foliage during fall may delay acclimation and increase the susceptibility of plants to winter injury. Species that are dependent on a photoperiodical response to initiate their dormancy are thus more exposed to damage by the first fall frosts (Sakai and Larcher, 1987). The photoperiod at the day of first fall frost was used to describe the severity of the conditions in relation to the induction of fall hardening of woody plants (PHOTO; Table 1).

Winter indices

Winter survival of cold-hardened plants are affected by harsh winter climatic conditions. During winter, deciduous fruit trees may be damaged by extreme or prolonged low temperatures. The tree vulnerability to low temperatures is increased by a loss of cold hardiness following exposure to warm temperatures.

Cold intensity and duration

In eastern Canada, winter temperatures frequently drop to potentially damaging levels even for fully acclimated plants. Adequately hardened deciduous fruit trees will be injured if the air temperature drops below the limit of their inherent resistance to cold temperatures. Perennial plants resist sub-freezing temperatures by avoiding the freezing of intracellular content by deep supercooling and by the freezing of extracellular content.

Most perennial horticultural crops in the temperate regions freeze extracellularly. In these plants, ice first forms within the extracellular spaces and water is then withdrawn from the cell to the extracellular sites of freezing by the vapor pressure deficit. Ice does not penetrate the cell and lethal intracellular freezing is avoided. Upon prolonged exposure to sub-freezing temperatures, this mechanism leads to cell dessication, alteration of membrane lipids, and mechanical stresses to cell walls due to decreasing cell volume (Sakai and Larcher, 1987). Since these physiological stresses are tolerated differently by each species when exposed to cold temperatures, the duration of the frost is very important in addition to its intensity.

Cumulated degree-days below –15°C are related to the coldness of the climate in a given area. In eastern Canada, air temperature drops below this threshold every year. In our study, –15°C was chosen as the temperature threshold below which plants, which tolerate extracellular freezing and experience cell dessication, are expected to undergo freezing damages. Consequently, the accumulation of cold degree days below –15°C (CDD–15) was used to express the threat associated to intensity and duration of freezing temperatures for species that tolerate extracellular freezing and are exposed to cell dessication. This index is hereafter called CDD–15 (Table 1).

Cold intensity

Deciduous fruit trees of cold and temperate regions, in addition to undergoing extracellular freezing, have the ability to retain cellular water of some tissues in a deep supercooled state. Freezing injury will occur when the ambient temperature reaches levels below the deep supercooling point of their most susceptible tissues, mainly the xylem tissues and the flower buds. In *Pyrus* and *Malus* species, xylem is the most susceptible tissue; freezing resistance is –35°C for apple cultivars grown in eastern Canada (Quamme, 1976) and –30°C for pear cultivars (Quamme, 1976). In most of the *Prunus* species, flower buds are the most susceptible tissues with a freezing resistance of –29 to –38°C for plum, –31 °C for cultivated cherry, –22 to –26°C for apricot, and –22 to –24°C for peach (Quamme *et al.*, 1982). In grape (*Vitis vinifera* L.), the dormant bud is usually the most susceptible tissue, with a cold resistance of about –24 °C as determined by the LT_{50} or the temperature at which 50% of the buds are killed (Quamme, 1986).

The degree of deep supercooling may be the factor limiting northern commercial production of cultivated fruit trees. The temperature at which injury occurs to the most susceptible tissues was closely related to the average annual minimum isotherm temperature at the limits of commercial production of apples and pears (Quamme, 1976) and at the northern limit of distribution of native *Prunus* species (Quamme *et al.*, 1982). In our study, we expressed the threat of freezing injury to the most susceptible tissues, for which freezing damage is associated to a well-known threshold temperature, by the annual minimum temperature (AMT; Table 1).

De-hardening

During fall, deciduous fruit trees of the temperate zones become dormant and acquire cold resistance. Dormancy is the physiological state in which the plant does not grow even though external conditions are favourable. Breaking the dormancy of deciduous fruit trees commonly grown in eastern Canada requires an exposure to low temperatures for 3 to 4 weeks (Larcher, 1980). After the dormancy has been broken, buds remain cold-hardy and quiescent until exposed to warm temperatures. If warm temperatures occur during winter, the fruit trees may deacclimate (Sakai and Larcher, 1987), making them more vulnerable to subsequent low temperatures (Howell and Weiser, 1970; Ketchie and Beeman,1973). Occurrence of high temperatures during winter, especially in January and February, has been correlated with winterkill or low yields in apple trees (Coleman, 1992; Caprio and Quamme, 1999). In our study, the accumulation of degree-days above 0°C from 1 January to the date of the last occurrence of the freezing temperature of –15°C was used to express the risks of damage due to the potential loss of hardiness of deciduous fruit trees during winter; this index is hereafter referred to as W-THAW (Table 1).

Spring indices

The developmental stages of the flower bud, from dormancy to fruit set, are associated with a progressively increasing vulnerability to damage by a late frost (Proebsting and Mills, 1961; Simons and Doll,1976). During spring, the growth rate of leaves and floral buds of fruit trees is related to air temperature. Likewise, temperature affects frost survival indirectly by delaying or advancing blooming (Anderson and Seeley, 1993). In the province of Québec, the leaf unrolling and blooming of lilac and honeysuckle may be predicted by the summation of the degree-days (base temperature of 0 to 5°C) commencing on 1 March (Castonguay *et al.*, 1984). Thermal requirements for growth may vary according to the physiological stage of the plant. Langlois (1985) reported that 0°C is the best threshold for predicting dates of early vegetative stages of apple trees by thermal summation and 8°C was most appropriate for the blooming stages; in the same study, the best starting date for the calculation of degree-days was 1 February. We used two indices, S-FROST1 and S-FROST2 (Table 1), to express the risks of damage to foliar and floral buds by a late frost. S-FROST1 is the accumulation of degree-days above 0°C from 1 January to the last occurrence of a minimum temperature of 0°C, and S-FROST2 is the accumulation of the degree-days above 5°C from 1 January to the last occurrence of a minimum temperature of –2°C.

MATERIALS AND METHODS

Climatic data

Weather stations

Sixty-nine weather stations within agricultural areas of eastern Canada (42°2'N to 49°24'N, and 52°47'W to 89°20'W) were selected for this study, based on their representativeness of agricultural regions and on data availability (Fig. 1). Stations were required to have daily maximum and minimum air temperatures and rainfall available for at least 26 continuous years within the 1961–1990 period. Data were originally obtained from Environment Canada (1999) and reformatted into daily records with missing data estimated. Data were stored in a Daily Climate Archive maintained at Agriculture and Agri-Food Canada, Eastern Cereals and Oilseeds Research Centre, Ottawa.

Climate change scenario and its application to current climatic data

Climate change scenarios for two future time periods (2010–2039 and 2040–2069) were based on a 2001-year "transient" simulation by the first generation coupled Canadian General Circulation Model (CGCMI) that included the effects of aerosols (Boer et al., 2000). This simulation used an effective greenhouse gases (GHG) forcing corresponding to that observed from 1900 to the present and a 1% increase after that until year 2100. Scenarios based on the average results of an ensemble of three simulations were extracted from the Intergovernmental Panel on Climate Change, Data Distribution Centre CD-Rom (IPCC, 1999). Data based on 30-year averages for each of 12 months were extracted for 33 grid points covering all of eastern Canada, ranging from 38°58'N to 50°06'N in latitude and from 52°30'W to 90°00'W in longitude

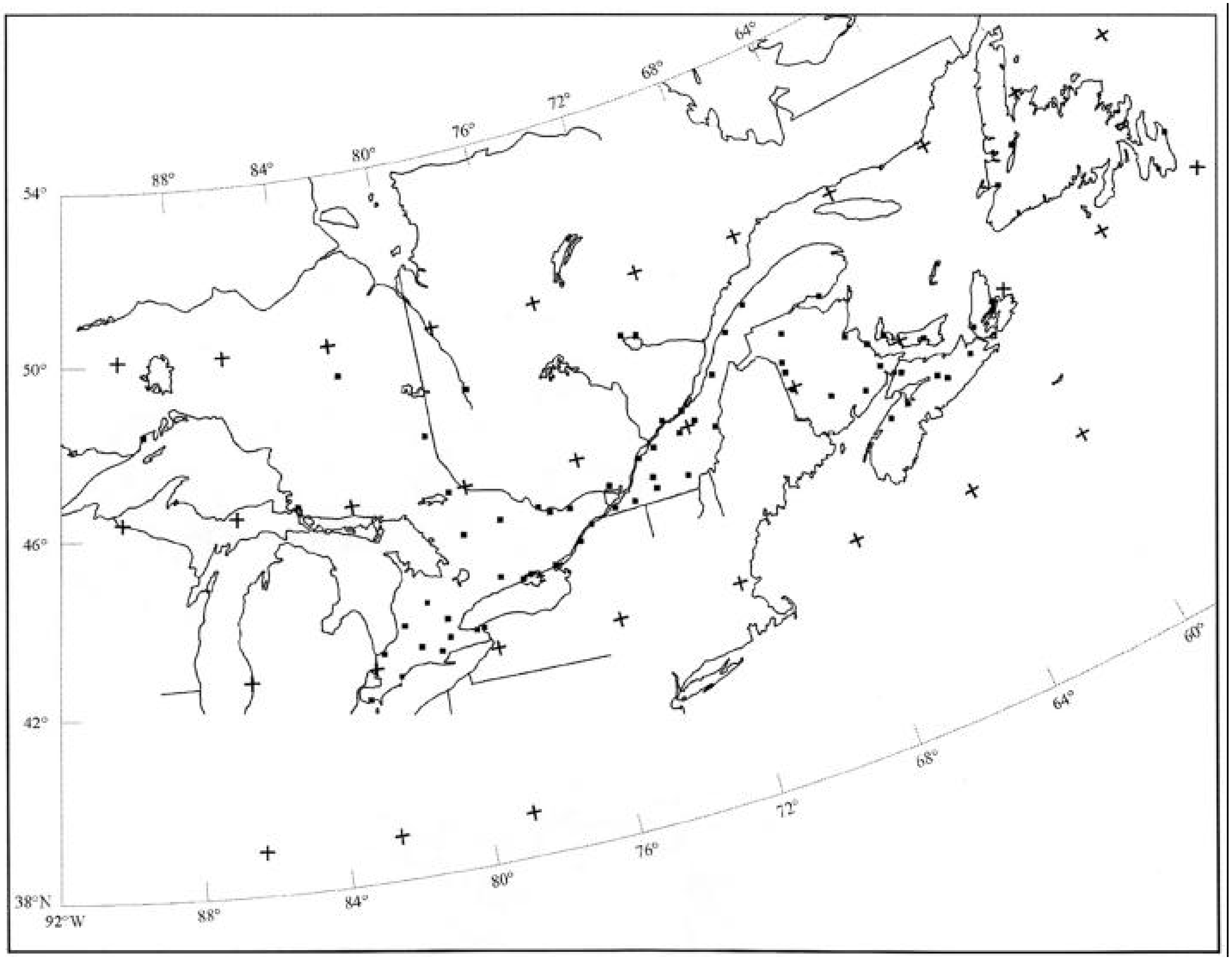

Figure 1. Distribution of weather stations used for the study on the impact of climate change on the winter damage to deciduous fruit trees in eastern Canada. Grid points (+) of the Canadian General Circulation Model are also presented.

Table 2. Description of the agricultural areas included in the study.

Agricultural region (province)	Weather station	Elevation† (m)	Latitude (N)	Longitude (W)
Harrow (ON)	Harrow CDA, Ridgetown, Sarnia A	193	42°2' – 43°0'	81°53' – 82°54'
Guelph (ON)	Brucefield, Guelph, London A, Mount Forest	322	43°2' – 43°59'	80°14' – 81°33'
Delhi (ON)	Brantford MOE, Delhi CDA	214	43°8' – 45°52'	80°14' – 80°33'
Vineland (ON)	St. Catharines A, Vineland Station	89	43°12' – 43°12'	79°10' – 79°24'
North Bay-Huntsville (ON)	Huntsville WPCP, Madawaska, North Bay A	320	45°21' – 46°22'	77°59' – 79°25'
Kingston (ON)	Belleville, Kingston A, Peterborough A, Smithfield CDA	120	44°5' – 44°14'	76°36' – 78°22'
Eastern Ontario-St. Lawrence Riv. (ON, QC)	Brockville PCC, Morrisburg, Saint-Anicet	75	44°36' – 45°8'	74°21' – 75°40'
Ottawa Valley (ON)	Arnprior Grandon, Chenaux, Ottawa CDA	90	45°23' – 45°35'	75°43' – 76°41'
Continental North (ON, QC)	Earlton A, Kapuskasing CDA, Amos, Normandin CDA, Péribonka	202	47°42' – 49°24'	72°2' – 82°26'
South Québec (QC)	Berthierville, Farnham, Lachute, Lennoxville CDA, Sainte-Clothilde CDA, Saint-Hyacinthe 2	70	45°10' – 46°3'	71°49' – 74°20'
Central Québec (QC)	Laurierville, Nicolet, Québec A, Scott, Saint-Alban, Saint-Prosper	126	46°12' – 46°48'	70°30' – 72°37'
Lower St. Lawrence-Gaspé Peninsula (QC)	Caplan, La Pocatière CDA, Mont-Joli A, Trois-Pistoles	40	47°21' – 48°36'	65°41' – 70°2'
West New Brunswick (NB)	Aroostook, Centreville, Grand Falls-Drummond, Kedgwick	179	46°23' – 47°39'	67°21' – 67°43'
East Coast (NB)	Chatham A, Rexton	20	46°40' – 47°1'	64°52' – 65°28'
Moncton (NB)	Fredericton CDA, Moncton, Sussex, Nappan CDA	23	45°43' – 46°6'	64°15' – 66°37'
Annapolis Valley (NS)	Clarence, Kentville CDA	51	44°55' – 45°4'	64°29' – 65°10'
Truro (NS)	Truro, Upper Stewiacke	32	45°13' – 45°22'	63°0' – 63°16'
Cape Breton (NS)	Baddeck, Collegeville, Port Hood	37	45°29' – 46°6'	60°45' – 62°1'
Prince Edward Island	Charlottetown CDA, O'Leary	31	46°15' – 46°42'	63°8' – 64°16'
Newfoundland (NF)	Deer Lake, St. John's West CDA, Stephenville A	44	47°31' – 49°10'	52°47' – 58°33'
Thunder Bay (ON)	Thunder Bay A	199	48°22'	89°20'
Sault Ste Marie (ON)	Sault Ste. Marie 2	212	46°32'	84°20'

† Averaged elevation of the weather stations used in each region

(Fig. 1). Grid spacing for the Canadian GCM is approximately 3.75E lat. x 3.75E long. For temperature, we extracted the changes in monthly mean average daily maximum and minimum air temperature (*d*T) for the two future time periods with respect to the 1961–1990 period. For precipitation, we extracted the mean average daily precipitation rate (mm d^{-1}) for each month based on the 1961–1990 period and the change in the precipitation rate for each of the two future time periods. Monthly precipitation ratios (R) were computed by dividing the rates for each of the future time periods by the rate for the 1961–1990 period. The values for *d*T and R were interpolated to each of the 69 climate stations by weighting values from the four nearest grid points, using an inverse distance weighting procedure (Tabios and Salas, 1985). Daily weather data for the 1961–1990 period at each station were then adjusted to the 2010–2039 and 2040–2069 periods by applying the monthly values for *d*T and R to the daily maximum and minimum air temperatures and precipitation in each of the respective months. If the minimum temperature exceeded the maximum, which occurred infrequently, the two were simply reversed.

Calculation of climatic indices and variables

The 69 weather stations were grouped into 22 agricultural regions (Table 2) based on their climate and the predominant crops. Indices were calculated yearly for the 1961–1990, 2010–2039 and 2040–2069 periods and at each selected weather station. Values of the indices were averaged for each period across agricultural regions and across stations within each of the 22 agricultural regions.

A total of 10 variables including the six indices already described, were calculated yearly from daily climate data for 1961–1990, 2010–2039 and 2040–2069 (Table 1) for each weather station. Variables were computed over a two-calendar year period ranging from 1 August to 31 July . If a temperature of #–15EC was not reached, L–15 (Table 1) was set to zero and W-THAW (Table 1) was not computed.

RESULTS AND DISCUSSION

Values of the indices and other variables of interest averaged across 22 agricultural regions of eastern Canada are presented for current climate and climate change scenarios for two future periods (Table 3). For brevity, more detailed results are only presented for the three major regions of eastern Canada where deciduous fruit trees are commercially grown: Vineland, South Québec, and Annapolis Valley. Results for the Continental North are also presented for the purpose of comparison with a region characterised by a colder climate.

Table 3. Values of agroclimatic indices and other variables of interest averaged across 22 agricultural regions in eastern Canada for the current 30-year period (1961–1990) and the two future periods (2010–2039 and 2040–2069) under climate change scenario.

	Current and future periods								
	1961–1990			2010–2039			2040–2069		
Index or variable (units)	**Mean**	Min.†	Max.†	**Mean**	Min.	Max.	**Mean**	Min.	Max.
Fall index									
PHOTO (hrs)	**11.9**	10.8	13	**11.4**	10.6	12.5	**11.1**	10.2	12.1
Winter indices									
CDD–15 (CDD–15)	**69.2**	1.7	359.8	**38.7**	0.1	239.6	**27.1**	0	174.7
AMT (°C)	**–29.1**	–40.9	–19.7	**–25.8**	–37.5	–15.3	**–24.3**	–35.1	–13.5
W-THAW (DD0)	**19.2**	6.9	30	**34.1**	13.9	54.6	**42.8**	10.2	88.5
Spring indices									
S-FROST1 (DD0)	**361.8**	231.8	492.1	**349.2**	194.2	464.60	**364.9**	194.7	511.4
S-FROST2 (DD5)	**63**	21.7	118.8	**63.2**	17.8	107.20	**73.1**	23.4	138.2
Other variables of interest									
FFF (day-month)	**28-9**	9-9	21-10	**8-10**	19-9	27-10	**15-10**	25-9	5-11
LSF0 (day-month)	**20-5**	29-4	6-6	**8-5**	13-4	25-5	**30-4**	4-4	17-5
LSF–2 (day-month)	**5-5**	15-4	22-5	**26-4**	2-4	12-5	**19-4**	20-3	6-5

† Maximum and minimum values are based on averaged data for each agricultural region

Fall index

PHOTO was chosen to express the severity of fall conditions in relation to the induction of fall hardening of deciduous fruit trees. On average in eastern Canada, the date of the first fall frost is expected to be delayed from the current 28 September to 8 October in 2010–2039, and to 15 October in 2040–2069 (FFF, Table 3). Consequently, the photoperiod at the first fall frost, which is currently 11.9 h, would decrease to 11.4 h by 2010–2039, and to 11.1 h by 2040–69 (PHOTO, Table 3).

The date of the first fall frost is expected to be later by 19 d in the Annapolis Valley, by 18 d in Continental North, and by 15 d in Vineland and South Québec. Accordingly, the expected decrease in PHOTO will range from 0.6 h in Vineland to 1 h in Continental North (Fig. 2). For the fruit tree species currently grown in those areas and which are well adapted to the current seasonal photoperiod, this would mean that the risks of damage due to the first fall frosts will decrease. This would also mean that new conditions more favourable for fall hardening may permit the introduction of species or cultivars provided temperature requirements for growth, production, and survival are met.

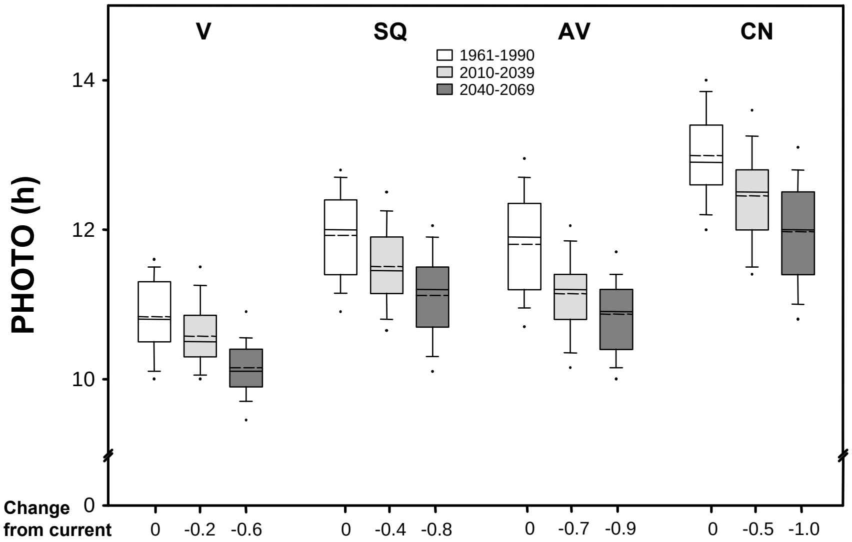

Figure 2. Fall index in three regions where deciduous fruit trees are commercially cropped and one extreme climate region (CN) in eastern Canada based on current climate and future climate scenarios. V, Vineland; CN, Continental North; SQ, South Québec; and AV, Annapolis Valley. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

Winter indices

Climate change is predicted to modify considerably winter conditions in eastern Canada. The mean daily temperature for the period between 1 November and 30 April is expected to increase by 1.9°C by 2010–2039 and by 3.3°C by 2040–2069 (not shown).

Cold intensity and duration

CDD–15 (Table 1) reflects the threat of damage from prolonged exposure to freezing temperatures. As a result of the warming of winter temperatures, CDD–15 is expected to decrease across eastern Canada from the current 69.2 to 27.1 CDD–15 by 2040–2069 (Table 3). The Continental North region is likely to experience the largest decrease with 185.1 CDD–15 (Fig. 3). It is predicted that in Vineland, there would be no cumulated CDD–15 in three years out of four by 2010–2039, and there would be no cumulated CDD–15 in one year out of two in the Annapolis Valley by 2040–2069 (Fig. 3).

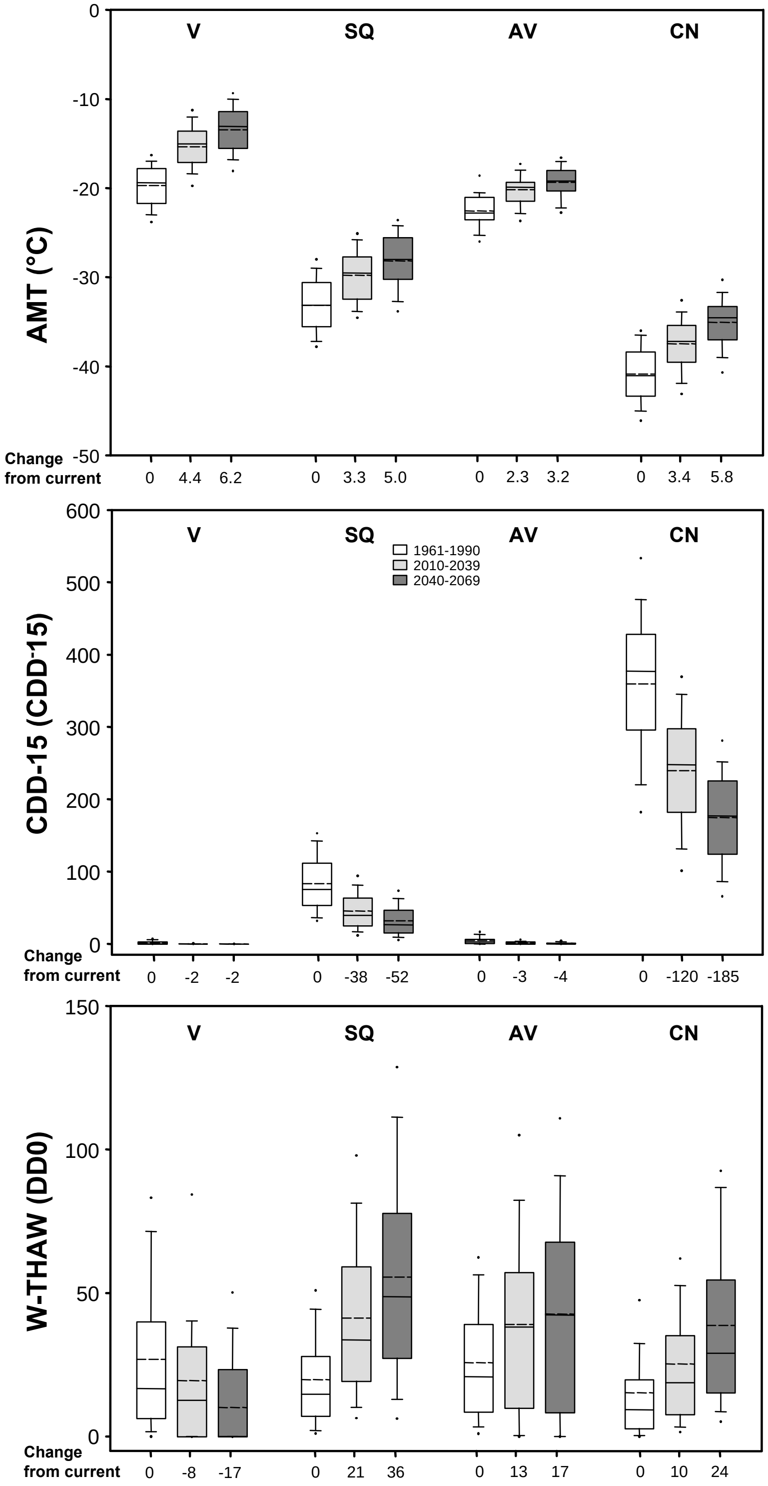

Figure 3. Winter indices in three regions where deciduous fruit trees are commercially cropped and one extreme climate region (CN) in eastern Canada based on current climate and future climate scenarios. V, Vineland; CN, Continental North; SQ, South Québec; and AV, Annapolis Valley. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

Vineland and Annapolis Valley currently enjoy relatively mild winters with a mean daily minimum temperature of their coldest month (MTCM) of respectively –10.8 and –12.2°C, compared to –19.9°C in South Quebec and –26.9°C in the Continental North. By 2040–2069, the MTCM is expected to increase to –4.2°C in Vineland and –8.9°C in Annapolis Valley; thus the occurrence of temperatures below –15°C would be less frequent, and consequently less CDD –15 would be accumulated.

In addition, the date of last occurrence of a temperature equal or below –15°C in Vineland is expected to advance significantly from the current 17 February to 3 January by 2040–2069. This means that the period used for the calculation of CDD –15, from 1 August to the date of last occurrence of a temperature equal or below –15°C, would be reduced by 45 days in that region. According to our results, the risks of damage associated to intensity and duration of freezing temperatures for species that tolerate extra-cellular frost and are exposed to cell dessication are likely to diminish with the expected climate change.

Cold intensity

AMT is expected to increase by 4.8°C on average across eastern Canada (Table 3); the highest increase will occur mostly in regions located in southern Ontario (more than 6°C) whilst lower increases will occur in the regions located in the southern Maritimes (less than 4°C). Across the selected regions, AMT ranging currently from –19.7 °C in Vineland to –40.9°C in Continental North is likely to increase to –13.5 °C in Vineland and –35.1 °C in Continental North (Fig. 3).

The deciduous fruit tree species are limited in their northern distribution to AMT isotherms that coincides with characteristics of deep supercooling of their most susceptible tissues (Quamme, 1976; Pierquet *et al.*, 1977; Quamme *et al.*, 1982). The frequency of low temperature extremes and their distribution within the cold acclimation cycle of the trees should also be considered for the determination of plant distribution. Our results already showed that the occurrence of temperatures below –15°C are predicted to be less frequent. As indicated by a predicted increase of AMT, we may expect that the deciduous fruit tree production will be extended beyond its current northern limits by 2040–2069.

De-hardening

The risk of loss of hardiness during winter was expressed by W-THAW. Warmer winter temperatures under climate change is expected to result in an averaged increase of W-THAW of 23.6 DD0 across agricultural regions of eastern Canada (Table 3).

W-THAW is predicted to increase in the Annapolis Valley, South Québec and Continental North (Fig. 3). However, W-THAW is likely to decrease by 16.8 DD0 by 2040–2069 in Vineland (Fig. 3). For the calculation of this index, the degree-days were cumulated from 1 January to the last observation of a temperature below –15 °C (L–15, Table 1). In Vineland, the predicted 45 d-earlier occurrence of L–15 would result in a period of three days, from 1 to 3 January, for the cumulation of degree-days above 0°C; this explains the expected decrease in W-THAW in this region.

Consequently, the risks of damage due to a loss of hardiness during winter are predicted to increase in most areas of eastern Canada, but to decrease in Vineland.

Spring indices

The dates of the last spring frost (LSF0 and LSF–2, Table 3) are expected to occur earlier across agricultural regions of eastern Canada. Compared to current conditions, the average LSF0 is expected to advance by 12 d by 2010–2039 and by 20 d by 2040–2069. LSF–2, is likely to advance by 10 d by 2010–2039 and by 16 d by 2040–2069. In our study, the risks of damage to foliar and floral buds by a late frost were expressed by S-FROST1 and S-FROST2.

On average, across agricultural regions of eastern Canada, S-FROST1 is expected to remain almost unchanged under the climate change scenarios, with an expected decrease of 3.5% by 2010–2039 and an increase of 0.9% by 2040–2069. Among the selected regions, the change may vary from a decrease of 25% in Continental North to an important increase of 41% in Vineland (Fig. 4).

S-FROST2 is predicted to increase by 0.3% by 2010–2039 and by 16% by 2040–2069 in eastern Canada (Table 3). Again, the expected change in S-FROST2 may vary considerably among the selected regions, with an important decrease of 35% predicted in Continental North and a noticeable increase of 129% in Vineland (Fig. 4).

Both indices are expected to change in the same way for each of the selected fruit-producing regions. Two factors influence the value of these indices, the occurrence of warm temperatures above 0 or 5°C and the date of the last spring frost of 0 or –2°C. The expected increase in accumulation of degree-days above 0 and 5 °C by 2040–2069 in Vineland, despite the fact that the respective periods of accumulation of degree-days is predicted to be shorter by 26 and 25 d, indicates that the rates of accumulation of degree-days will likely be markedly higher than currently in that region. As for Vineland, but to a lesser extent, the warming of temperatures from 1 January to the last spring frost is expected to be more rapid in Annapolis Valley compared to current conditions. In the case of Continental North, the expected decrease in the accumulation of degree-days is due to both a lower rate of accumulation of degree-days and a shorter period of accumulation of degree-days; this may be explained by its latitudinal position characterized by low winter temperatures and a deeper snow cover.

These results suggest that, by 2040–2069, the risks of damage to leaf and floral buds by a late frost is likely: i) to increase in Vineland and in the Annapolis Valley, ii) to remain almost unchanged in South Québec, and iii) to diminish in Continental North.

This conclusion is made on the assumption that the chilling requirements are still met before 1 January under climate change scenario. This assumption probably applies to species with low or moderate chilling requirements for dormancy completion. But for species with relatively high chilling requirements, or for species grown in Vineland, it is most likely that the bud burst may be delayed. In this case, the delay in dormancy completion would override the effect of the increased warming on bud development.

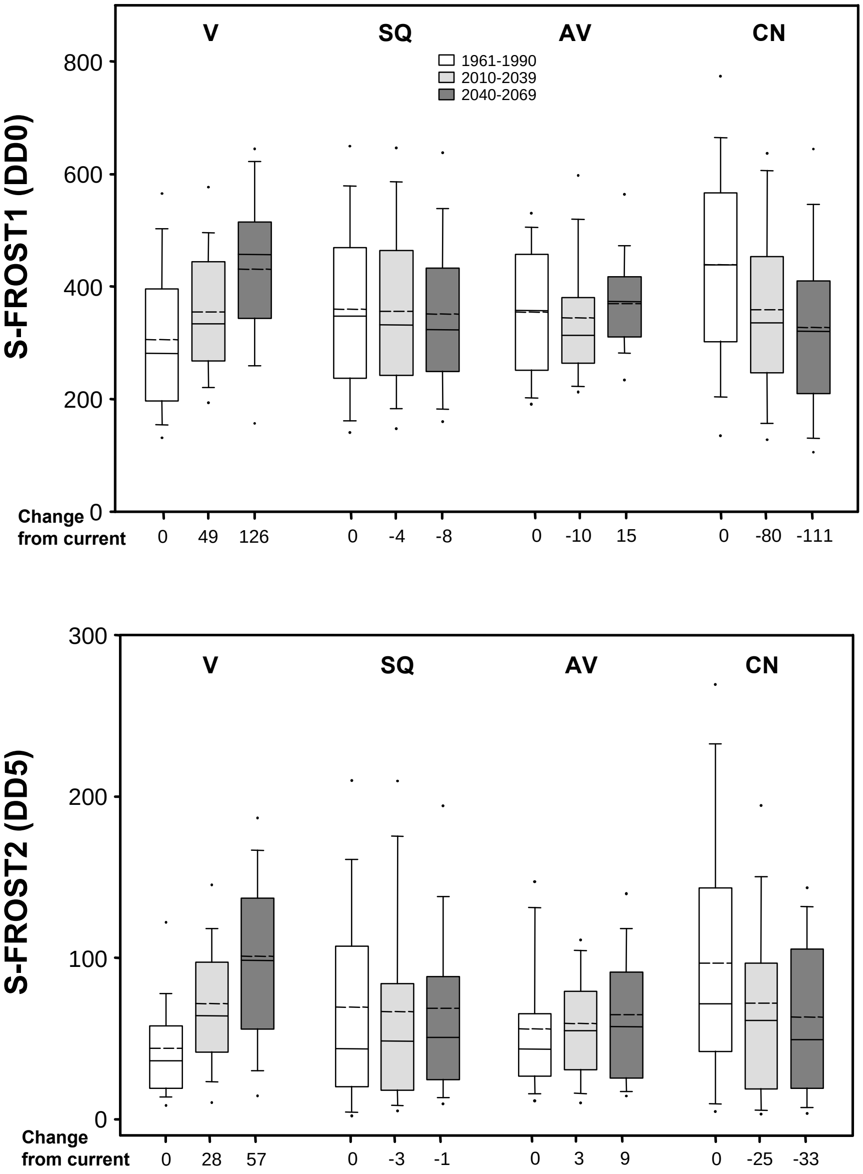

Figure 4. Spring indices in three regions where deciduous fruit trees are commercially cropped and one extreme climate region (CN) in eastern Canada based on current climate and future climate scenarios. V, Vineland; CN, Continental North; SQ, South Québec; and AV, Annapolis Valley. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

CONCLUSIONS

According to our estimates, the climate change is predicted to noticeably affect fall, winter and spring climatic conditions that influence the winter survival of deciduous fruit trees in eastern Canada. By 2040–2069, the risks of winter damage to deciduous fruit trees in eastern Canada are likely to decrease because of: 1) a shorter photoperiod at the time of the first freezing fall temperatures resulting in an early induction of cold hardening, 2) milder winter temperatures reducing the cold stress, and 3) a modified spring temperature regime reducing damage to floral buds by late frosts, except for the currently warmer regions. On the other hand, more frequent winter thaw events will likely result in a loss of hardiness and increase vulnerability to late winter low temperatures.

Since the production and the distribution of deciduous fruit trees are mostly related to their winter survival, we may expect that these predicted changes will permit 1) the introduction of new varieties and species in regions where deciduous fruit trees are currently cropped; 2) an extension further north of the limits of commercial production; and 3) a stabilisation of the year-to-year production in currently marginal producing-regions because of lesser risks of damage to floral buds.

ACKNOWLEDGMENTS

The assistance of D. Anderson (AAFC, Ottawa) in data processing and A. Jones (AAFC, Ottawa) in writing computer programs to compute the variables used is gratefully acknowledged. This project was funded in part by the Canadian Climate Change Action Fund.

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SECTION 3

Potential impact of climate change on agricultural perennial crops and recommendations for agricultural practices more suitable for the predicted future climate.

Perennial forage crops

Under climate change, all parts of eastern Canada will likely experience a substantial modification in agro-climatic conditions that is expected to have a negative impact on the winter survival of perennial forage crops. The increased risks of winter damage to perennial forage crops will likely be due to i) warmer fall temperatures, which would prevent adequate fall hardening, ii) loss of cold hardiness during winter due to warmer temperatures, and iii) significant reduction of snow cover protection which will likely increase risks of damage due to ice and freezing temperatures.

Several agricultural practices can be envisaged to alleviate these effects on forage crop production.

- The choice of species and cultivars should be based on their tolerance to freezing temperatures and/or anoxia, their capacity to harden effectively under warm fall conditions, their capacity to maintain a high level of cold hardiness under warm winter temperatures, and their capacity to re-harden rapidly after short exposure to warm temperatures in winter.
- The longer growing season would permit an additional harvest. The number and timing of harvests should be re-evaluated in order to optimize the level of organic reserves for adequate overwintering. The harvest management should also consider the necessity to leave a sufficient stubble to promote the accumulation of snow over forage stands.
- Since most grass species are more cold-hardy than legumes, the establishment of perennial forage stands composed of mixed grass and legume species would ensure a minimum yield every year.
- Techniques for re-seeding winterkilled forage fields with minimum tillage should be re-evaluated and improved.

The increased risk of winter damage to perennial crops will require the development and identification of new tools and practices.

- Reliable models and predictive methods of winter damage to perennial forage crops will be required; producers could take the necessary steps for re-seeding if a prediction of winter damage is made early enough.
- The development of new cold hardy cultivars for different climate conditions is essential.
- The income security programs and crop insurance programs might have to be adapted to the new context.

The warming of the climate will also offer new opportunities.

- New warm-season species such as switchgrass and others, now commonly grown in the United Sates but not adapted to the current climatic conditions of eastern Canada, might be adapted under the climatic conditions of the future.

Deciduous fruit trees

It is predicted that the climatic conditions will become more favourable for the production and winter survival of deciduous fruit trees in eastern Canada. Consequently, we may expect:

- An introduction of new cultivars and species in regions where deciduous fruit trees are currently cropped.
- An extension further north of the limits of commercial production.
- A stabilisation of the year-to-year production in currently marginal producing-regions, for example the blueberry production in the Continental North.

Despite the fact that climate change will generally affect positively the fruit tree sector, the occurrence of climatic accidents is likely to be more frequent. Damage due to a winter thaw is currently infrequent but may become more frequent under climate change; a judicious choice of cultivars may help to prevent the damage due to a winter thaw.

Decision support resources, such as maps of the zonation of agroclimatic risks to fruit production, should be expanded and updated on a more frequent basis; such tools will be useful for the planning of the timely introduction of new species or cultivars in new areas. In addition to the use of appropriate cultivars, cultural practices will contribute to further enhance the hardiness of new species and cultivars in a given region. Since the genotype is the most critical factor in determining hardiness, developing cold hardy cultivars for different climate conditions is essential.

Appendix A

Agro-climatic indices expressing the risks associated to the most probable causes of damage to perrenial agricultural crops during fall, winter and spring. Units are enclosed in parentheses.

Fall	**I1=**	Sum of cold degree days < 5°C (CDD5) from Aug. 1 to date of first occurrence of Tmin < or = -10°C
	I2=	Sum of CDD5 from day after date when sum of CDD5 - GDD5 = 0 to date of first occurrence of Tmin < or = -10°C
	I3=	Rate of accumulation of CDD5 - GDD5 during the hardening phase
	I4=	Sum of daily precip from day after date when sum of CDD5 - GDD5 = 0 to date of first occurrence of Tmin < or = -10°C (mm)
	I5=	Photoperiod or daylength on date of first occurrence of Tmin < or = 0°C (hrs)
Winter	**I6=**	Mean daily minimum temperature of the coldest month (Celsius)
	I7=	Sum of cold degree days < -15°C (CDD-15) from Aug. 1 to July 31
	I8=	Lowest daily Tmin from Aug. 1 to July 31 (Celsius)
	I9=	Rate of GDD>0 during cold period
	I10=	Rate of rainfall accumulation during cold period (mm/day)
	I11=	Difference between the period with a snow cover of at least 10 cm and the period in which cold temperatures (Tmin < or = -15°C) can occur (days)
	I12=	Sum of GDD>0 from date of first occurrence of Tmin < or = -15°C to day before date of last occurrence of Tmin < or = -15°C
	I13=	Sum of GDD>0 from Jan. 1 to day before date of last occurrence of Tmin < or = -15°C
Spring	**I14=**	Sum of GDD>0 from Jan. 1 to day before date of last occurrence of Tmin < or = 0°C
	I15=	Sum of GDD>5 from Jan. 1 to day before date of last occurrence of Tmin < or = -2°C

Appendix B

List of Variables computed from daily weather data for CCAF project on risk of winter injury to perennial agricultural plants

V1= Sum of cold degree days < 5 C (CDD5) from Aug. 1 to day V2-1
V2= Date of first occurrence of Tmin < or = -10 C
V3 = Sum of CDD5 - GDD5 from Aug. 1 to day V2-1
V4= Date following last day when V3 = 0
V5= Sum of Growing Degree-Days >5 C (GDD5) from day V4 to day V2-1
V6= Sum of CDD5 from day V4 to day V2-1
V7= Length of hardening phase (V2-V4) (days)
V8= Rate of accumulation of V3 (i.e. V3/V7)
V9= Sum of daily precip from day V4 to V2-1 (mm)
V10= Date of first occurrence of Tmin < or = 0 C
V11= Photoperiod or daylength on day V10 (hrs)
V12= Date of first occurrence of Tmin < or = -15 C
V13= Date of last occurrence of Tmin < or = -15 C
V14= Length of cold period (V13 - V12) (days)
V15= Mean daily minimum temperature of the coldest month (Celsius)
V16= Sum of cold degree days < -15 C (CDD-15) from Aug. 1 to July 31
V17= Lowest daily Tmin from Aug. 1 to July 31 (Celsius)
V18= Sum of GDD>0 from day V12 to day V13-1
V19= Sum of GDD>0 from Jan. 1 to day V13-1
V20= Sum of daily rainfall from day V12 to day V13-1 (mm)
V21= Sum of GDD>0 from Jan. 1 to day V22-1
V22= Date of last occurrence of Tmin< or = 0 C
V23= Rate of GDD>0 during cold period (i.e. V18/V14)
V24= Rate of rainfall accumulation during cold period (i.e. V20/V14) (mm/day)
V25= Sum of GDD>5 from Jan. 1 to day V26-1
V26= Date of last occurrence of Tmin< or = -2 C
V27= Average daily maximum temperature for November (Celsius)
V28= Average daily maximum temperature for March (Celsius)
V29= Rainfall for March (mm)
V30= Sum of snowfall from Aug.1 to July 31 (cm)
V31= Sum of daily rainfall from Nov.1 to Apr. 31 (mm)
V32= Number of days with a snow cover of at least 0,1m (d)
V33= Difference between the number of days with a snow cover and the cold period (V32 - V14) (d)

Appendix C

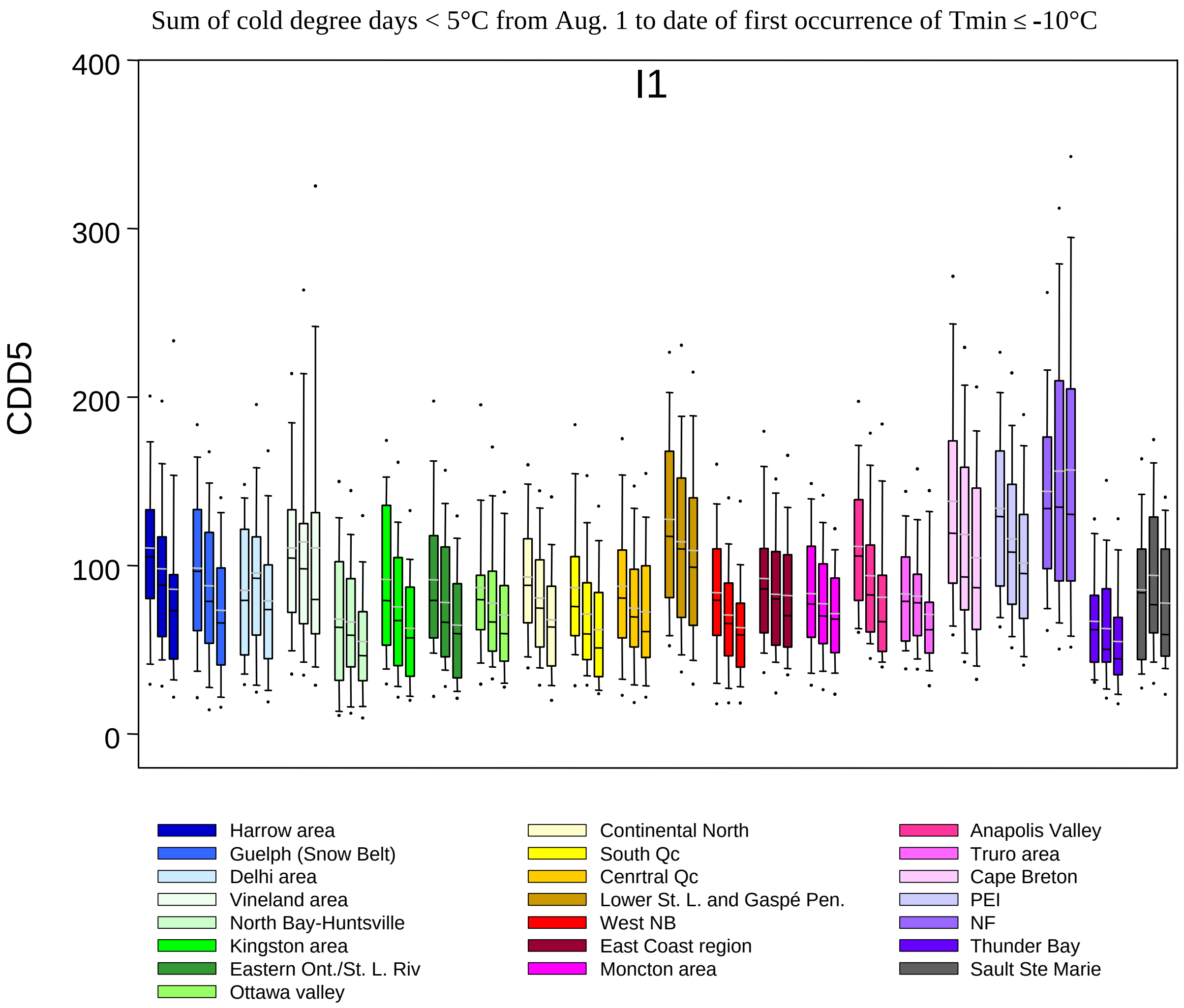

Figure C1. Index I1 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

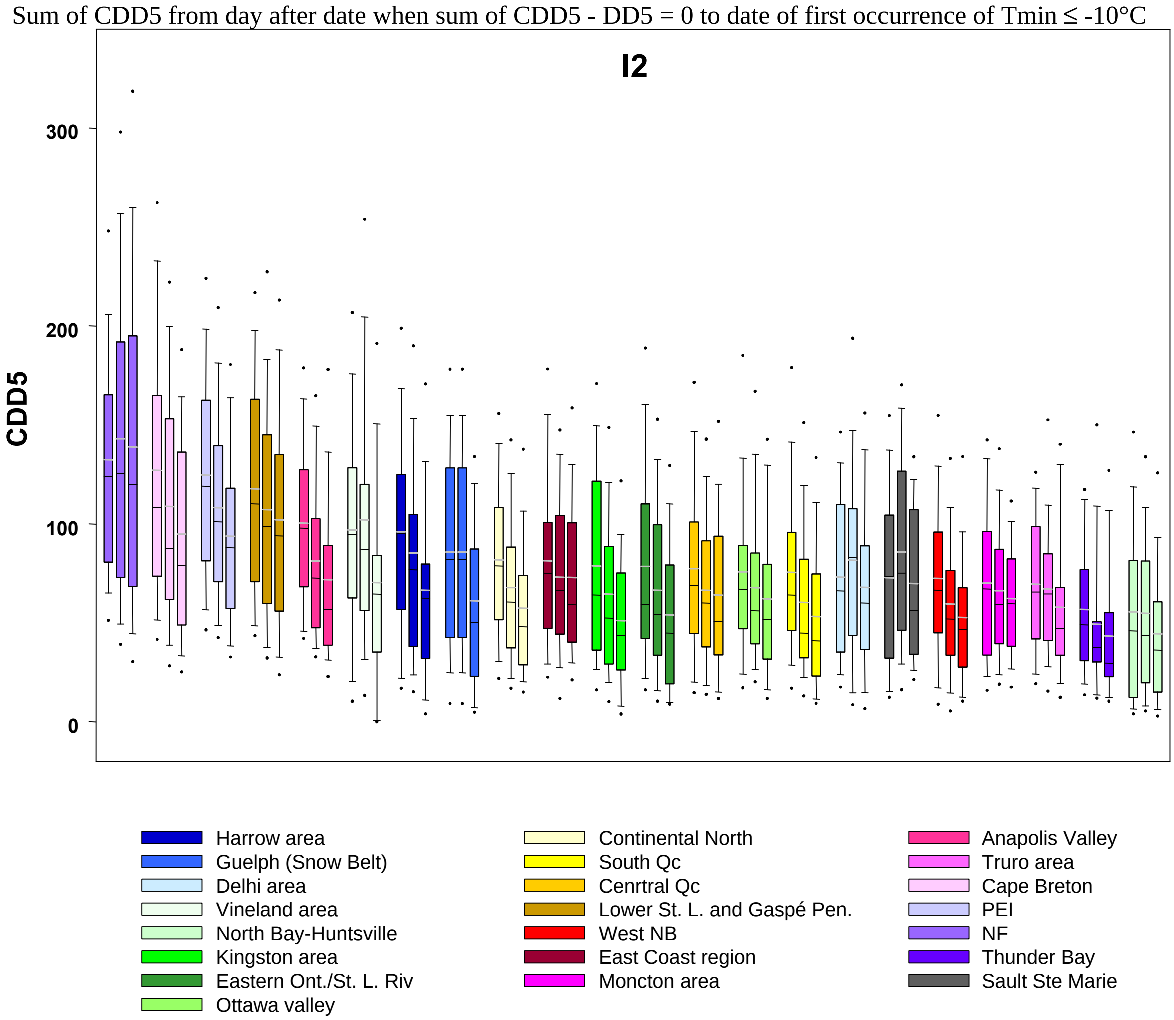

Figure C2. Index I2 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

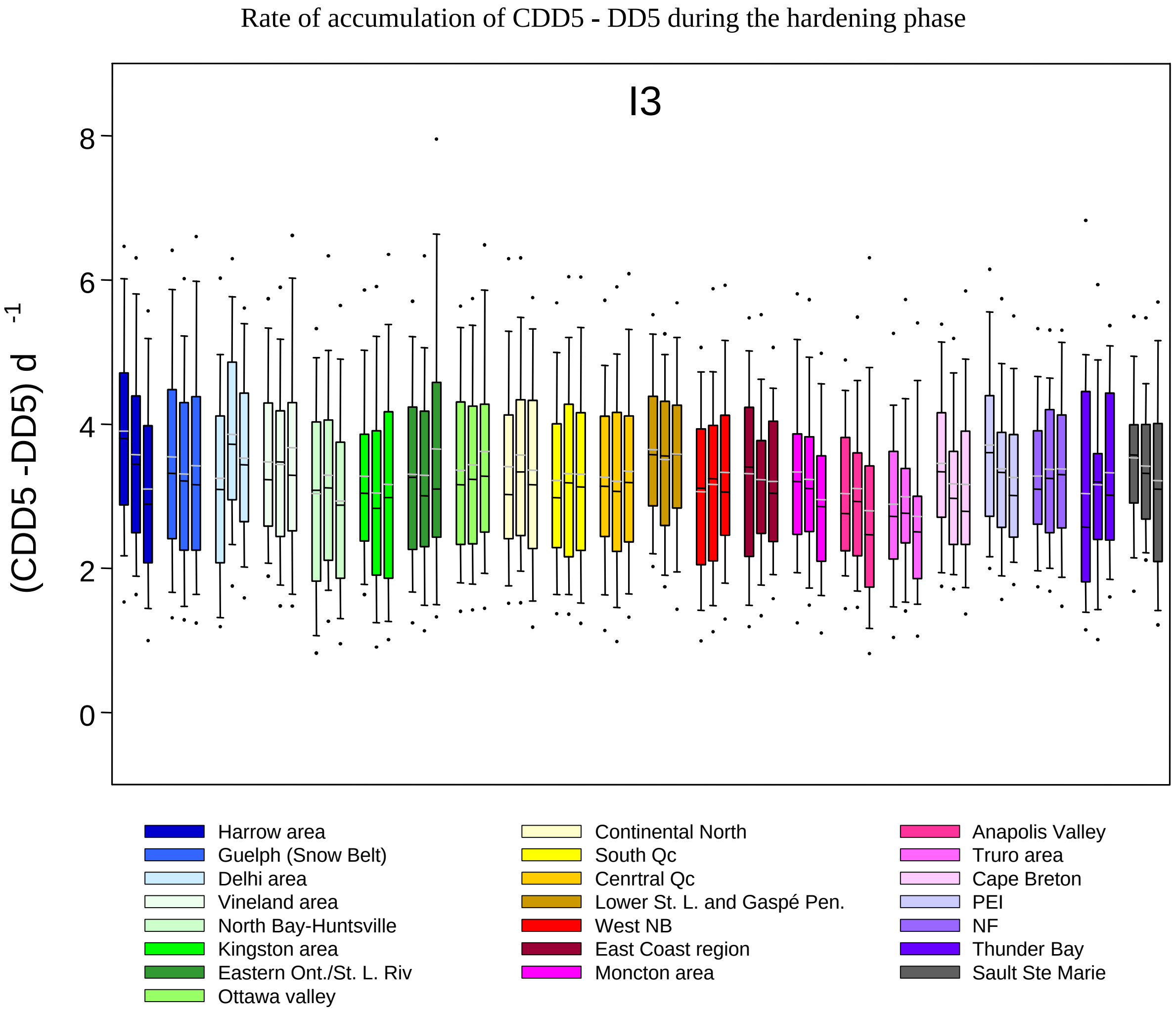

Figure C3. Index I3 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

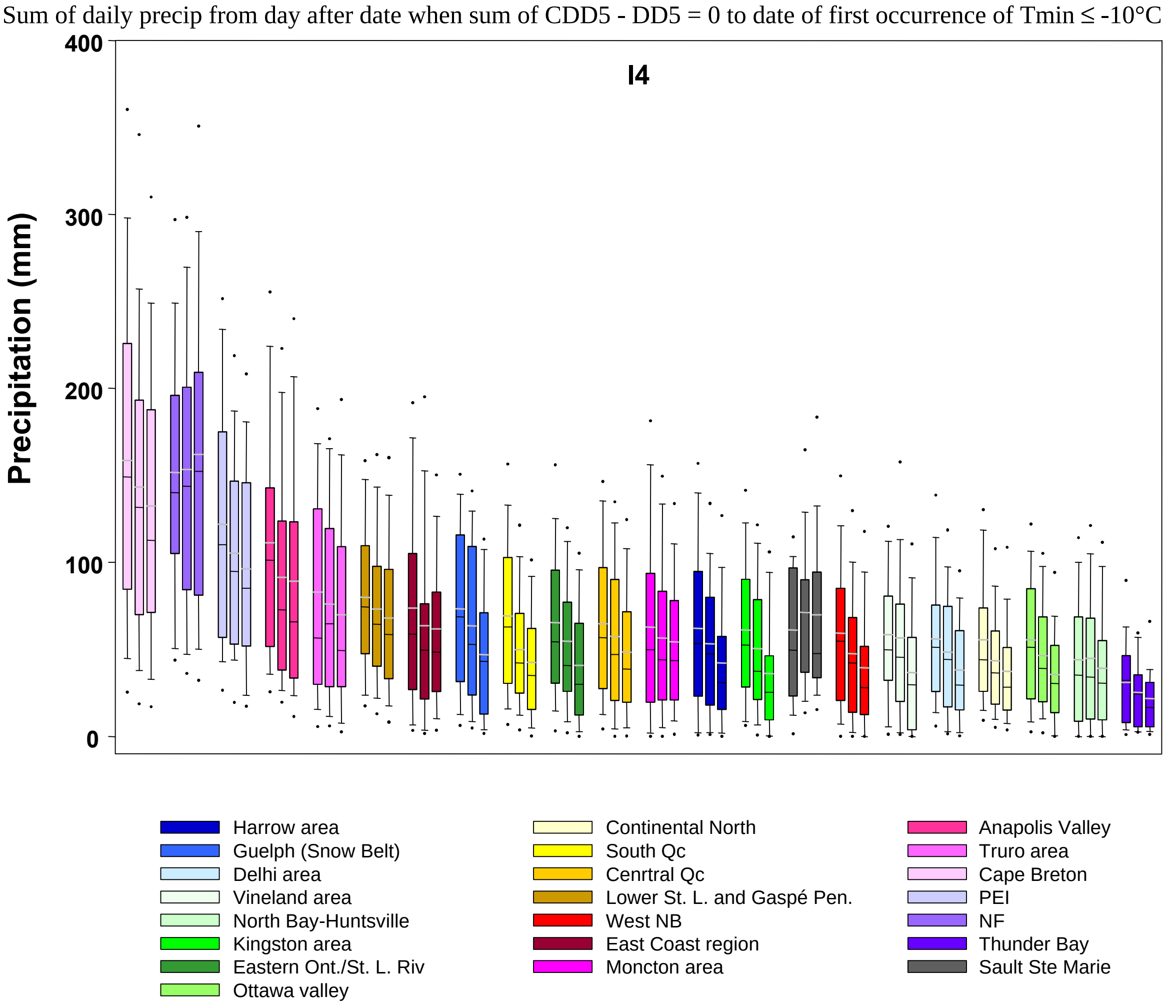

Figure C4. Index I4 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

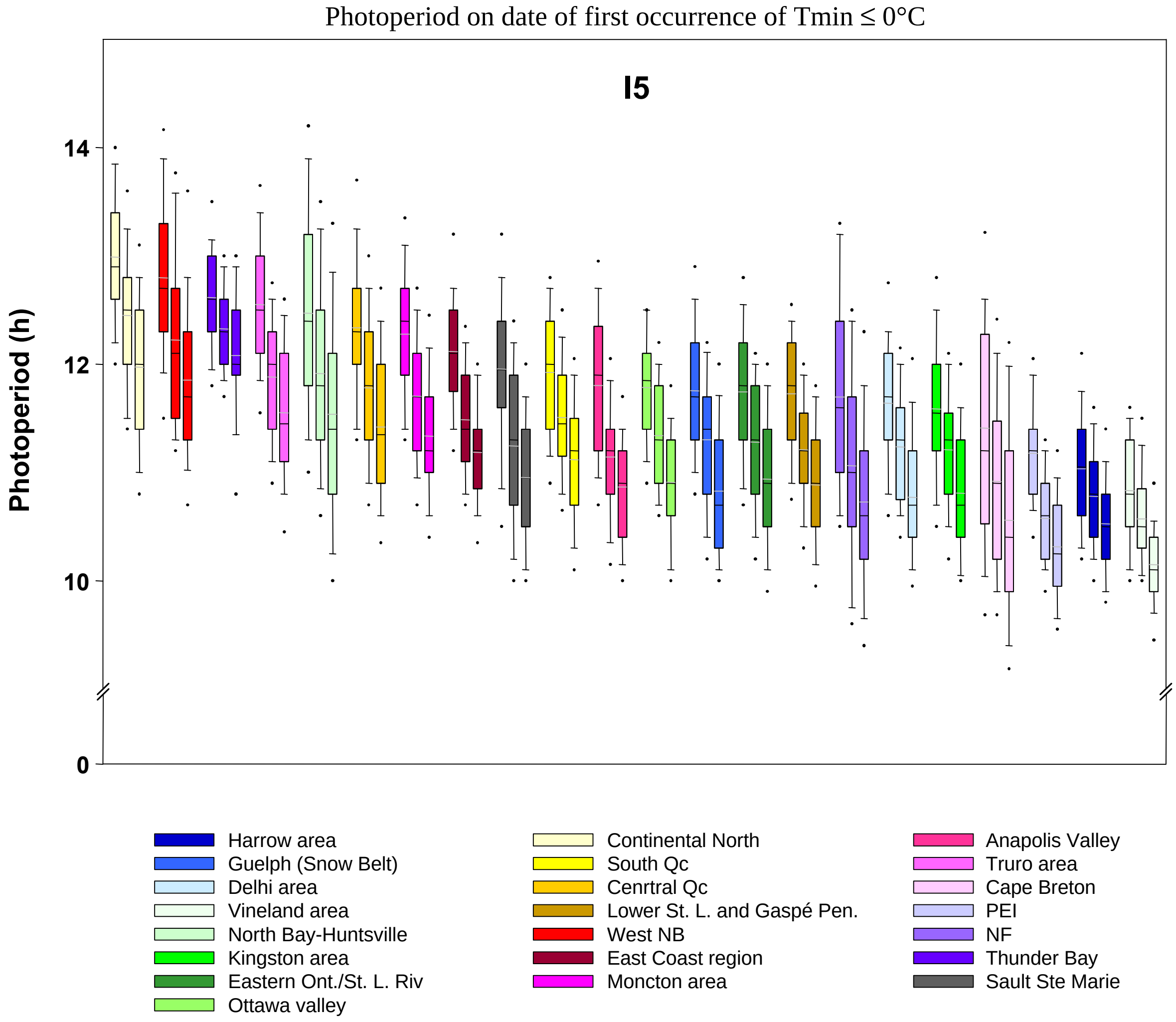

Figure C5. Index I5 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

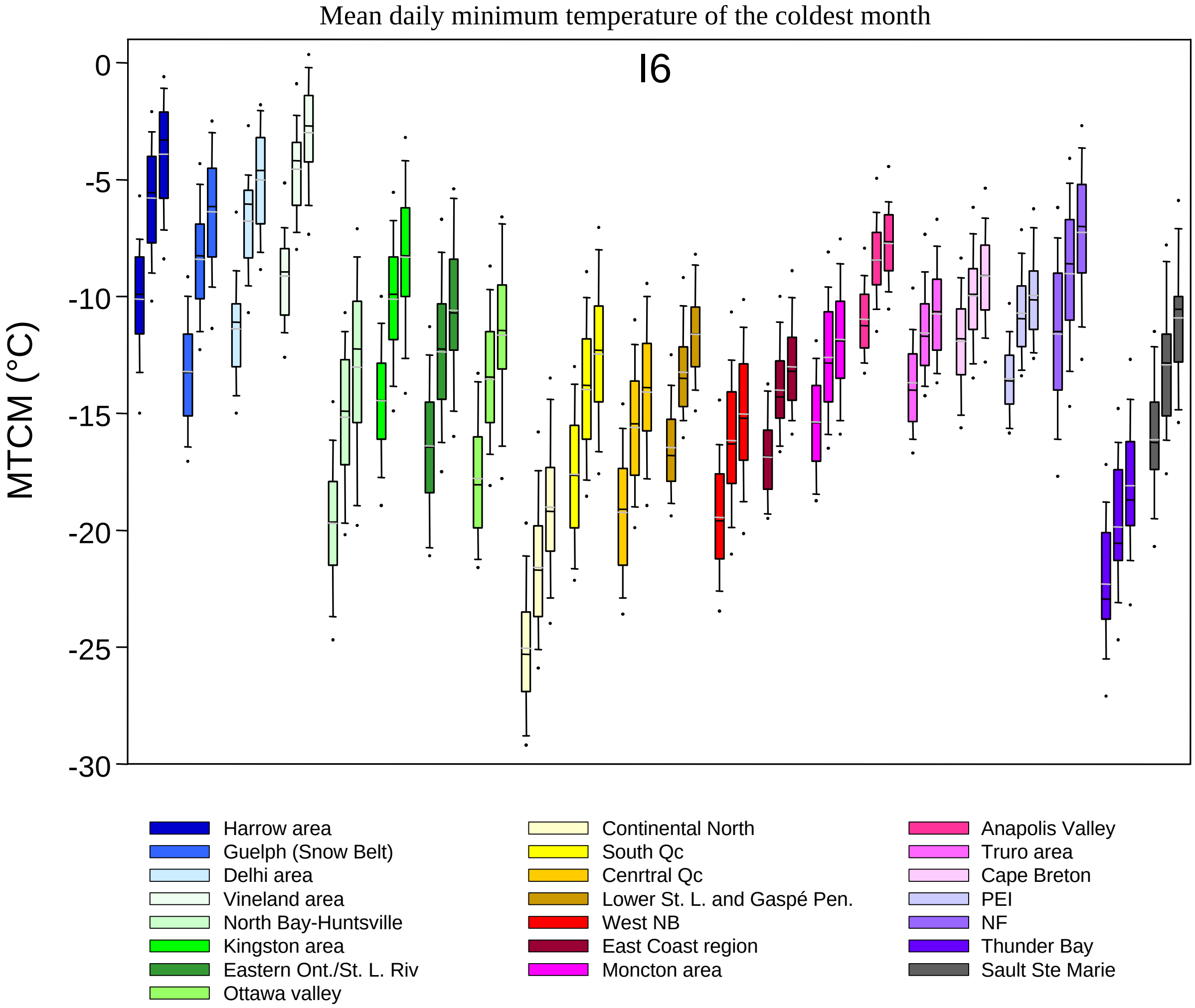

Figure C6. Index I6 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

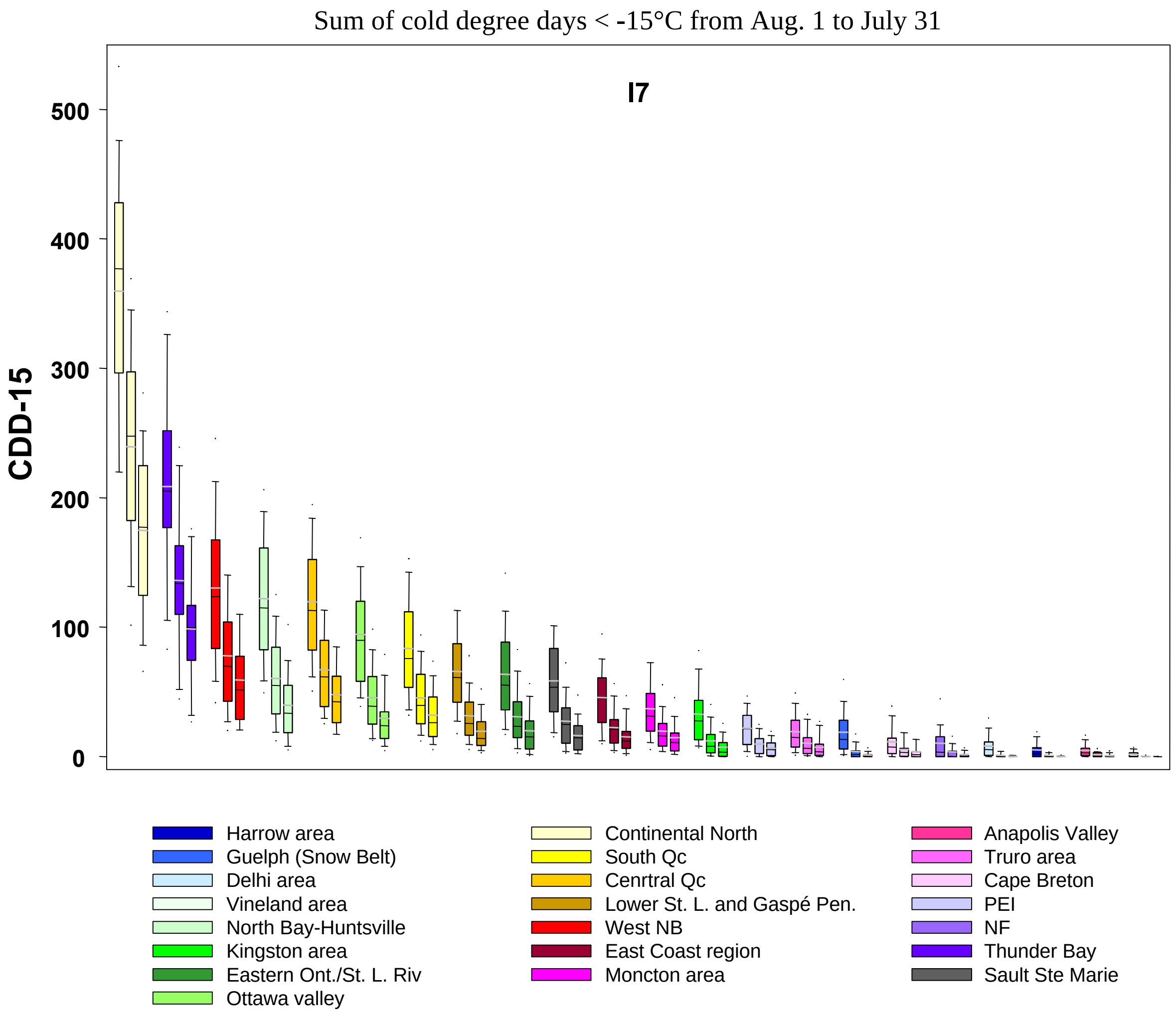

Figure C7. Index I7 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

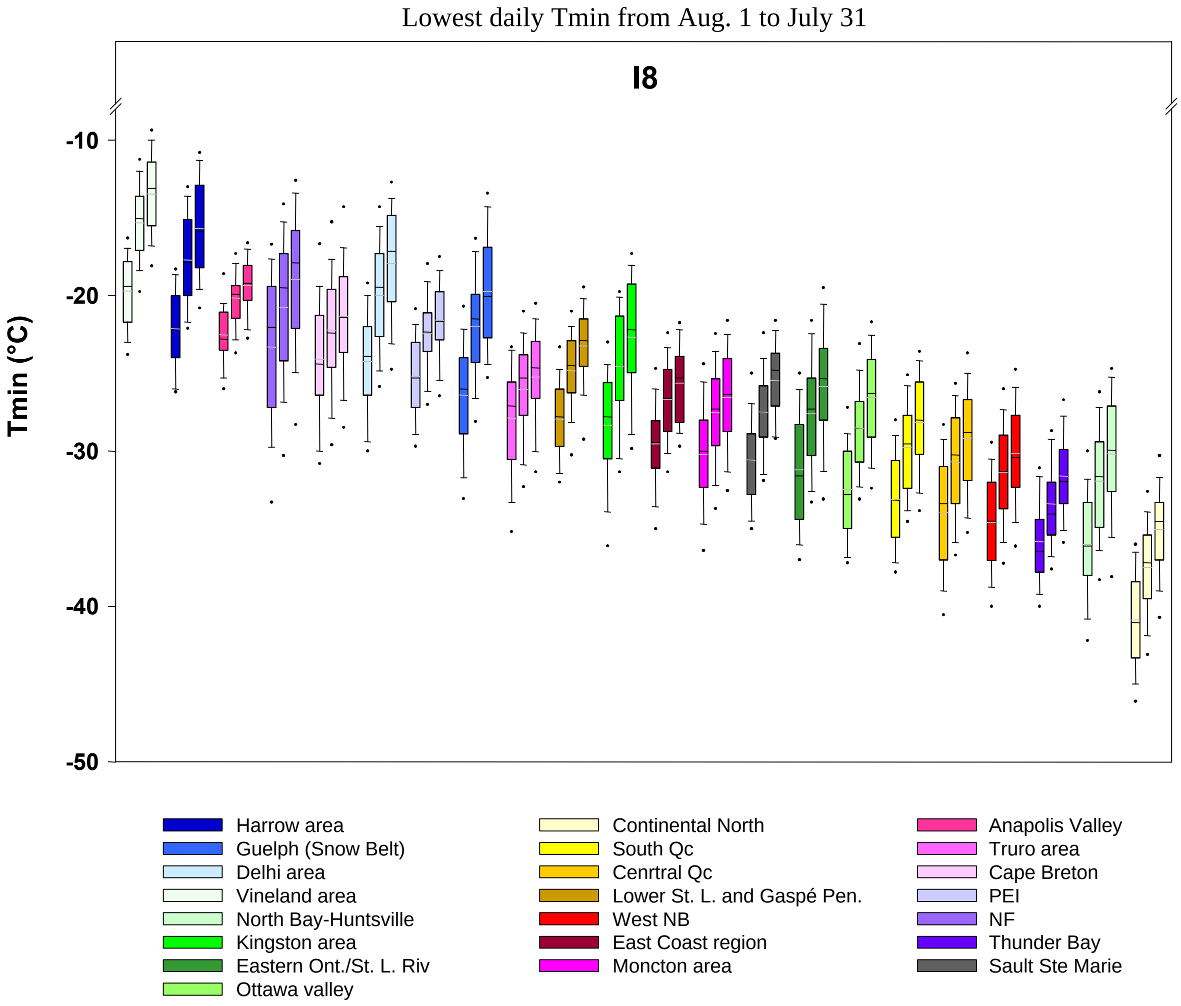

Figure C8. Index I8 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

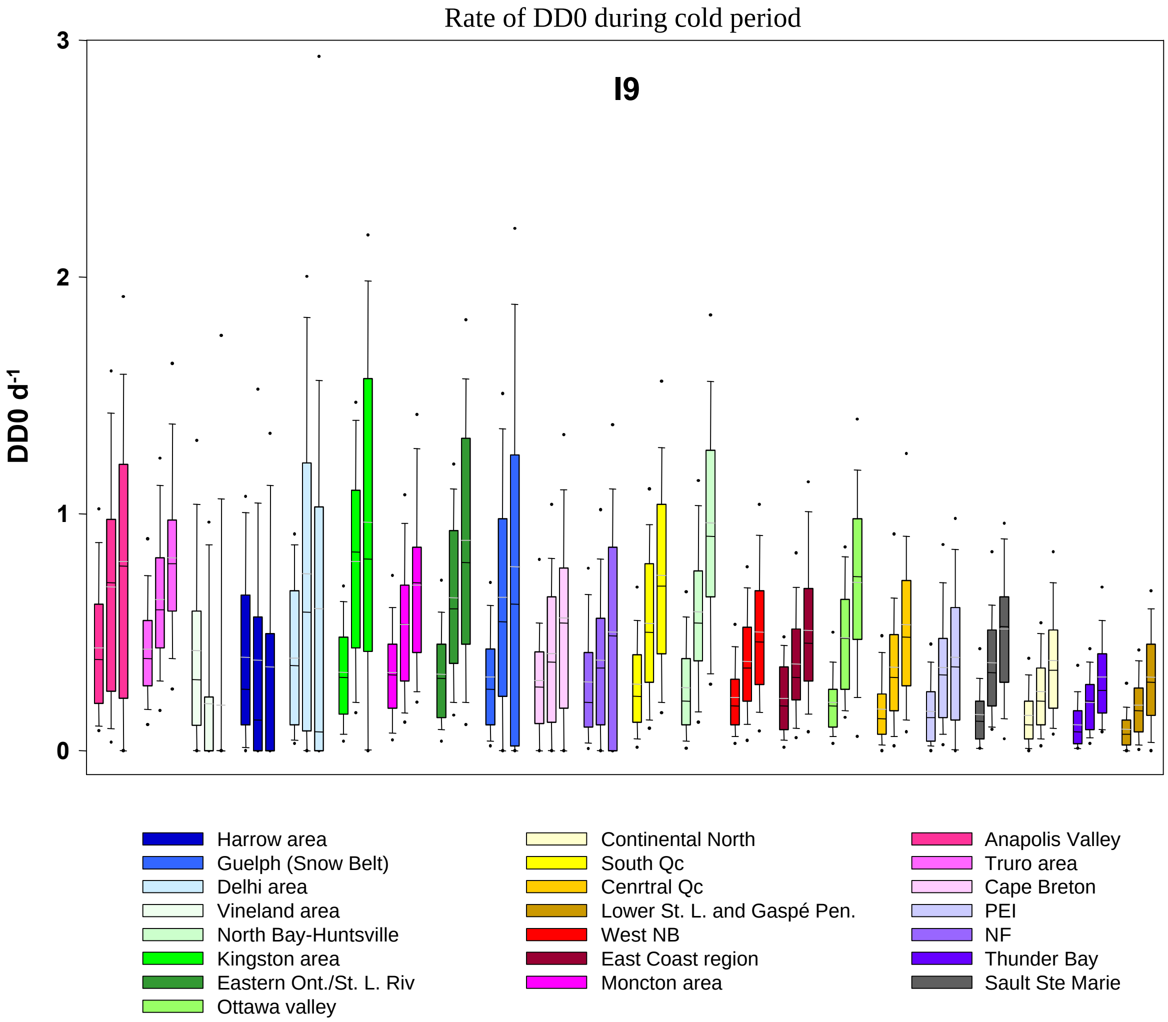

Figure C9. Index I9 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

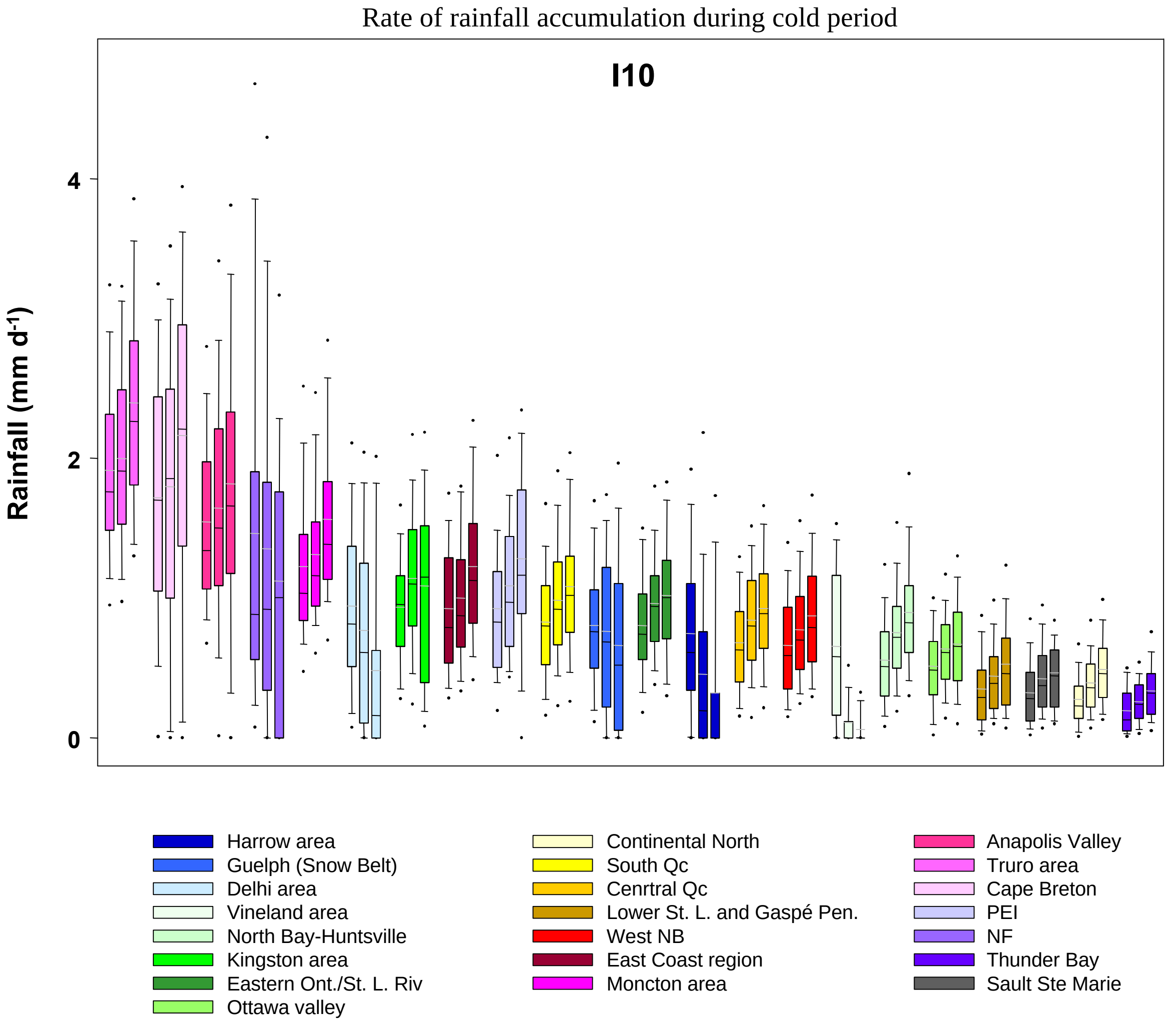

Figure C10. Index I10 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

Difference between the number of days with a snow cover of at least 10 cm and the cold period

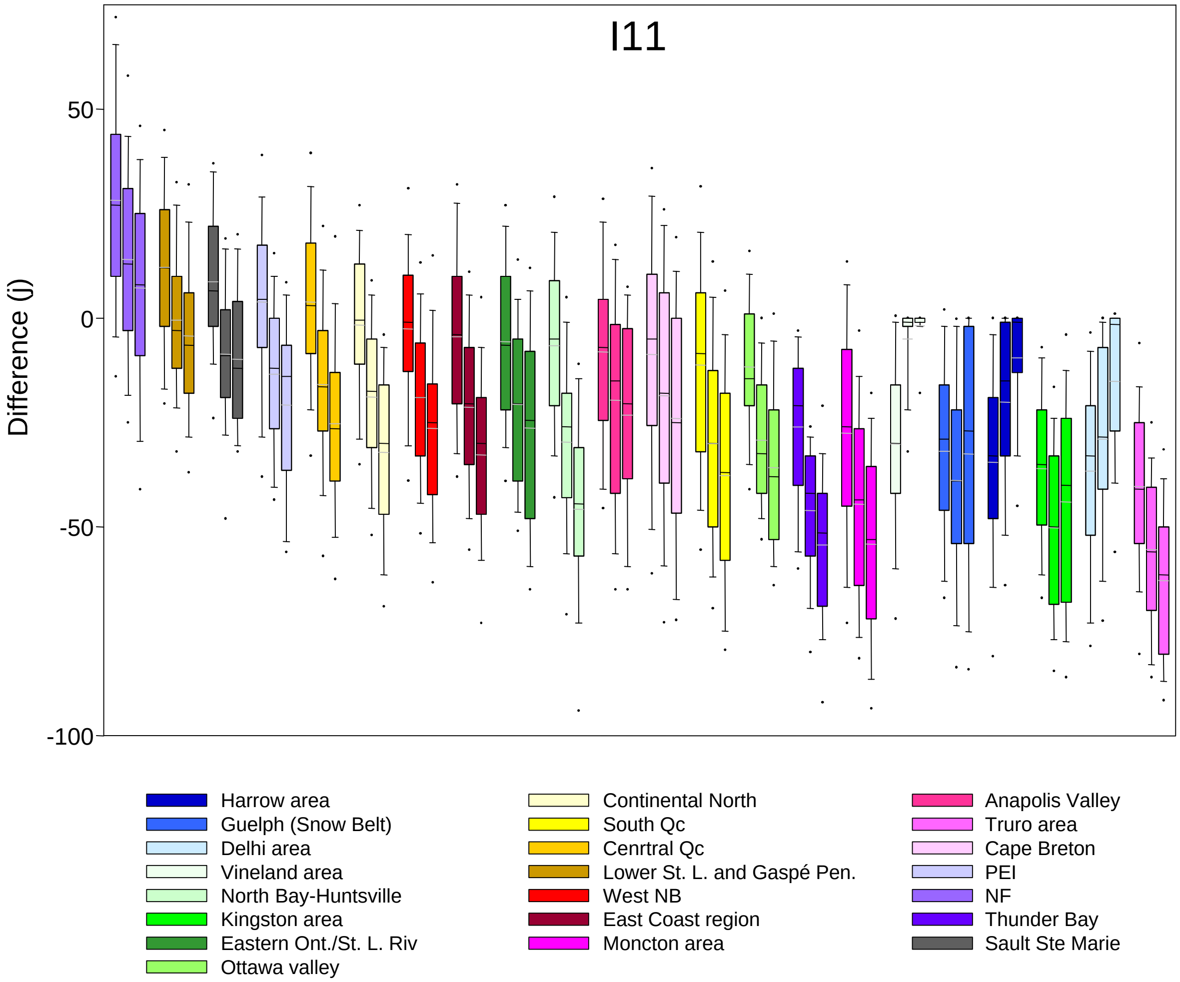

Figure C11. Index I11 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

Sum of DD0 from date of first occurrence of Tmin ≤ -15°C to day before date of last occurrence of Tmin ≤ -15°C

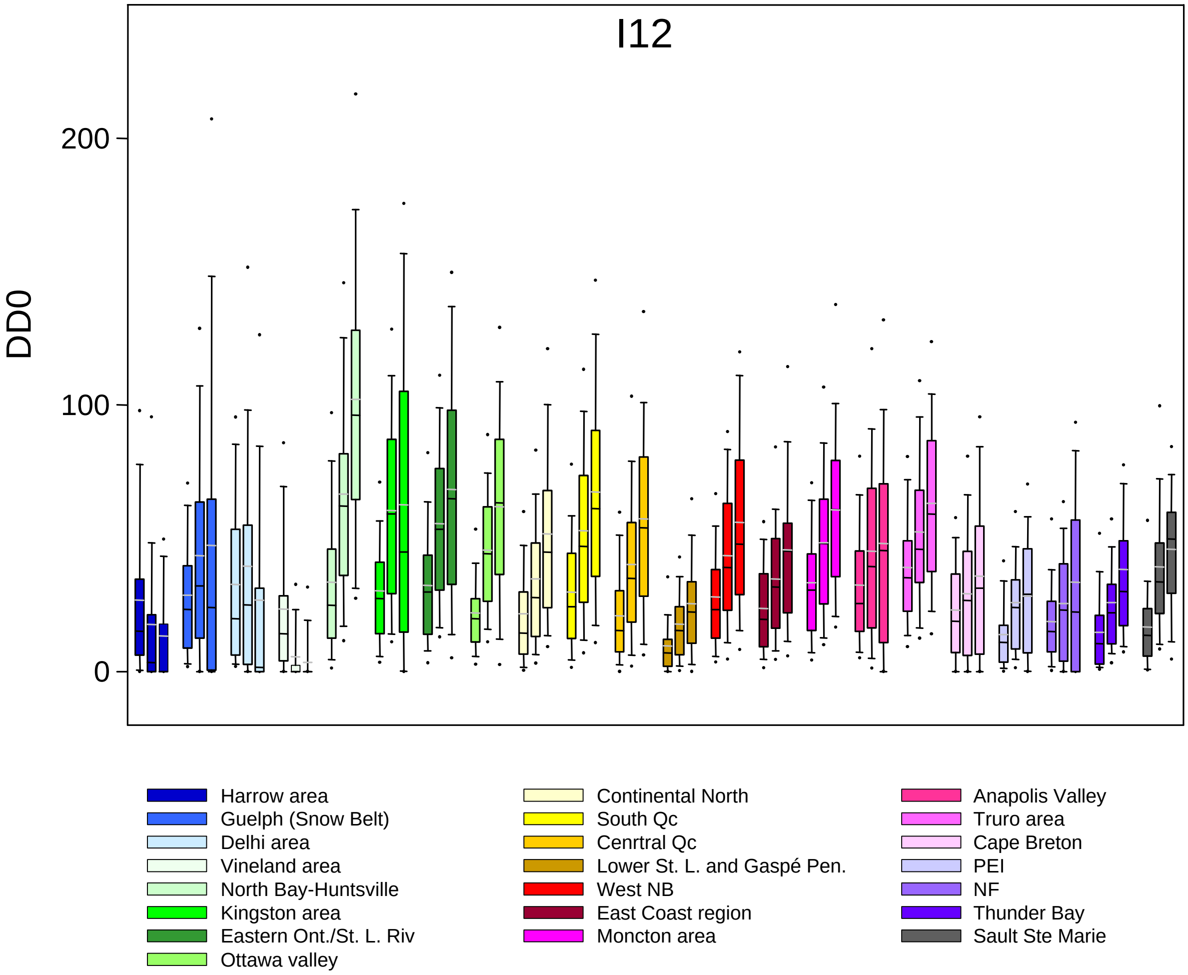

Figure C12. Index I12 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

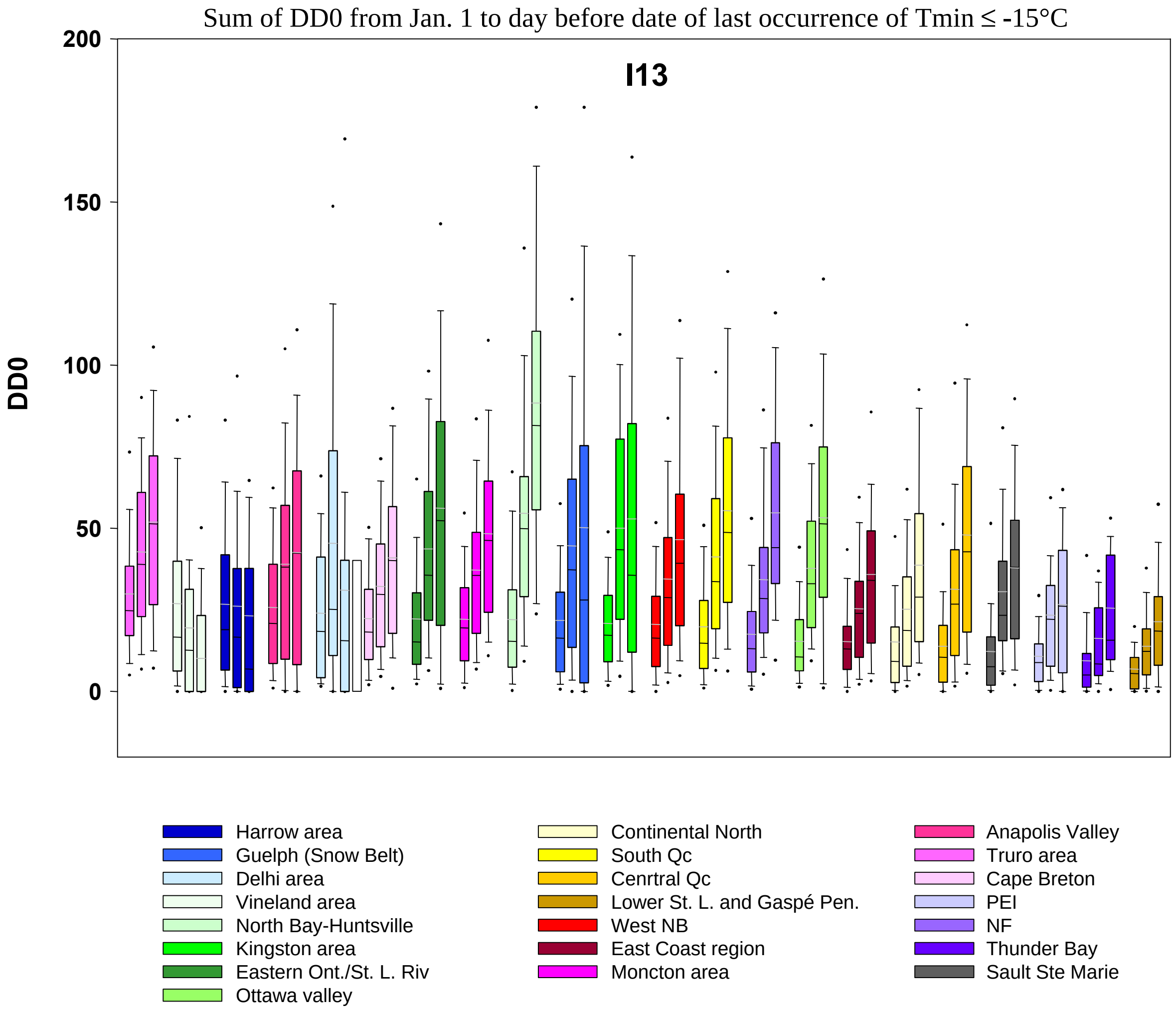

Figure C13. Index I13 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

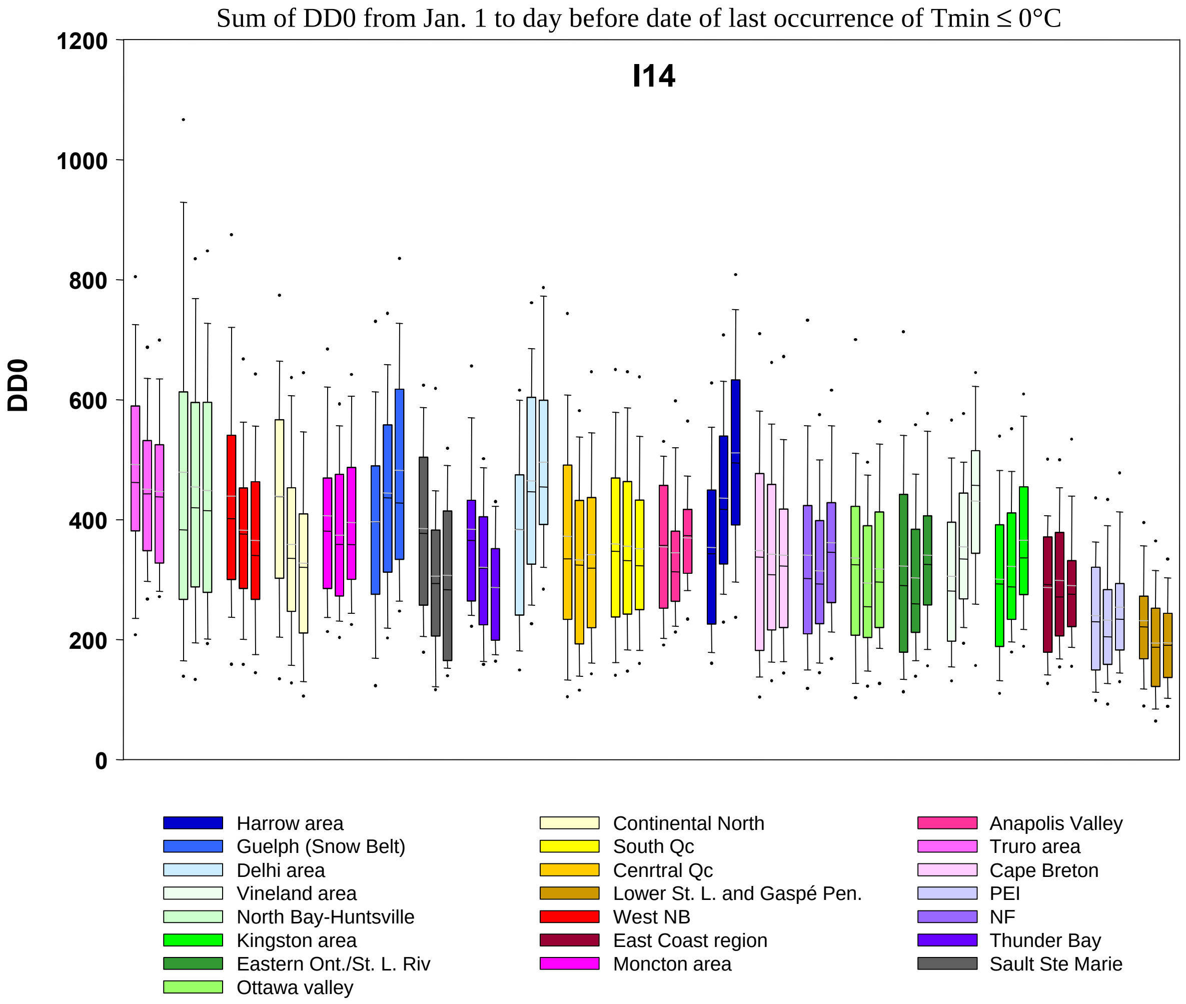

Figure C14. Index I14 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

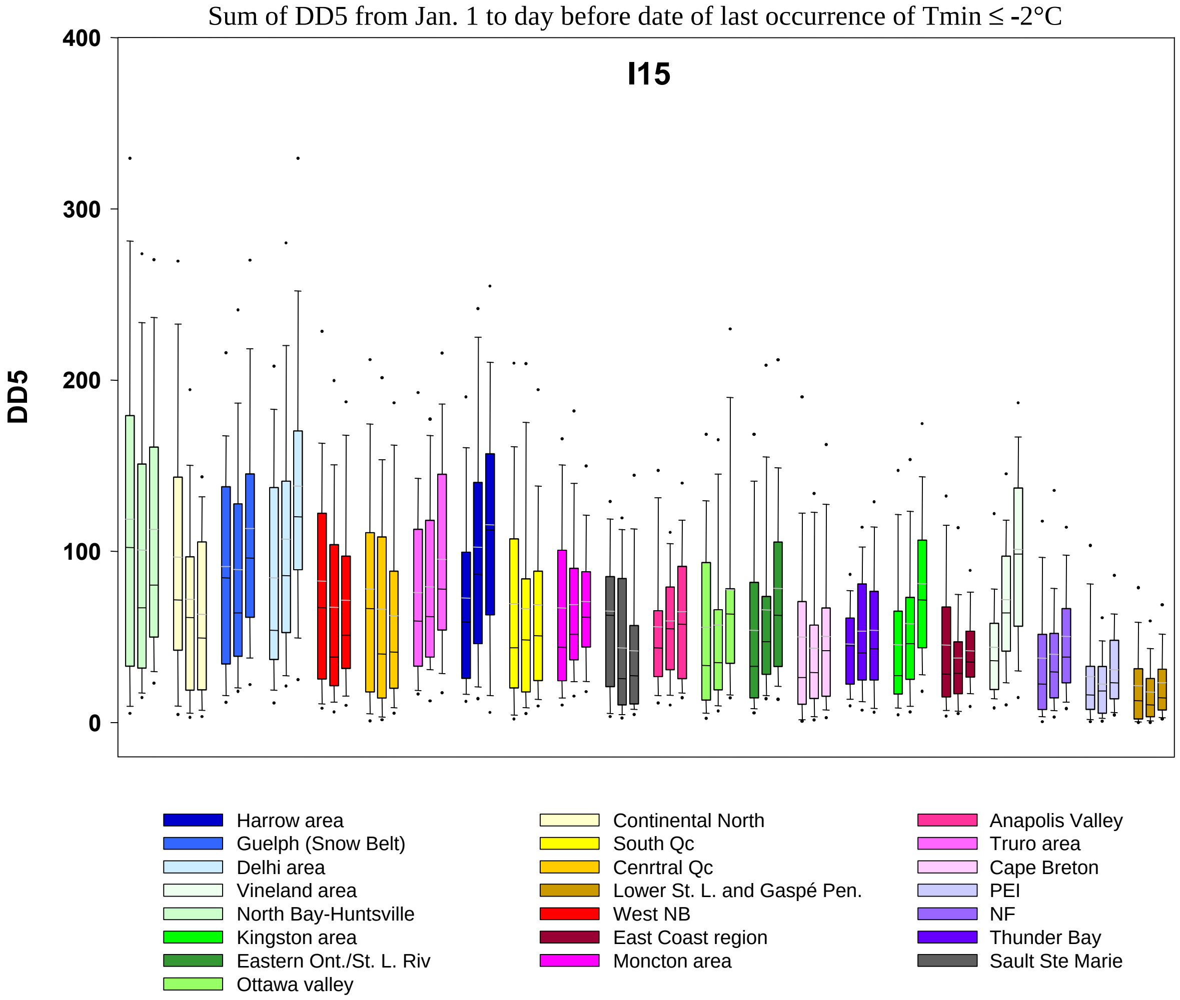

Figure C15. Index I15 in 22 agricultural regions of eastern Canada based on current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles; dots below and above whiskers indicate the 5th and 95th percentiles respectively.

Appendix D

CCAF project A084: list of communications

G. Bélanger. 2001. Climat plus chaud mais plus de mortalité hivernale. Short release in the *La recherche en bref* column. Info-fourrage 1: 11.

D. Mongrain, G. Bélanger, P. Rochette, A. Bootsma and Y. Castonguay. 2001. Changements climatiques et survie à l'hiver des plantes fourragères au Québec méridional. Lecture presented at the Demi-journée d'information scientifique sur les fourrages, conjoint meeting of the Comité des plantes fourragères and the Conseil des Plantes Fourragères du Québec (CQPF), February 1, Victoriaville, Canada.

A. Bootsma, G. Bélanger, P. Rochette, Y. Castonguay, and D. Mongrain. 2001. Potential impacts of climate change on winter survival of perennial forage crops in the Québec region of Canada. Poster presented at the annual meeting of the *American Meteorological Society,* January 14-19, Albuquerque, USA.

G. Bélanger, P. Rochette, A. Bootsma, Y. Castonguay, and D. Mongrain. 2000. Climate change and winter survival of perennial crops in Eastern Canada. Poster presented at the annual meeting of the American Society of Agronomy, the Soil Science Society of America and the Crop Science Society of America; November 5-9, Minneapolis, USA.

G. Bélanger, P. Rochette, A. Bootsma, Y. Castonguay, and D. Mongrain. 2000. Climate change and winter survival of perennial forage crops in Québec. Lecture presented at the Agri-Food 2000 Conference of the Canadian Scientific Societies in Agriculture; July 17-19, Winnipeg, Canada.

P. Rochette, G. Bélanger, A. Bootsma, Y. Castonguay, and D. Mongrain. 2000. Changements climatiques et survie à l’hiver des plantes pérennes au Québec méridionnal. Lecture presented at the annual meeting of the Quebec Society for Plant Protection; June 14-15, Saint-Félicien, Canada. Abstract published in Phytoprotection 81(1): 42.

G. Bélanger, P. Rochette, A. Bootsma, Y. Castonguay, D. Mongrain and A. Bertrand. 2000. Climate change and survival of perennial herbaceous crops in Eastern Canada. Poster presented at a Seminar arranged by the Nordic Association of Agricultural Scientists (NJF) in cooperation with International Workshop on Plant-Microbe Interaction at Low Temperatures under Snow (this is NJF Seminar number 311); May 19-21, Akureyri, Iceland.