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# FORAGES

## Climate Change and Winter Survival of Perennial Forage Crops in Eastern Canada

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### ABSTRACT

**Severe winter climatic conditions cause recurrent damage to perennial forage crops in eastern Canada. Predicted increases of 2 to 6°C in minimum temperature during winter months due to global warming will likely affect survival of forage crops. Potential impacts of climate change on overwintering of perennial forage crops in eastern Canada were assessed using climatic indices reflecting risks of winter injuries related to cold intensity and duration, lack of snow cover, inadequate cold hardiness, soil heaving, and ice encasement. 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). Climate scenario data were extracted from the first-generation Canadian Global Coupled General Circulation Model. Compared with current conditions, the hardening period in 2040 to 2069 would be shorter by 4.0 d, with a lower accumulation of hardiness-inducing cool temperatures. The period during which a temperature ≤−15°C can occur (cold period) 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 would be reduced by 15.6 d. Under predicted future climate, risks of winter injury to perennial forage crops in eastern Canada will likely increase because of less cold hardening during fall and reduced protective snow cover during the cold period, which will increase exposure of plants to killing frosts, soil heaving, and ice encasement.**

Perennial forage crops are grown on more than 2.1 million ha in eastern Canada, which represents about 40% of the cultivated land (Stat. Can., 1996) and an annual estimated farm gate value of Can$1.3 billion. The winter survival of perennial crops depends largely on climatic conditions. Subfreezing temperatures, loss of cold hardiness, ice encasement, and soil heaving result in frequent losses of stands and yield reduction of perennial forage crops in many forage-growing areas of eastern Canada (Ouellet, 1976). Climatological models predict that the minimum temperature of the winter months will increase by 2 to 6°C over the next 50 yr (Can. Inst. for Climate Studies, 2001). This warming trend will potentially affect winter survival of perennial forage crops and have a significant impact on their economic sustainability in eastern Canada.

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Agroclimatic indices are commonly used to characterize plant–climate interactions. Degree-days or crop-specific heat units have been successfully related to plant growth and development (Arnold, 1959; Brown and Chapman, 1961). Water requirements for plant growth have also been associated with potential evapotranspiration (Thorntwaite, 1948). Rochette and Dubé (1993a, 1993b) proposed agroclimatic indices to assess the risk of winter damage to broad groups of perennial plants and to express relative spatial differences in the mean intensity of the causes of damage in the province of Quebec, Canada. Their indices were based on the knowledge of plant–environment relationships during the cold period, and they were calculated from readily available climate variables such as air temperature and precipitation.

Our objectives were to develop agroclimatic indices reflecting the risks of winter damage to perennial forage crops and to use these indices to assess the relative impact of climate change on the winter survival of perennial forage crops in eastern Canada.

## MATERIALS AND METHODS

### Agroclimatic Indices

In our study, we followed an approach similar to that of Rochette and Dubé (1993a, 1993b) to develop five indices specific to perennial forage crops. These indices estimate the relative risk associated with the most probable climatic causes of damage during fall and winter. Fall indices express the influence of temperature and soil moisture on the acquisition of cold hardiness. Winter indices assess the impact of (i) low temperatures, (ii) the loss of cold hardiness due to warm temperatures, and (iii) the potential damage to the root system by soil heaving and ice encasement. The justification for selecting each of these indices follows.

### Fall Indices

Temperature and soil moisture during fall affect plant growth and the storage of reserves in roots. Hence, they have a direct influence on the level of cold hardiness of forage crops at the onset of winter.

#### Fall Hardening—Temperature

Conditions favorable for growth of perennial forage crops delay the development of cold hardiness (Smith, 1961; McKenzie and McLean, 1980). Conversely, hardening of perennial forage crops in fall is promoted by cool temperatures, which trigger the storage of assimilates in roots. Therefore, the level

**Abbreviations:** CDD5, cold degree-days below 5°C; DD0, degree-days above 0°C; DD5, degree-days above 5°C.

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

| Indices and variables | Description |
|---|---|
| **Agroclimatic indices** | |
| FH-COLD | Net accumulation of CDD5† during fall hardening period (CDD5) (V6 − V5) |
| FH-RAIN | Mean daily rainfall during fall hardening period (mm $d^{-1}$) (V7/V4) |
| W-THAW | Mean daily accumulation of DD0‡ during cold period (DD0 $d^{-1}$) (V14) |
| W-RAIN | Mean daily rainfall during cold period (mm $d^{-1}$) (V15) |
| W-COLD | Difference between days of snow cover and cold period (d) (V17) |
| **Variables used for the calculation of the agroclimatic indices** | |
| V1 | Date of first occurrence of minimum air temperatures ≤ −10°C |
| V2 | Sum of daily difference between CDD5 and DD5§ from 1 Aug. to day V1 − 1 (when V2 was < 0, then V2 was set = 0) |
| V3 | Date following last day when V2 = 0 |
| V4 | Length of fall hardening period (d) (V1 − V3) |
| V5 | Sum of DD5 from day V3 to day V1 − 1 |
| V6 | Sum of CDD5 from day V3 to day V1 − 1 |
| V7 | Sum of daily precipitations from day V3 to V1 − 1 (mm) |
| V8 | Date of first occurrence of minimum air temperature ≤ −15°C |
| V9 | Date of last occurrence of minimum air temperature ≤ −15°C |
| V10 | Length of cold period (V9 − V8) (d) |
| V11 | Sum of cold degree-days < −15°C from 1 Aug. to 31 July |
| V12 | Sum of DD0 from day V8 to day V9 − 1 |
| V13 | Sum of daily rainfall from day V8 to day V9 − 1 (mm) |
| V14 | Rate of accumulation of DD0 during cold period (DD0 $d^{-1}$) V12/V10) |
| V15 | Rate of rainfall accumulation during cold period (mm $d^{-1}$) (V13/V10) |
| V16 | Number of days with a snow cover of at least 0.1 m (d) |
| V17 | Difference between the number of days with a snow cover and the cold period (d) (V16 − V10) |
| **Additional variables used for the development of the snow cover model** | |
| V18 | Sum of CDD5 from 1 Aug. to day V1 − 1 |
| V19 | Rate of accumulation of V2 [(V6 − V5)/V4] |
| V20 | Date of first fall frost (≤0°C) |
| V21 | Photoperiod or daylength on day V20 (h) |
| 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 DD0 from 1 Jan. to day V9 − 1 (DD0) |
| V25 | Sum of DD0 from 1 Jan. to day V26 − 1 (DD0) |
| V26 | Date of last occurrence of minimum temperature ≤ 0°C |
| V27 | Sum of DD5 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) |

† CDD5, cold degree-days below 5°C.
‡ DD0, degree-days above 0°C.
§ DD5, degree-days above 5°C.

of cold hardiness reached at the onset of winter is the net result of the exposure to hardiness-promoting cool temperatures and to growth-promoting warm temperatures. The transition between growth and hardening processes of perennial forage crops as temperature declines in the fall accelerates when the mean air temperature decreases below 5°C (Paquin and Pelletier, 1980). Consequently, degree-days above 5°C (DD5) and cold degree-days below 5°C (CDD5) were used to express the impact of air temperature on growth and hardening, respectively. We assumed that any DD5 and CDD5 have equal but opposite effects on plant hardening. Therefore, any CDD5 accumulated in the fall could be negated by the subsequent occurrence of an equal amount of DD5. The net accumulation of CDD5 was calculated from 1 August to the end of the fall hardening period (V2; Table 1). The fall hardening period was set to begin at the latest date when the net accumulation of CDD5 = 0 and to end at the date of the first occurrence of a temperature ≤−10°C when plant foliage was assumed to die (V1, V3; Table 1). The net accumulation of CDD5 during the fall hardening period is referred to as FH-COLD (Table 1).

### Fall Hardening—Rainfall

Plants fail to harden properly under excessively wet soil conditions (Calder et al., 1965; Paquin and Mehuys, 1980). Evapotranspiration is low during fall, and soil moisture is closely related to rainfall. The mean daily rainfall during the hardening period (FH-RAIN) was therefore used as an index reflecting excessive soil moisture conditions during acquisition of cold hardiness (Table 1). Low soil water content also affects plant physiology and the acquisition of cold hardiness. However, these conditions were assumed to have a negligible impact on fall hardening of forage crops under the humid fall climate of eastern Canada.

## Winter Indices

Winter survival of cold-hardened plants is often affected by harsh winter climatic conditions (Ouellet, 1976). Causes of winter damage to perennial 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

Herbaceous plants at high latitudes survive low temperatures by limiting freezing to extracellular spaces. Extracellular freezing creates a gradient in vapor pressure between intra- and extracellular 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 desiccation, 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 depends on both the intensity and the duration of the exposure to cold temperatures. 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, 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 Quebec rarely goes below −14 to −15°C and, in some cases, only to −11 to −12°C (Paquin and Mehuys, 1980). In our study, −15°C was chosen as the temperature threshold. Plants of intermediate hardiness, such as alfalfa, red clover (*Trifolium pratense* L.), or orchardgrass (*Dactylis glomerata* L.), that tolerate extracellular freezing and experience cell desiccation are expected to undergo freezing damage below this temperature threshold. We defined the cold period as the duration in days between the first and last occurrence of air temperature ≤−15°C (V10; Table 1).

In eastern Canada, air temperature drops below this threshold every year, with minimum annual temperatures ranging from −20 to −44°C in areas where perennial forage crops are grown. The winter survival of perennial forage crops therefore depends on the protection of their roots and crown buds by adequate snow cover. Snow provides excellent insulation against variations in air temperature (Steppuhn, 1981). When snow cover is absent or inadequate, temperature at the crown level remains close to air temperature and can decrease to potentially damaging levels. On fine- and medium-textured soils, a minimum snow cover of 0.075 m was necessary to protect winter wheat (*Triticum aestivum* L.) from winterkill due to low air temperatures in southeastern North Dakota (Brun et al., 1986). In Saskatchewan, winter wheat and perennial forage grasses were protected from winterkill by a 0.1-m snow cover (Fowler and Limin, 1986), whereas a 0.2-m snow cover was required to prevent low-temperature injury to alfalfa (Jame et al., 1986). Leep et al. (2001) in Michigan concluded that a snow cover of 0.1 m adequately protects alfalfa from winter injury. In our study, the minimum depth of snow cover providing insulation against killing frosts was set to 0.1 m. The risk associated with the occurrence of a killing temperature in absence of a protective snow cover was expressed by the difference between the number of days with a snow cover ≥0.1 m and the length of the cold period (W-COLD; Table 1). A positive difference indicates that the duration of the period when perennial forage crops are protected by the snow exceeds that when low killing temperatures may occur. Conversely, a negative difference expresses the number of days when perennial forage crops are potentially exposed to freezing temperatures in the absence of sufficient snow insulation. This index is based on the assumption that both the snow cover period and the cold period are continuous and centered on the same date. Because of this assumption, it is worth noting that the index W-COLD does not provide a precise estimate of the level of risk, but it is used in relative terms to compare regions within a given period of time or periods of time for a given region.

### Dehardening

Fully acclimated perennial forage plants can maintain a high level of cold hardiness, provided crown temperatures remain below freezing and the plants have an adequate energy supply (McKenzie and McLean, 1980). Exposure to temperatures above 0°C in winter results in a gradual loss of cold hardiness (Sakai and Larcher, 1987) and increases the susceptibility to injury by subsequent exposure to low temperatures. Thus, the mean daily accumulation of degree-days above 0°C (DD0) during the cold period (W-THAW; Table 1) was used to express the potential loss of hardiness during winter.

### Soil Heaving and Ice Encasement

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 (Gudleifsson, 1993). Ice encasement of roots can also occur with associated physical damage to plant tissues. In imperfectly drained soils, these conditions may also result in damage to roots due to soil heaving (Portz, 1967). Perennial forage plants, with 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 favors deeper frost penetration and subsequent damage to roots. The mean daily rainfall accumulation during the cold period, hereafter referred as W-RAIN, was used as an index to express the risk of winter damage associated with ice sheeting, ice encasement, and soil heaving (Table 1).

## Calculation of Climatic Indices and Variables

A total of 33 variables and five agroclimatic indices previously described (Table 1) were calculated yearly at each selected weather station for the 1961 to 1990, 2010 to 2039, and 2040 to 2069 periods. Variables were computed over a two calendar-year period ranging from 1 August to 31 July and were averaged for each period across stations within each of 22 agricultural regions, described in the Climatic Data section, and across these agricultural regions.

The start of the hardening phase (V3; Table 1) was defined as the date when accumulated daily differences between CDD5 and DD5 beginning from 1 August (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 ≤−10°C (V1; Table 1). During the two future periods, if a minimum temperature ≤−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. Similarly, if a temperature ≤−15°C was not reached, V10 and V11 (Table 1) were set to zero, and V12 to V15 and V24 (Table 1) were not computed. V10 was set to 1 if there was only one occurrence of a temperature ≤−15°C.

## Climatic Data

### Weather Stations

The agricultural land in eastern Canada (42°02′ N to 49°24′ N and 52°47′ W to 89°20′ W) was divided into 22 agricultural regions (Table 2) based on agroclimatological characteristics and predominant crops. Sixty-nine weather stations were then selected, based on their representativeness of agricultural regions and 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 to 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.

**Table 2. Description of the agricultural regions and their respective weather stations included in the study.**

| Agricultural region (province) | Weather station | Elevation† | Latitude (N) | Longitude (W) |
|---|---|---|---|---|
| | | m | | |
| Harrow (ON) | Harrow CDA, Ridgetown, Sarnia A | 193 | 42°02′–43°00′ | 81°53′–82°54′ |
| Guelph (ON) | Brucefield, Guelph, London A, Mount Forest | 322 | 43°02′–43°59′ | 80°14′–81°33′ |
| Delhi (ON) | Brantford MOE, Delhi CDA | 214 | 43°08′–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°05′–44°14′ | 76°36′–78°22′ |
| Eastern Ontario-St. Lawrence Riv. (ON, QC) | Brockville PCC, Morrisburg, Saint-Anicet | 75 | 44°36′–45°08′ | 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°02′–82°26′ |
| South Quebec (QC) | Berthierville, Farnham, Lachute, Lennoxville CDA, Sainte-Clothilde CDA, Saint-Hyacinthe 2 | 70 | 45°10′–46°03′ | 71°49′–74°20′ |
| Central Quebec (QC) | Laurierville, Nicolet, Quebec 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°02′ |
| 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°01′ | 64°52′–65°28′ |
| Moncton (NB) | Fredericton CDA, Moncton, Sussex, Nappan CDA | 23 | 45°43′–46°06′ | 64°15′–66°37′ |
| Annapolis Valley (NS) | Clarence, Kentville CDA | 51 | 44°55′–45°04′ | 64°29′–65°10′ |
| Truro (NS) | Truro, Upper Stewiacke | 32 | 45°13′–45°22′ | 63°00′–63°16′ |
| Cape Breton (NS) | Baddeck, Collegeville, Port Hood | 37 | 45°29′–46°06′ | 60°45′–62°01′ |
| Prince Edward Island (PEI) | Charlottetown CDA, O'Leary | 31 | 46°15′–46°42′ | 63°08′–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.

## Climate Change Scenarios and Their Application to Current Climatic Data

Climate change scenarios for two future periods (2010–2039 and 2040–2069) were based on a 2001-year *transient* simulation by the first-generation Canadian Global Coupled General Circulation Model (CGCMI) that included the effects of aerosols (Boer et al., 2000). This simulation used an effective greenhouse gases forcing corresponding to that observed from 1900 to the present and a 1% increase per year 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-yr averages for each of 12 mo were extracted for 33 grid points covering all of eastern Canada, ranging from 38°58′ N to 50°06′ N and from 52°30′ W to 90°00′ W (Fig. 1). Grid spacing for the CGCMI is approximately 3.75° lat by 3.75° long. For temperature, we extracted the changes in monthly mean daily maximum and minimum air temperature for the two future periods with respect to the 1961 to 1990 period. For precipitation, we computed the mean daily precipitation rate (mm $d^{-1}$) for each month based on the observations in the 1961 to 1990 period and extracted the change in the precipitation rate for each of the two future periods. Monthly precipitation ratios were computed by dividing the rates for each of the future periods by the rate for the 1961 to 1990 period. The values for changes in monthly mean daily maximum and minimum air temperature and for monthly precipitation ratios 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 to 1990 period at each station were then adjusted to the 2010 to 2039 and 2040 to 2069 periods by applying the values for changes in monthly mean daily maximum and minimum air temperature and for monthly precipitation ratios 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

Rainfall (RAIN) and snowfall (SNOW) for the two future periods were estimated from daily precipitation ($P$) using the following formula:

$$\mathrm{RAIN} = F_r \times P$$

$$\mathrm{SNOW} = (1 - F_r) \times P$$

where $F_r$ is the fraction of total daily precipitation falling as rain, estimated as follows:

$$F_r = (T_r - T_{max})/(T_r - T_s);\ \text{if } T_{max} > T_r,\ F_r = 1.0;\ \text{if } T_{max} < T_s,\ F_r = 0$$

where $T_r$ and $T_s$ (°C) are threshold temperatures for rain and snow, respectively, and $T_{max}$ (°C) is the daily maximum temperature. Optimum threshold temperatures were determined for each station using all available observed data for which there was measurable precipitation from November to March within the period 1961 to 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. The estimation of rainfall from November to March over the 1961 to 1990 period from the partitioning of total precipitation using optimum $T_r$ and $T_s$ at each station gave biases ranging from $-4$ to 5 mm $yr^{-1}$ (average of $-0.3$ mm $yr^{-1}$). Values of $T_r$ ranged from 2.5 to 5.0°C, and those of $T_s$ ranged from 0 to 2.5°C. Optimum $T_r$ and $T_s$ values for each station were then used to partition daily precipitation into rainfall and snowfall for the 2010 to 2039 and 2040 to 2069 periods. A water equivalent ratio of 10:1 was assumed for snowfall.

## Snow Cover Model

Because variables V16 and V17 (Table 1) were not available for the two future periods, it was necessary to develop a snow cover model to estimate these variables. Variables V1 to V15 and V18 to V33 (Table 1) were calculated yearly from historic

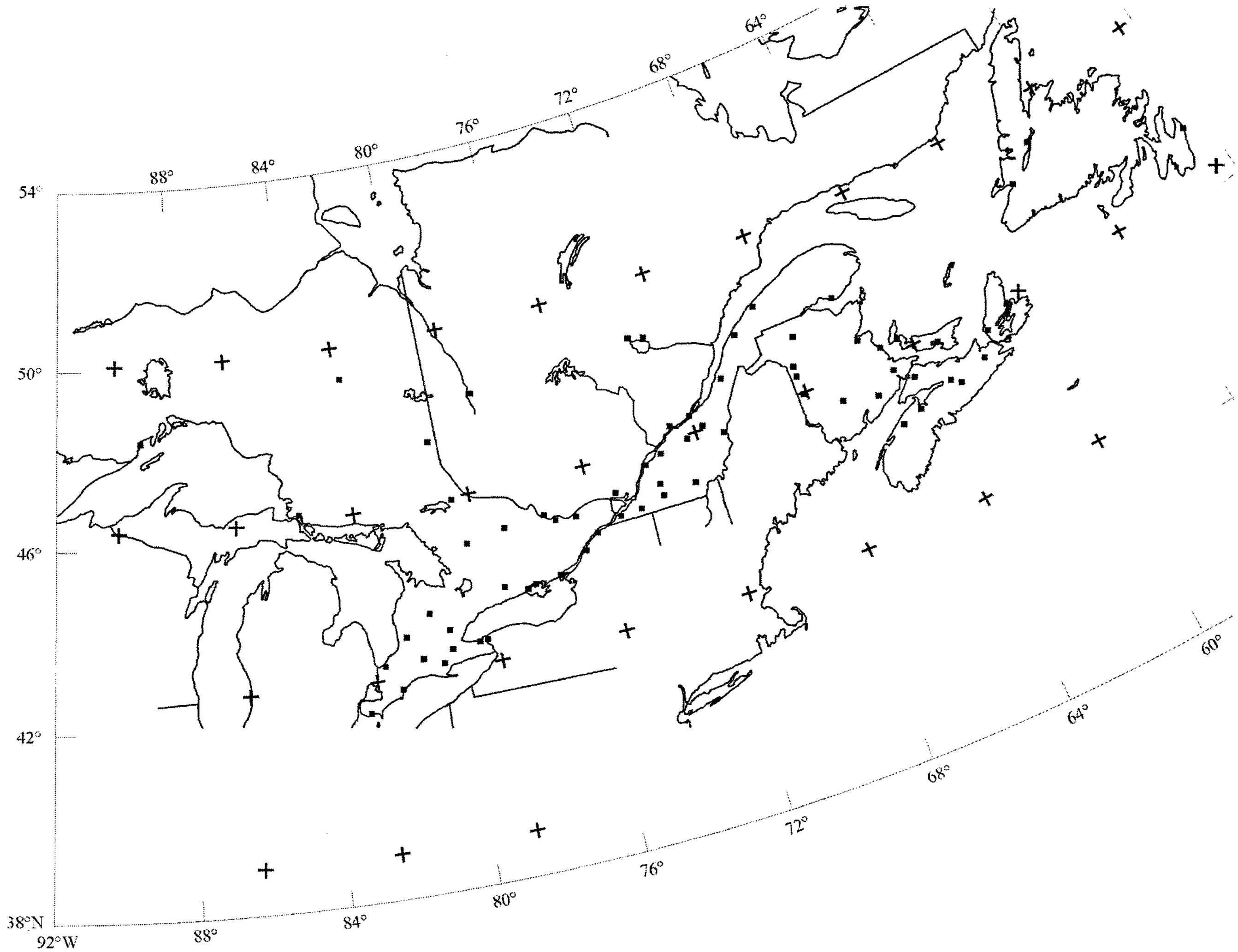


**Fig. 1. Distribution of 69 weather stations used for the study on the impact of climate change on the winter survival of perennial forage crops in eastern Canada. Grid points (+) of the Canadian Global Coupled General Circulation Model are also presented.**

climatic data (1961–1990 period) for 60 weather stations in eastern Canada and six stations in the USA (Baltimore, 39°10′ N, 76°41′ W; Concord, 43°12′ N, 71°32′ W; Indianapolis, 39°43′ N, 86°16′ W; Lexington, 38°02′ N, 84°36′ W; Nashville, 36°07′ N, 86°41′ W; and Newark, 40°43′ N, 74°10′ W; NCDC, 1995). Weather stations from the USA were added to include a wider range of snow cover, which may be experienced under future climate scenarios in eastern Canada. Daily snow cover data were not available for all years at some locations, and only years with measurable snow cover were used. Therefore, the number of years ranged from 1 to 30 per weather 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 the number of days where the depth of the snow cover is ≥0.1 m (V16; Table 1). First, a random sample of years and observations was 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 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 on 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 on 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, station effects were added to the model. Coefficients accounting for station effects were calculated as least square estimates from the GLM procedure in the Statistical Analysis System (SAS Inst., 1990). Parameters and coefficients of the resulting model are presented in Table 3. Based on 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 V16 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 weather stations (Ridgetown, Brucefield, Brockville PCC, Morrisburg, Chenaux, Kedgwick, Grand Falls Drummond, Centreville, and Sault Ste. Marie 2). For these locations, the average coefficient of the agricultural region 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 (V16).†**

| | | 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 |
| V6 | 0.27 | Guelph | −26.74 | Earlton A | −27.70 | La Pocatière CDA | −6.56 | Charlottetown CDA | −19.01 |
| V7 | 0.03 | London A | −31.30 | Kapuskasing CDA | −12.87 | Mont-Joli A | −25.92 | O'Leary | −14.78 |
| V10 | 0.38 | Mount Forest | −32.74 | Normandin CDA | −29.38 | Trois-Pistoles | −12.51 | Deer Lake | 8.68 |
| V12 | −0.28 | Brantford MOE | −11.84 | Péribonka | −23.98 | Aroostook | −14.35 | St. John's West CDA | −4.02 |
| V13 | −0.05 | Delhi CDA | −20.73 | Berthierville | 7.34 | Chatham A | −14.69 | Stephenville A | −15.50 |
| V14 | 6.40 | St. Catharines A | −32.12 | Farnham | −29.03 | Rexton | −16.83 | Thunder Bay A | −31.42 |
| V18 | −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 | Quebec 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*: $V16_i = 26.38 - 0.39V4_i + \dots \dots - 0.02V33_i$ + adjustment term for station *i*.
‡ See Table 1 for description of variables.
§ 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.

**Table 4. Values of agroclimatic indices and other variables of interest averaged across 22 agricultural regions in eastern Canada for the current 30-yr 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† | Mean | Min.‡ | Max.‡ | Mean | Min. | Max. | Mean | Min. | Max. |
| Fall indices | | | | | | | | | |
| FH-COLD, CDD5§ | 76.4 | 45.8 | 119.4 | 70.3 | 44.0 | 131.0 | 60.6 | 37.6 | 126.3 |
| 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 | | | | | | | | | |
| V3: Beginning of the hardening period, day and month | 1-11 | 15-10 | 16-11 | 6-11 | 22-10 | 22-11 | 11-11 | 25-10 | 27-11 |
| V1: End of the hardening period, day and month | 25-11 | 6-11 | 13-12 | 29-11 | 8-11 | 20-12 | 1-12 | 10-11 | 20-12 |
| V4: Length of the hardening period, d | 24.3 | 16.5 | 36.7 | 22.5 | 15.3 | 38.0 | 20.3 | 12.8 | 37.3 |
| V10: Length of the cold period, d | 94.5 | 44.9 | 138.7 | 80.0 | 5.3 | 134.2 | 70.7 | 1.8 | 131.2 |
| V16: 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 |

† See Table 1 for detailed description of indices and variables.
‡ Maximum and minimum values are based on averaged data for each agricultural region.
§ CDD5, cold degree-days below 5°C.
¶ DD0, degree-days above 0°C.

## RESULTS AND DISCUSSION

Mean, maximum, and minimum values of indices averaged across 22 agricultural regions of eastern Canada are presented for the current climate and climate change scenarios for two future periods (Table 4). For the sake of brevity, detailed results are presented for only five forage-producing regions spread across eastern Canada: Guelph, Continental North, South Quebec, Lower St. Lawrence–Gaspé Peninsula, and Moncton (Table 5; Fig. 2 and 3).

### Fall Indices

The hardening period in eastern Canada currently starts on 1 November and ends on 25 November (24.3 d; Table 4). By 2040 to 2069, the beginning of the hardening period would be delayed to 11 November and the end to 1 December. Accordingly, the length of the hardening period would be 17% shorter (20.3 d) by 2040 to 2069 (Table 4).

#### Fall Hardening—Temperature

The index 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 subfreezing temperatures. The value of FH-COLD is expected to decrease by 15.8 CDD5, 21% of the current value, by 2040 to 2069 in agricultural regions of eastern Canada mostly as a result of the shorter hardening period. All the selected forage-producing regions are expected to experience a decrease in FH-COLD ranging from 8.2 CDD5 in Moncton to 21.9 CDD5 in Guelph (Fig. 2).

The lower predicted decrease in FH-COLD in the Moncton region is due partly to the length of the harden-

**Table 5. Variables describing the hardening and the cold period of five forage-producing areas of eastern Canada for the current 30-yr 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 | | |
| Variables for each forage-producing region† | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. |
| **Guelph** | | | | | | | | | |
| V3: Beginning of the hardening period, day and month | 4-11 | 13-10 | 24-11 | 10-11 | 16-10 | 6-12 | 17-11 | 17-10 | 7-12 |
| V1: End of the hardening period, day and month | 28-11 | 23-10 | 21-12 | 2-12 | 23-10 | 5-1 | 4-12 | 29-10 | 20-1 |
| V4: Length of the hardening period, d | 23.5 | 1 | 52 | 21.6 | 1 | 53 | 17.5 | 1 | 56 |
| V10: Length of the cold period, d | 87.6 | 39 | 131 | 55.7 | 0 | 130 | 37.5 | 0 | 129 |
| V16: 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** | | | | | | | | | |
| V3: Beginning of the hardening period, day and month | 15-10 | 23-9 | 11-11 | 22-10 | 26-9 | 12-11 | 25-10 | 30-9 | 12-11 |
| V1: End of the hardening period, day and month | 7-11 | 15-10 | 27-11 | 10-11 | 18-10 | 1-12 | 11-11 | 19-10 | 9-12 |
| V4: Length of the hardening period, d | 23.5 | 1 | 53 | 19.3 | 1 | 53 | 17.3 | 2 | 53 |
| V10: Length of the cold period, d | 138.7 | 99 | 177 | 134.2 | 98 | 166 | 131.2 | 89 | 166 |
| V16: 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 Quebec** | | | | | | | | | |
| V3: Beginning of the hardening period, day and month | 31-10 | 8-10 | 24-11 | 6-11 | 13-10 | 29-11 | 10-11 | 17-10 | 30-11 |
| V1: End of the hardening period, day and month | 22-11 | 20-10 | 18-12 | 23-11 | 29-10 | 18-12 | 26-11 | 5-11 | 18-12 |
| V4: Length of the hardening period, d | 21.8 | 1 | 60 | 17.5 | 1 | 48 | 16.0 | 1 | 48 |
| V10: Length of the cold period, d | 104.7 | 67 | 130 | 96.8 | 48 | 129 | 88.7 | 42 | 129 |
| V16: 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–Gaspé Peninsula** | | | | | | | | | |
| V3: Beginning of the hardening period, day and month | 24-10 | 4-10 | 12-11 | 29-10 | 7-10 | 14-11 | 3-11 | 13-10 | 20-11 |
| V1: End of the hardening period, day and month | 24-11 | 3-11 | 21-12 | 26-11 | 8-11 | 21-12 | 29-11 | 11-11 | 23-12 |
| V4: Length of the hardening period, d | 30.3 | 4 | 62 | 28.4 | 2 | 60 | 26.4 | 3 | 65 |
| V10: Length of the cold period, d | 100.7 | 59 | 131 | 90.5 | 54 | 121 | 79.1 | 4 | 121 |
| V16: 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** | | | | | | | | | |
| V3: Beginning of the hardening period, day and month | 3-11 | 8-10 | 18-11 | 7-11 | 17-10 | 19-11 | 10-11 | 19-10 | 30-11 |
| V1: End of the hardening period, day and month | 23-11 | 20-10 | 16-12 | 26-11 | 22-10 | 21-12 | 29-11 | 22-10 | 21-12 |
| V4: Length of the hardening period, d | 20.1 | 2 | 49 | 19.3 | 3 | 48 | 19.1 | 2 | 40 |
| V10: Length of the cold period, d | 98.5 | 65 | 148 | 89.7 | 49 | 123 | 85.8 | 49 | 119 |
| V16: 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 |

† See Table 1 for detailed description of variables.

ing period, which is expected to be only 1 d shorter by 2040 to 2069 compared with a decrease of 4 d in the Lower St. Lawrence–Gaspé Peninsula and 6 d in Guelph, Continental North, and South Quebec (Table 5). In addition, the higher decrease in FH-COLD predicted for Guelph, Continental North, and South Quebec is associated with a greater increase in mean air temperature during the hardening period (>2.0°C) than in the Lower St. Lawrence–Gaspé Peninsula (1.8°C) and Moncton (1.7°C).

Hardening of perennial plants is closely associated with 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 4 wk of hardening under a constant temperature of 1.0°C (Paquin, 1977), and timothy (*Phleum pratense* L.) reached a maximum frost tolerance of −19°C after 4 wk of constant exposure to a temperature of 1.5°C (Paquin and Saint-Pierre, 1980). The accumulation of CDD5 during that period (98–112 CDD5; average = 105) was therefore used as the reference for optimum fall hardening conditions.

Because of the moderating effect of the St. Lawrence River on prevailing fall temperatures, the Lower St. Lawrence–Gaspé Peninsula currently enjoys a longer hardening period (Table 5) with a greater accumulation of CDD5 than the other four forage-producing regions (Fig. 2). The 110 CDD5 occurring in that region during the hardening phase corresponds to 105% of the optimum conditions for fall hardening (105 CDD5); hence, under average climatic conditions, perennial forage crops would be expected to fully harden before minimum temperature reaches −10°C. Current FH-COLD in the other four regions range from 58% of optimum conditions for fall hardening in Moncton to 72% in Guelph. As a result of the warming of fall temperatures, FH-COLD by 2040 to 2069 is predicted to decrease to 91% of the reference in the Lower St. Lawrence–Gaspé Peninsula, 51% in Guelph, 50% in Moncton, 48% in Continental North, and 45% in South Quebec. Consequently, all regions of eastern Canada would experience future fall climatic conditions that would result in lower level of cold hardiness than under the current climate. Furthermore, these values would be well below the optimum accumulation of CDD5 required to fully harden perennial forage crops and may result in greater winterkill.

## Fall Hardening—Rainfall

The index FH-RAIN is expected to decrease from the current average of 2.97 to 2.75 mm $d^{-1}$ for the 2040 to 2069 period (Table 4). Hence, fall hardening conditions across agricultural regions of eastern Canada would be slightly drier by 2040 to 2069 (Table 4). The largest decrease in FH-RAIN among the forage-producing regions is likely to be experienced in South Quebec (0.34 mm $d^{-1}$), whereas the smallest decrease is predicted to occur in Moncton (0.05 mm $d^{-1}$) (Fig. 2).

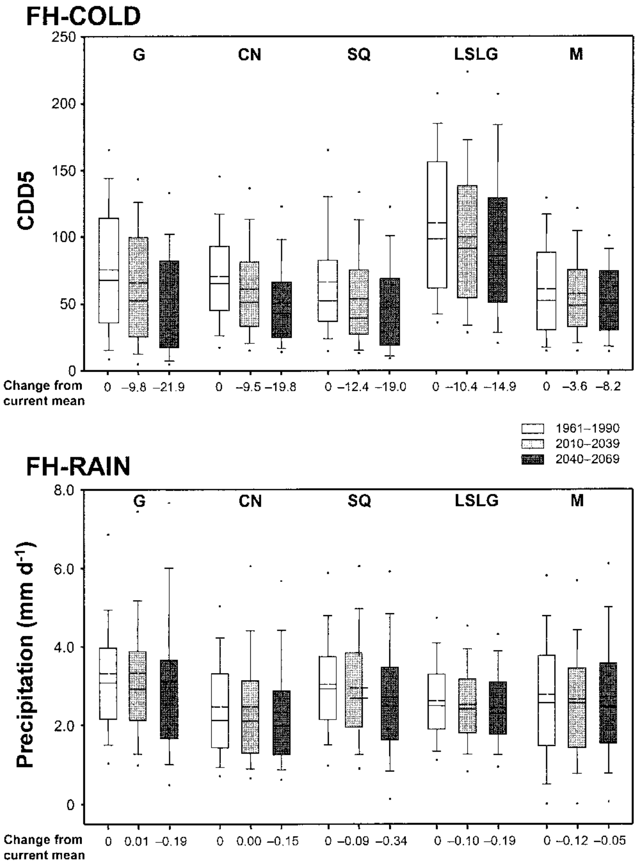


**Fig. 2. Fall indices in five forage-producing regions of eastern Canada for current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles, respectively; and dots below and above whiskers indicate the 5th and 95th percentiles, respectively. Indices are described in Table 1. CDD5, cold degree-days below 5°C; G, Guelph; CN, Continental North; SQ, South Quebec; LSLG, Lower St. Lawrence–Gaspé Peninsula; M, Moncton.**

During fall, plants fail to harden properly under high soil-moisture conditions (Paquin and Mehuys, 1980). The FH-RAIN is currently 2.47 mm $d^{-1}$ in Continental North, 2.62 in the Lower St. Lawrence–Gaspé Peninsula, 2.77 in Moncton, 3.04 in South Quebec, and 3.32 in Guelph. Assuming that soil moisture is the same in each region at the onset of the hardening period, hardening of forage crops would proceed under more favorable 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 <7% of the current values, and changes of this magnitude will not likely have significant effects on fall hardening of forage plants.

## Winter Indices

Climate change is predicted to considerably modify winter conditions in eastern Canada. The coldest daily minimum temperature during winter would increase by 4.8°C by 2040 to 2069; the greatest increases (>6°C) are expected predominantly in regions located in southern

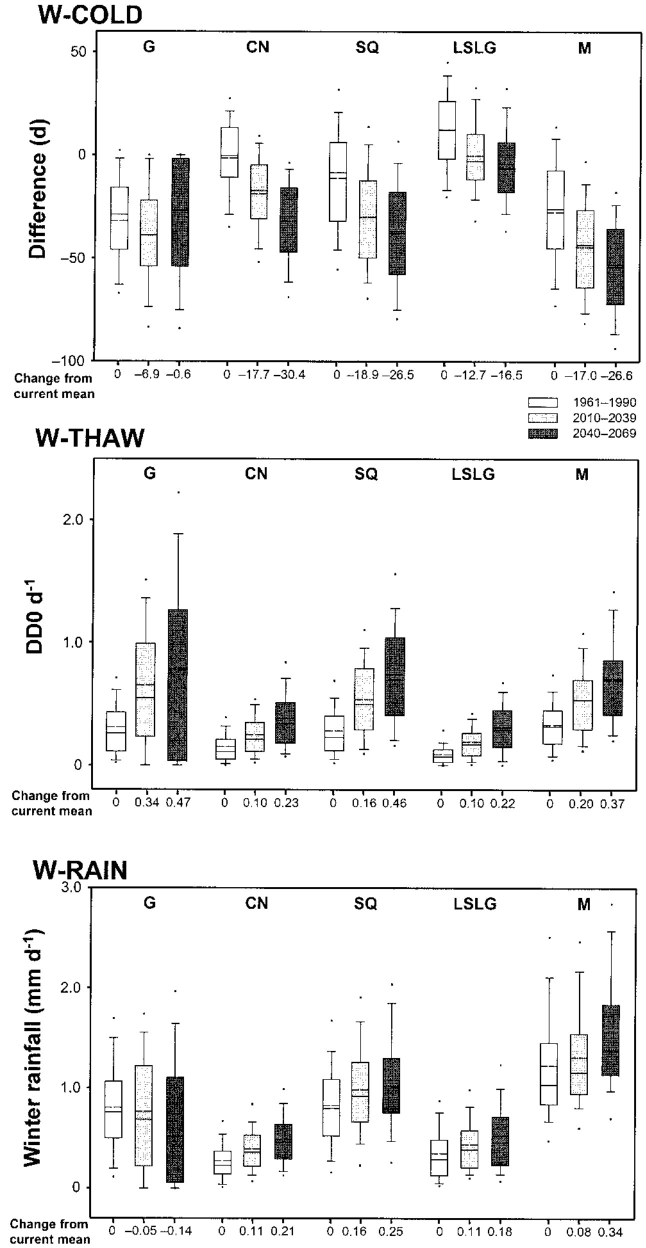


**Fig. 3. Winter indices in five forage-producing areas of eastern Canada for current climate and future climate scenarios. Lower and upper boundaries of box indicate 25th and 75th percentiles, respectively; plain and dashed lines within box indicate median and mean, respectively; whiskers below and above box indicate the 10th and the 90th percentiles, respectively; and dots below and above whiskers indicate the 5th and 95th percentiles, respectively. Indices are described in Table 1. DD0, degree-days above 0°C; G, Guelph; CN, Continental North; SQ, South Quebec; LSLG, Lower St. Lawrence–Gaspé Peninsula; M, Moncton.**

Ontario while the smallest increases (<4°C) would occur in regions located in the southern part of the Atlantic provinces of Canada. The mean daily temperature for the period between 1 November and 30 April is expected to increase by 1.9°C by 2010 to 2039 and by 3.3°C by 2040 to 2069 (data not shown). As a result, the current average length of the cold period (94.5 d) is expected to decrease by 23.8 d in eastern Canada (Table 4).

General circulation models are not predicting large differences in total precipitation between 1 November and 30 April for the future periods. However, a greater proportion of the precipitation will be as rain because of the warmer temperatures. Cumulated rainfall between 1 November and 30 April would increase by 43.9 mm by 2010 to 2039 and by 83.0 mm (32% increase from current) by 2040 to 2069 (data not shown). The average snowfall is predicted to decrease from the current 232 cm to 179 cm by 2010 to 2039 and to 157 cm by 2040 to 2069 (data not shown). Accordingly, the number of days with a snow cover ≥0.1 m would decrease from the current 82.3 d in eastern Canada to 56.4 d by 2010 to 2039 and to 42.9 d by 2040 to 2069 (Table 4).

**Cold Intensity and Duration**

The threat related to subfreezing temperatures in the absence of a protective snow cover was expressed by W-COLD. Under current climatic conditions, the number of days with a snow cover exceeds or equals the period of prevailing subfreezing temperatures (W-COLD ≥ 0) in the Continental North and in the Lower St. Lawrence–Gaspé Peninsula (Fig. 3). In the other areas, plants are exposed to potentially harmful temperatures during the cold period (W-COLD < 0) for 12 d in South Quebec, 28 d in Moncton, and 32 d in Guelph. These values of W-COLD are in agreement with the occurrence of winter damage to forage crops. For example, during 1985 to 1999, an annual average of 63% of the alfalfa superficies insured by the Quebec Crops Insurance Program incurred losses due to winterkill in South Quebec compared with only 19% in the Lower St. Lawrence–Gaspé Peninsula (S. Pion, Quebec Crops Insurance Program, personal communication, 2001). Under climate change, W-COLD is expected to decrease from the current average of −12.1 to −23.7 d by 2010 to 2039 and to −27.8 d by 2040 to 2069 (Table 4), thus leading to increased risk of winter damage as plants would be more likely exposed to subfreezing temperatures in the absence of snow cover.

Climate change would increase the risk of damage to perennial forage crops by low temperatures in eastern Canada as W-COLD will decrease in all regions but Guelph where it will remain constant. The largest decreases in W-COLD by 2040 to 2069 would occur in Continental North (30.4 d), Moncton (26.6 d), and South Quebec (26.5 d) (Fig. 3). Significant increases in winterkill of forage crops could therefore be expected in these regions as a result of global warming. The W-COLD would also decrease in the Lower St. Lawrence–Gaspé Peninsula during the same period. However, W-COLD will remain close to zero (−4.3 d), and the risk for winter damage would still be relatively low. Guelph is the only region where W-COLD would not decrease as both the length of the cold period (V10) and the number of days with a snow cover ≥0.1 m (V16) are estimated to decrease at the same rate in this region (Table 5).

The value of W-COLD is determined from the length of the cold period (V10) and the number of days with snow cover of at least 0.1 m (V16). The length of the cold period (V10) would be affected by warming of winter temperatures as is the case in Guelph where V10 is expected to decrease by as much as 50 d by 2040 to 2069 compared with a decrease of 21.6 d in the Lower St. Lawrence–Gaspé Peninsula, 16 d in South Quebec, 12.7 d in Moncton, and 7.5 d in Continental North (Table 5). This marked decrease of V10 in the Guelph area is correlated with 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 Quebec, from −16.5 to −11.6°C in the Lower St. Lawrence–Gaspé Peninsula, and from −15.4 to −11.8°C in Moncton (not shown). Because snow cover depends on ambient temperature for its establishment and maintenance, increased air temperatures above 0°C would result in reduced duration of snow cover (V16). The average mean daily temperature from 1 November to 30 April (V31) in the Guelph region is expected to increase from the current −2.0°C to 2.4°C by 2040 to 2069 (not shown). This indicates that temperatures > 0°C may be more frequent under climate change scenario and might explain the noticeable decrease of V16 by 50.6 d in the Guelph region (Table 5).

**De-hardening**

Warmer winter temperatures under climate change would result in an increase of W-THAW from the current 0.27 to 0.59 DD0 per day by 2040 to 2069 (Table 4). Currently, W-THAW ranges from 0.09 DD0 $d^{-1}$ in the Lower St. Lawrence–Gaspé Peninsula to 0.33 DD0 $d^{-1}$ in the Moncton region (Fig. 3). By 2040 to 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–Gaspé Peninsula and the Continental North would experience the smallest increase in W-THAW. By 2040 to 2069, however, predicted values of W-THAW in these two regions would be similar to the values currently experienced in the other three forage-producing regions. The W-THAW would reach 0.70 DD0 $d^{-1}$ in Moncton, 0.74 DD0 $d^{-1}$ in South Quebec, 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 hardiness during winter, particularly as snow cover is expected to diminish and may no longer be adequate to isolate forage plants from freeze–thaw cycles.

**Soil Heaving and Ice Encasement**

The value of W-RAIN in eastern Canada is expected to increase from the current 0.86 mm $d^{-1}$ to 0.98 mm $d^{-1}$ (Table 4). Hence, the risks of winter damage due to ice will likely increase under climate change scenario. Damage due to ice is rather infrequent in Continental North and in the Lower St. Lawrence–Gaspé Peninsula under current climate conditions; W-RAIN in these regions is currently low, 0.28 and 0.35 mm $d^{-1}$, respectively (Fig. 3). Heavy losses of alfalfa stands due to frost heaving frequently occur in the Atlantic provinces of Canada

(Grant and Saini, 1973); this is reflected by a current value of W-RAIN of 1.23 mm $d^{-1}$ in Moncton. By 2040 to 2069, W-RAIN would increase to 0.49 mm $d^{-1}$ in Continental North, 0.53 in Lower St. Lawrence–Gaspé Peninsula, 0.66 in Guelph, 1.08 in South Quebec, and 1.56 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 to 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 subfreezing temperatures. Warming of winter temperatures is expected to significantly decrease snow cover across eastern Canada, and this is likely to contribute to increasing the ice damage to the root system of perennial forage plants.

## Agronomic Implications

The agroclimatic indices developed and used in this study were not crop specific. Hence, our conclusion of increased risk of winter damage applies to all perennial forage species used in eastern Canada and the neighboring regions. However, some perennial forage species grown in eastern Canada are more sensitive to winter climatic conditions than others. For instance, alfalfa and orchardgrass are more susceptible to harsh winter conditions than is timothy. Consequently, the winter survival of those winter-sensitive species is more likely to be affected by climate change.

Our analysis of the impact of climate change is based on the current set of agronomic practices, species, and cultivars. Agronomic practices and cultivars will likely be different in the future, and this in turn will modify the impact of climate change on the winter survival of perennial forage crops. As an example, more winter hardy cultivars might be available in the future, and this would reduce the increased risk of winter damage due to climate change.

Spatially distributed or regionally average predictions of quantitative amounts of winter injury were not possible in our study because of the lack of quantitative data on forage crops. Reliable quantitative information on the area of forage crops and the levels of injury in the different regions of eastern Canada is not available.

# CONCLUSIONS

Under the climate change scenarios used in our study, all parts of eastern Canada will likely experience substantial modification in agroclimatic conditions that will affect 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 risks of winter damage to perennial forage crops are expected to increase because of (i) warmer fall temperatures, which would prevent adequate fall hardening; (ii) loss of cold hardiness during winter; and (iii) significant loss of snow cover protection, which will likely increase risks of damage due to subfreezing temperatures and ice.

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