IMPACTS OF FREEZING TEMPERATURES ON CROP PRODUCTION IN CANADA[1]

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Subzero temperatures are the most widespread hazard to crop production in Canada. This hazard ranges from temperature occurrences near 0°C in spring and fall that damage many annual crops and some perennials to the winter occurrences of −30°C and lower that damage or kill vegetative and/or reproductive tissues of some perennial species. Terminology, types of freeze damage, and the freeze risk are reviewed and discussed here along with some examples of the occurrence and adverse impact of freezing temperatures for the range of annual, winter annual and perennial crops grown in Canada. Spring grain losses from freeze damage occur about once every 3–4 yr in Saskatchewan, less frequently in Alberta (except the Peace River region), Manitoba and the northern clay belts in Ontario and Quebec, and seldom in the remainder of eastern Canada. Frequency of canola losses on the Prairies has been similar to cereals over the past 10–12 yr. The availability of short-season corn and soybean cultivars has expanded the production of these crops to areas with fewer than 2300 heat units over the last 20 yr. This has resulted in more frequent losses of these crops from fall freezes. Major losses of seed-corn occurred in southwestern Ontario on three occasions from 1965 to 1974, but very little freeze damage has occurred since 1974. Losses of vegetable crops from freezing occur less frequently than other crops because of the well-established cultural practices developed over the years that avoid or protect from frost. The high value per unit area of most vegetables makes freeze protection more affordable when needed. Forages and winter annuals are killed more frequently in central and eastern Canada by smothering and desiccation from formation of ice sheets than from low winter temperatures. Injury to young shoots and leaf buds of these crops occurs periodically from spring freezes. Losses of fruit trees occur periodically and apparently occurred more frequently 20–35 yr ago in British Columbia, whereas losses have been more severe in recent years in eastern Canada. Major declines in tender fruit production occur once or twice every 5–10 yr depending on location. Temperatures of −30°C or lower may kill the tender fruit trees and −25°C may damage the buds in winter, although late spring frosts during bloom reduce production more frequently.

Key words: Frost hazard, crop losses, indemnities

[Incidence des températures de congélation sur les cultures au Canada.]
Titre abrégé: Incidence des températures de congélation.
Au Canada, les températures inférieures au point de congélation constituent le danger le plus généralisé pour les cultures. Cela va des températures avoisinant zéro, au printemps et à l'automne, qui causent des dégâts à de nombreuses annuelles et à quelques vivaces jusqu'aux températures hivernales de −30°C et davantage qui endommagent

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ou détruisent les tissus végétatifs ou reproducteurs de certaines vivaces. Dans le présent article, les auteurs expliquent la terminologie utilisée, les types de dégâts causés par le gel et les risques de gel et donnent des exemples de la fréquence et de l'incidence néfaste des températures de congélation pour tout l'éventail de cultures annuelles, annuelles d'hiver et vivaces, pratiquées au Canada. Des pertes printanières de céréales dues au gel surviennent environ une fois tous les trois ou quatre ans en Saskatchewan, moins fréquemment en Alberta (sauf dans le bassin de la rivière de la Paix), au Manitoba et dans les enclaves argileuses du nord de l'Ontario et du Québec, mais rarement dans le reste de la partie orientale du Canada. La fréquence des pertes de canola dans les Prairies a été à peu près la même que pour les céréales au cours des dix à douze dernières années. L'existence, maintenant, de cultivars de maïs et de soja à cycle court a élargi, depuis vingt ans, la production de ces cultures à des régions ayant moins de 2300 unités thermiques. Cela a accru la fréquence des pertes causées à ces cultures par les gels automnaux. Les pertes de maïs-grain dans le sud-ouest de l'Ontario ont été graves à trois occasions de 1965 à 1974, mais elles sont négligeables depuis 1974. Pour les cultures maraîchères, les pertes sont moins fréquentes que dans les autres cas, à cause des pratiques culturales bien établies au fil des années en vue d'éviter des pertes ou de protéger ces cultures contre le gel. Étant donné la valeur élevée par unité de surface de la plupart des légumes, il est plus rentable de les protéger quand cela s'avère nécessaire. Dans le centre et dans l'est du Canada, les plantes fourragères et les vivaces hivernales meurent plus souvent par suffocation et desiccation dues à la formation de couches de glace que de la rigueur des températures hivernales. De plus, les gels printaniers infligent périodiquement des dégâts aux jeunes pousses et aux bourgeons foliaires de ces cultures. Quant aux pertes de vergers, elles se produisent périodiquement. Apparemment, elles étaient plus fréquentes en Colombie-Britannique il y a 20 à 35 ans de cela, tandis que, ces dernières années, c'est l'Est qui est le plus durement touché. La production de fruits tendres est frappée une ou deux fois tous les 5–10 ans, tout dépendant du lieu. Des températures de −30°C du moins peuvent tuer les jeunes arbres fruitiers et, de −25°C peuvent endommager les bourgeons en hiver, bien que la production souffre plus fréquemment des gels printaniers qui surviennent tardivement durant la floraison.

Mots clés: Dangers du gel, pertes de cultures, indemnités

Temperatures below the freezing point of water present the most widespread hazard to crop production in Canada. The danger of freezing injury to crops exists in every month of the year in the northern fringe areas of production and the length of the frost-free season imposes a limit to the crop species and cultivars that can be grown. Of the 46.1 million hectares of improved land (Statistics Canada 1981) there is only a small area in southwestern British Columbia that is frost-free most of the year. The problem is of two main types — occurrence of air temperatures at or below freezing during the growing season and much lower air temperatures during the dormant period in winter.

Our objective in this paper is to summarize the adverse impacts of freezing temperatures in Canada for annuals, winter annuals and perennials. Examples of recorded freeze losses of these crop groups in different parts of the country will be highlighted, demonstrating these adverse impacts. The terminology and detail on the types of freeze damage, and sources of information on frost dates and risk of damage are reviewed before summarizing and discussing the impacts.

BACKGROUND

Terminology

The terms frost and freeze are often used interchangeably. However, the word "freeze" should be used for subfreezing temperature conditions that cause crop damage, and has the same meaning as "killing frost". Whereas, "frost" refers to the condition that exists when air temperatures drop to 0°C, or lower, but which may or may not result in freeze damage to crops (Bootsma and Brown 1985).

Types of Freeze Damage

Temperatures 25–30°C below the freezing point of water are a problem in winter during the dormant period of the winter annual and perennial crops and −1 to −5°C temperatures create a threat to both annual and perennial crops during the growing season. Injury to crops like winter annual grains, alfalfa, and strawberries results from soil heaving due to thawing and freezing where there is insufficient snow cover. Flower bud and trunk damage to tree fruits and grapes in winter is another common low winter temperature problem. The latter has been documented by Mercier and Chapman (1956) and more recently by Fisher (1978) and Brown and Wyllie (1980). Early spring frosts often damage the buds and young shoots of crops like alfalfa and winter wheat when the temperature drops to −2°C or lower after these crops begin regrowth in the spring.

Late spring or early summer frosts sometimes damage seedlings or transplants of tender annuals and blossoms of perennial fruit crops. Frost injury of this type on crops such as corn, beans, tomatoes and tobacco, occurs fairly infrequently as most farmers and gardeners are aware of the safe dates of planting these crops in their region. When annuals are frozen, some are usually killed outright and have to be replanted while corn usually is killed back only to the soil surface and regrows because the growing point remains below the surface to about the sixth leaf stage. The frequency of damage to fruit blossoms depends on the species, early spring conditions, location and exposure of the plants, orchards or vineyards and to some extent on management and cultural practices.

Midsummer frosts are a constant threat to crops in the northern fringe farming areas. In the well-established grain-producing regions of the Prairies, the development period of crops such as spring grains and canola are often reduced by late summer or early autumn frosts. Frosts during the latter part of the growing season are a hazard in regions where crops such as tobacco, soybeans, corn, tomatoes, potatoes, peppers, and other tender horticultural crops are grown.

Late fall freezes sometimes cause losses of potato tubers too near the soil surface, of apple fruit before harvest, and of fruit trees that have not hardened-off for the dormant period.

Growing Season Frost Dates and Risk of Damage

Most farmers and growers are aware of the probable time of last spring and first fall frosts for their area and plant their annual crops accordingly. Some are prepared to provide freeze protection at that time for the crops with a high value per unit area, when needed. Maps showing the average dates of last spring and first fall frosts are presented in all provincial and regional climate publications (e.g., McKay et al. 1967; Brown et al. 1968; Dzikowski 1983) and in several national climate publications (e.g., Chapman and Brown 1966; Agriculture Canada 1976). There are two empiricisms that are used in Ontario to estimate the probabilities or "odds" of crops being damaged by frost. The first applies to the average dates of occurrences of 0°C in spring and fall. The average date is usually close to the 50% probability date. This probability can be reduced to 25 and 10% by any actions that will protect crops for 1 and 2 wks, respectively, later in spring and earlier in fall than the average dates. The second empiricism applies to temperatures below 0°C. The average date of occurrence of the last −1.0°C and −2.0°C minimum temperatures in spring are about one and two weeks respectively, before the average date of the last 0°C. The same intervals can be applied in the fall, but later than the average first 0°C occurrence. Using these empiricisms could help growers in avoiding freeze injury or planning for freeze protection.

MATERIALS AND APPROACH

The database used in this study is derived from two sources. The first is from a survey conducted to investigate the occurrence, range and frequency of crop losses caused by freezing temperatures in Canada's agricultural regions, between 1960 and 1969 (Brown and Baier 1970b); the second is from a collection of crop loss data between 1974 and 1985 obtained from provincial Crop Insurance Commissions. Analyses of these data emphasize regional diversities in low temperature effects on the production of both annual and perennial crops, the variability in losses, and the economic impact such losses have on Canadian agriculture.

OCCURRENCE AND IMPACT OF FREEZING TEMPERATURES

A general overview of crop losses caused by growing season frosts and from winterkill is provided for Alberta on an annual basis (Table 1) and for New Brunswick on a crop basis (Table 2) as information from these two provinces was reported in this manner. Growing season frosts can result in freezes that cause significant crop losses. Data for Alberta indicate that up to 24% of crop losses can be the result of injury from frost (Table 1). The variability of frost damage among years is clearly demonstrated with four of the 8 yr experiencing significant losses. Significant losses in New Brunswick were attributed to growing season frosts and winterkill of strawberry and apple over the ten-year period up to 1984 (Table 2).

Annuals

Temperatures of −2°C or lower are of con-

Table 1. Indemnities for crop losses caused by growing season (GS) freezes and winterkill† and the percent of the total crop insurance indemnities, on an annual basis in Alberta

Year	$ GS freezes	% of total	$ winterkill	% total
1978	2 233 866	16.16		
1979	74 295	0.53		
1980	3 444 743	24.43		
1981	69 154	0.53		
1982	5 183 466	17.59		
1983	344 038	0.69		
1984	793 981	0.47	140 406	0.08
1985	12 521 053	5.32	3 852 843	1.64

Source: Alberta Hail and Crop Insurance Corporation.
†Winterkill may result from below 0°C or smothering and desiccation due to ice sheet formation in winter or early spring.

Table 2. Indemnities for crop losses caused by growing season (GS) freezes and winterkill† and the percent of the total crop insurance indemnities by crop for different periods of years in New Brunswick

Years	Crop	$ GS freezes	% of total	$ winterkill	% total
1974–1984	Apple	9 585	19.0	7 373	14.8
1975–1984	Strawberry	60 259	22.4	142 077	52.8
1980–1984	Spring wheat	—	0	NA	NA
1980–1984	Barley	—	0	NA	NA
1980–1984	Oats	—	0	NA	NA
1980–1984	Mixed grain	—	0	NA	NA
1983–1984	Processing bean	—	0	NA	NA
1983–1984	Potato (seed)	108 619	1.06	NA	NA
	(Red pontiac)	4 080	0.04	NA	NA
	Regular-round	192 084	1.87	NA	NA
	Regular-russet	151 162	1.47	NA	NA

Source: New Brunswick Crop Insurance Commission.
†Winterkill may result from below 0°C or smothering and desiccation due to ice sheet formation in winter or early spring.
NA = not applicable.

Table 3. Indemnities for crop losses caused by growing season freezes in Saskatchewan

Year	$ for cereals†	$ for oilseeds‡	$ for other crops§
1974	11 144 909	760 849	1 525 153
1975	764 682	104 220	40 476
1976	13 498	962	3 432
1977	3 563 522	660 350	437 910
1978	2 019 905	174 748	103 591
1979	12 144 580	5 507 041	1 011 107
1980	1 861 013	1 396 843	289 371
1981	88 341	71 958	15 559
1982	13 437 346	4 806 677	1 649 776
1983	60 087	885	2 183
1984	93 198	29 028	9 643
1985	5 061 608	2 523 267	1 028 993
Total	50 252 689	16 036 828	6 117 194

†Cereals include: spring wheat, durum wheat, utility wheat, oats, barley, fall rye, spring rye.
‡Oilseeds include: canola (rapeseed), sunflower.
§Other includes: flax, mustard, field peas, lentils, canary seed, fababeans.
Source: Saskatchewan Crop Insurance Corporation.

cern for spring grains, canola and the hardiest annual vegetables, like peas, carrots, beets and cole crops. Temperatures of 0 to −1°C cause losses of tender annuals like tomatoes, cucumbers, etc. For this paper, we have attempted to determine the frequency of occurrence of losses in production of annual crops caused by below freezing temperatures and the economic impact for spring grains, corn, certain oilseed crops and vegetables.

SPRING GRAINS. Spring cereals are the most extensively grown crops in Canada. Most of this production occurs in areas with a frost-free season of 90 d or more (Chapman and Brown 1966; Edey 1977), although the Peace River region and the northern clay belts in Ontario and Quebec lie north of this isoline.

Sensitivity of cereal plants to low temperatures is quite variable. Temperatures lower than −9°C are lethal at all stages of crop development, but a light freeze (0 to −1°C) can damage floral parts at anthesis. Immature grain can be damaged at temperatures below −2°C depending on the moisture content of the grain and the duration of the freeze.

Both spring and fall frosts have reportedly caused damage to spring grains in the Prairies, but no losses have been reported in the production areas in eastern Canada or British Columbia where the mean frost-free season is longer than 100 days (Brown and Baier 1970a). The Crop Insurance Commission in Manitoba and Saskatchewan reports considerable losses in three of the last 12 years (Tables 3 and 4). Indemnities for cereals for losses caused by freezes in Saskatchewan, for example, ranged from $11 M to $13 M in 1974, 1979 and 1982. The freeze in 1982 occurred on 28 Aug. and losses for cereals totalled approximately $13.4 M in Saskatchewan (Table 3) and $1.6 M in Manitoba (Table 4). Of these totals, about $8.9 M and $3.3 M were losses due to the freezing of spring wheat and barley, respectively, for Saskatchewan, and similarly, $0.3 M and $0.9 M for Manitoba.

CORN GRAIN/SEED/SILAGE. This crop is largely confined to southern Ontario, southern Québec and southern Manitoba where the frost-free season is long enough and at least 2300 corn heat units (CHU) accumulate during the growing season. Corn grown for feed grain is confined to these regions since all hybrids require at least 2400 CHU for the grain to reach physiological maturity. Most of the seed corn produced in Canada is grown in regions with more than 2700 CHU. Silage corn is also grown in southern Alberta and in the Atlantic region, especially Nova Scotia. The area of corn could expand consider-

Table 4. Indemnities for crop losses caused by growing season freezes in Manitoba

Year	$ for cereals†	$ for oilseeds‡	$ for other crops§
1975	42 823	13 487	20 689
1976	0	0	983
1977	67 172	20 376	85 160
1978	27 611	12 668	97 702
1979	128 556	119 471	360 635
1980	1 407 278	1 248 748	1 193 311
1981	1 426		51 198
1982	1 644 022	4 499 448	5 790 836
1983	26 321	132 933	53 289
1984	52 726	126 227	99 323
Total	3 397 935	6 173 358	7 753 126

†Cereals include: wheat, durum wheat, red spring wheat, utility wheat, mixed grain, fall rye, oats, barley.
‡Oilseeds include: canola (rapeseed), sunflower.
§Other includes: buckwheat, flax, mustard, field peas, silage corn, sugar beets, lentils, fababeans, canary seed, field beans.
Source: Manitoba Crop Insurance Corporation.

ably in these regions if earlier maturing hybrids or inexpensive methods of frost protection were available.

Even in the established corn-growing regions some losses due to freezing temperatures occur periodically. Losses are greater and occur more frequently in Manitoba and Québec than in Ontario and most are caused by the first −2°C freeze in the fall. The last spring freeze sometimes kills back corn seedlings, but most of these regrow because the growing point usually escapes injury. Consequently, corn losses due to spring freezes are usually minor.

Corn grown for seed is subject to germ injury when approaching maturity and temperatures below −2°C occur. The higher the moisture content of the seed the shorter the interval of below freezing temperatures which will cause germ damage (Rossman 1949). The duration of below freezing temperatures that results in lack of germination of corn seed for different kernel moisture contents and temperature levels is shown in Table 5. As a result, most of the seed corn produced in Canada is grown in southwestern Ontario, where the growing season is long enough to mature the seed before a freeze occurs. Even there, germ damage occurs periodically. An appreciable amount of seed was lost from the occurrence of below freezing temperature damage in 1965, 1969 and 1974, although losses were minimal for the next 11 yr. In 1969, a large portion of the crop was planted late and excessive moisture and cool temperatures retarded development. Recorded temperatures dropped to −3.4°C in seed fields for a period of 9 h on 15 Oct., when some seed crops contained more than 40% kernel moisture. At least 381 t of corn harvested for seed in 1969 could not be sold for this purpose due to lack of germination. In 1965 the injury and losses were more widespread and extensive (Brown and Baier 1970b). Losses in 1974 were caused by sub-freezing (−2°C) temperatures in late September following a cool growing season.

OILSEEDS. The major oilseed crops produced in Canada are soybeans, canola (rapeseed) and sunflower. All three are annuals and are susceptible to freeze damage with canola being the hardiest and soybeans the tenderest. Canola has a similar growing season to spring cereals; freeze susceptibility is very similar to the cereals. The temperature at which freeze damage occurs depends on stage of development and hardening. For example, canola in the seedling stage that has been subjected to some cool temperatures for a period can withstand −8 or −9°C, whereas the seedlings that have not undergone

Table 5. Duration (h) of below-freezing temperatures that results in lack of seed germination in relation to moisture content of corn and temperature level

Temp. (°C)	Moisture content of corn kernels (%)							
	60	50	40	30	25	20	17	14
	Number of hours below freezing temperatures							
−2.2	8	12	16	24				
−4.5	6	8	12	20	24			S
−6.7	4	4	9	14	18			A
−9.0			6	9	12	24		F
−11.2			4	6	8	16		E
−13.4			2	4	6	12		
−15.7				2	4	8	12	
−18.0						5	16	
−20.2							6	

Source: Adapted from Rossman (1949).

hardening can be killed by temperatures at −3 to −4°C. Also, −3°C can kill immature seeds containing 50 to 60% moisture and −1°C can cause flower abortion when frost occurs at flowering time (Thomas 1984). The tolerance of sunflower to freezing temperatures is similar to canola in the seedling stage, but past the six to eight leaf stage plants are susceptible to light frosts (0° to −2°C) according to Dubé (1981). Consequently sunflower can be planted earlier than soybeans, although growing season length is about the same for both, because soybeans are susceptible to freeze damage when temperatures drop to just below 0°C at all stages of growth and flowering.

Evidence of significant losses of oilseed crops in western Canada is provided in Tables 3 and 4, amounting to over $16 M in Saskatchewan in the past 12 yr and over $ 6 M in Manitoba in 10 yr. In 1982, 57% of the sunflower losses in Manitoba were attributed to freeze damage. In Saskatchewan these losses were 50, 100 and 38% in 1974, 1978 and 1982, respectively. Of the total oilseed losses reported in Tables 3 and 4, canola was damaged more frequently than sunflower, with some losses from freeze damage occurring nearly every year. Canola losses in 1982 were very significant when temperatures dropped to the −3 to −5°C level in late August in eastern Saskatchewan and southwestern Manitoba, when the crop was still quite immature. Apparently, soybean losses from freeze damage occur less frequently than for either canola or sunflower, as practically all soybeans are produced in southern Ontario where the growing season is long enough to mature the recommended varieties.

VEGETABLES. Most vegetable production areas are located in relatively close proximity to major urban centres where produce can be readily transported to markets. Production is common in some of the major river valleys of southern Canada such as the lower Fraser, south Saskatchewan, Red, St. Lawrence, St. John, and Annapolis valleys and in areas of major organic soil deposits, such as the Bradford Marsh in Ontario. Although vegetable crops are susceptible to injury by temperatures between 0 and −5°C, potential damage is often minimized by planting after the risk of spring frost and by using freeze protection methods to increase the soil and/or ambient air temperature around the plant. Although freeze resistance is the main factor in determining the hardiness of a particular species, the length of the preflowering period is also a factor (Edey 1977).

Potatoes and tomatoes are damaged by spring or fall frosts more frequently than sweet corn, peppers, carrots, peas and cole crops presumably because the first two crops are more extensively grown than most other vegetables and because planting and harvesting dates extend earlier and later into the growing season. Freezing damages potatoes in two ways. In spring, top growth is often injured or killed. This will contribute to yield reductions, higher susceptibility to further damage by insects and disease, and delayed maturity, thereby reducing opportunities for selling produce on early markets, especially in areas such as southwestern Ontario (e.g., Leamington). In autumn, frost acts as a top-killer when it occurs early enough, yet its frequency, intensity and uniformity over a field is variable. Most losses result when temperatures drop low enough in late fall to freeze potato tubers near the soil surface. Injury to tomato transplants or seedlings by late spring frosts appears to occur more frequently than fall frost injury, although economic losses as a result of fall frosts are usually much greater. Most spring losses can be partially rectified by re-transplanting but losses in the fall cannot. When it is desired to have a vegetable crop ready for the early fresh market and a late spring frost ruins this possibility the economic loss is much greater than just the cost of replanting because this market opportunity, when returns are usually greater, is lost. Freezes occurring after June 1 usually cause some damage to vegetables such as tomatoes, peppers, beans, cucumbers and squash. Crop records indicate that once in seven to 10 years as much as 15% of the commercial carrot crop has been left in the ground (Brown and Baier 1970b) due to an earlier than normal freezing of the soil, preventing the complete harvesting of the carrot crop.

Winter Annuals

Winter wheat and rye are the most extensively grown winter annuals. Winter rye is more cold hardy than winter wheat but the Norstar wheat cultivar has cold hardiness qualities that allows it to be produced in Saskatchewan (Fowler 1983). Plantings of winter wheat exceeded 750 000 ha for the 1985/1986 crop year, with nearly one-half of this area in Saskatchewan and most of the remainder in Ontario and Alberta. Winter wheat plantings in Saskatchewan have grown from around 1000 ha in 1974/1975 to over 350 000 ha in 1985. The practice of direct seeding into stubble from a previous crop allows snow trapping by the stubble which helps protect the crop from the sub-zero winter temperatures in the Prairies (Fowler 1983). Most of the winter wheat grown in Ontario has snow cover protection from the coldest winter temperatures. Here, losses of winter grains mostly result from smothering due to ice sheet formation, heaving with frozen soil, and desiccation due to high evaporative demand when there is little snow cover. Late spring frosts have been known to damage seeds of winter grains when a freeze occurs around the time of anthesis with injury to floral parts causing reduced seed set. Rye was ruined in southern Saskatchewan in 1969 as a result of a freeze on 11 June when the temperature dropped to −6.5°C over a wide area.

Other winter annuals grown are barley and canola. Winter barley has not been very successful because of the lack of cultivars with sufficient cold tolerance. Winter canola is a new crop grown only in regions of southern Ontario where snow cover is usually adequate throughout the winter.

Perennials

Perennials (forage and fruit crops) may be sensitive to both growing season length and winter sub-freezing conditions. Thus forage production tends to be concentrated in areas with a frost free season of 90 d or more. Blossoms of perennial fruit species may be damaged by late spring frosts, fruit by early fall frosts, and whole plants, canes, vines or trees, as well as the fruit buds, may be damaged by extremely low winter temperatures. Thus tree fruit production in Canada is largely confined to the areas with more moderate climates, the most notable of which are the Niagara region of southern Ontario, the Okanagan Valley of the interior of British Columbia and the Annapolis Valley of Nova Scotia. The former two areas support the production of the tender fruits (peaches, cherries, plums, apricots and grapes). All three areas are also important for hardier fruit crops including apple, although apple production also extends into other areas of Ontario (bordering Lakes Erie, Ontario and Georgian Bay), Quebec and New Brunswick. Small fruit are more closely linked to "pick-your-own" operations, and hence production areas tend to be near urban areas.

FORAGES. Hay and pasture crops begin growth when the mean daily temperatures reach 5°C in the spring. However, night-time temperatures usually drop to 0°C or lower periodically during the first month after growth begins, which may result in slight to severe injury to leaves. It has been reported (Rosenberg et al. 1983) that transpiration from alfalfa decreases considerably for a day or two following frosts, when compared with transpiration on the day before the subfreezing temperature occurred.

Smothering, heaving and desiccation are the most common factors resulting in losses of legumes and perennial grasses. Smothering usually occurs in late winter or early spring and is caused by ice sheets formed by thawing and freezing of snowmelt. Heaving results when saturated soils freeze under conditions where there is very little or no snow cover. Desiccation causes plants to die when evaporative demand is high on sunny and/or windy days and the soil is frozen preventing water from moving to the roots. This occurs in winter and early spring when there is very little or no snow cover. Autumn frosts cause no permanent damage to established stands of perennial forage crops.

In most regions losses of forage crops due to low temperatures are fairly small and occur relatively infrequently. This is the result of improved cultivars and management practices. Through trial and error most farmers have learned to avoid seeding alfalfa on poorly drained land or in regions where there is inadequate snow cover. In the Cariboo country of British Columbia where sometimes snow cover is inadequate, winter damage to alfalfa and grasses can be disastrous. Losses of about 90% have been reported in some winters and can be equivalent to half the value of one year's beef production. This may occur 1 year in 10. In the southern interior, similar losses of hay crops have occurred due to inadequate snow cover.

TREE FRUITS. Loss of tree fruits results from four types of freezing injury. Two types occur in winter when extreme temperatures may kill the trees and/or flower buds. In spring, frosts frequently kill some of the buds or blossoms before or after pollination takes place thereby reducing potential yield. In fall, freeze damage may occur before the fruit is picked. Figure 1 shows how the critical temperature level varies for tree fruits depending on phenological stages (adapted from Ballard 1978; Stewart et al. 1984) and indicates temperatures that will result in 10 and 90% bud kill within 30 min for the various phenological stages from bud development through flowering. These temperatures depend also upon the fruit species and cultivar, rootstock, tree age and recent weather conditions.

The effect of three major low temperature events that killed trees in the Okanagan Valley of British Columbia in a fifteen-year period is shown in Table 6. These data show that significant tree losses do occur in the Okanagan region. Some tree types were more susceptible in one of the three winters (e.g., 34% loss of peach trees in 1949/1950, 40% loss of cherry trees in 1955/1956) while others were fairly consistent (e.g., apples 10–12%). The overall percentage loss for all tree types in each of the three winters was relatively constant (12–15%). These significant tree losses were associated with extreme minimum temperataures (e.g., −30.2°C in January 1950; −19.0°C on 11 Nov. 1955; −26.9°C in December 1964). In addition, some tree losses and heavy crop losses resulted from temperatures of −29.7°C on 28 Dec. 1968 (D. Lane, Summerland Research Station, pers. commun.). No significant fruit tree losses due to winterkill have been reported since.

In the more frost-prone locations of Ontario some loss of fruit production occurs quite frequently, although it is difficult to tell in some years whether the losses are due to frost injury or poor pollinating weather. Estimates vary from 5 to 25% once every 5–10 yr for the regions of southern Ontario outside the Niagara peninsula (Brown and Baier 1970b). Spring frosts appear to be the primary hazard to fruit production in Ontario. Blossom damage to tender fruits, particularly apricots, may occur 3 yr out of 10 in the less favorable areas of the Niagara peninsula (Table 7).

Stone fruit losses from winter injury in southwestern Ontario have not been carefully documented over the years. According to R. Layne at the Harrow Research Station (pers. commun.) data indicate that each major decline in production can be associated with

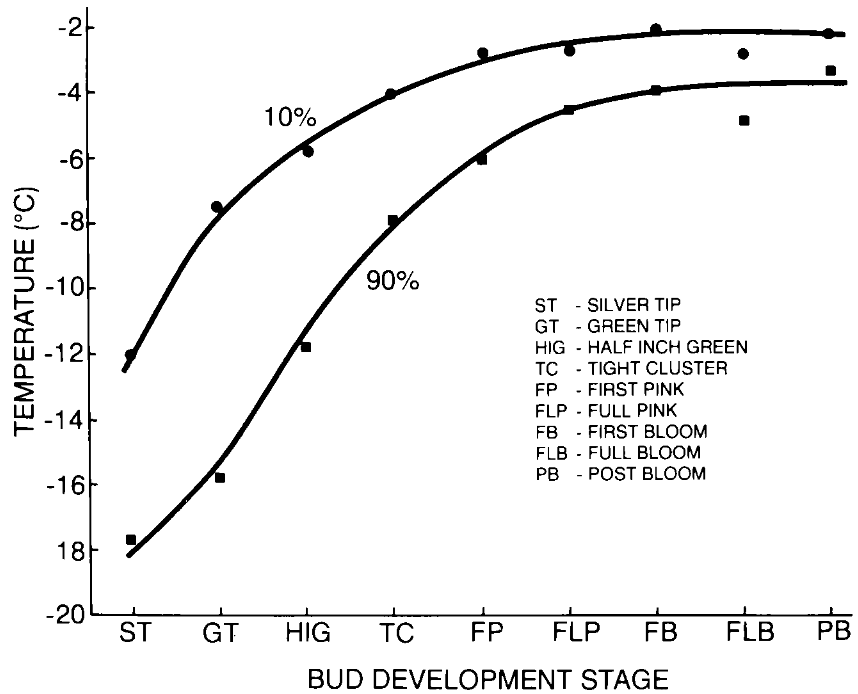

Fig. 1. Illustration of the change in critical temperatures at which 10% and 90% of apple buds have been reported killed at different bud development stages. (Adapted from Ballard (1978).)

either a severe winter with minimum temperatures of −25°C or colder, or a late frost during or after bloom (Mercier and Chapman (1956) used −12°F). In the past 22 yr there have been only two peach crop failures in southwestern Ontario, one in 1972 and the other in 1982, although some losses occur each year. Each winter some bud kill is sustained, especially on the more bud tender cultivars (e.g., Loring). Wood damage is less frequent and usually not significant unless temperatures fall below −25°C. The frequency of such temperatures in the last 10 years appears to have been higher than in previous decades.

Laboratory studies (e.g., Layne 1982; Quamme et al. 1982) have shown that if one artificially acclimates peach shoots using a stepwise drop in temperature over a 3-wk period, it is possible to acclimate representative cultivars so that it will require −27.3°C to kill 50% of the flower buds and −28.5°C to kill 90% of them. To kill 50% of the shoot xylem tissue it requires a temperature of −31.6°C and to kill 90% of the xylem it requires −32.9°C. Seldom do we have weather conditions that permit maximum acclimation, thus, in the orchard situation you can generally expect significant crop reduction at temperatures below −25°C and tree loss at temperatures below −28°C in midwinter (R. Layne, Harrow Research Station, pers. commun.). Such temperatures in December before trees are fully acclimated or in March when they are losing acclimation, or in midwinter if unseasonably warm above-freezing temperatures occur a few days before the occurrence of −25°C or colder, can result in crop loss and tree loss that can be devastating to the industry.

Freeze damage to apple fruit in autumn occurs periodically when inclement weather

Table 6. Estimated tree kill in the Okanagan Valley, British Columbia, as a result of extremely low winter temperatures

Tree type	1949/1950 No.	1949/1950 %	1955/1956 No.	1955/1956 %	1964/1965 No.	1964/1965 %
Apples	112 476	10.1	126 162	11.8	142 668	10.0
Peaches	117 229	34.1	23 041	8.1	88 478	29.0
Apricots	37 375	20.1	17 759	8.8	9 875	9.0
Cherries	19 049	19.0	60 272	40.4	37 159	20.0
Pears	21 168	6.3	5 092	1.3	11 923	3.0
Plums and prunes			34 722	19.5		
Plums	4 169	25.8			460	11.1
Prunes	35 034	17.5			7 150	7.5
B.C. Total	346 500	15.1	272 048	11.7	297 713	11.8

Source: British Columbia Crop Insurance.

Table 7. Frequency of crop losses of some tree fruits in the Ontario Niagara peninsula

Crop	Frequency of loss in 10 yr	Range of loss (%)
Apples†	1	10–25
Peaches‡	2	10–40
Apricots†	3	10–60

†Loss experienced solely from adverse spring weather.
‡Loss experience equally from adverse spring weather and severe winter temperatures.
Source: Horticultural Research Institute of Ontario, Vineland.

delays or prevents complete harvesting. This occurred in Ontario in 1969 when an early preharvest fall freeze damaged about 8% of the apple crop in some areas. Such injury is generally infrequent. Severe winter injury in 1980/1981 resulted in significant tree losses in eastern Canada (Embree 1984; Warner 1982; Blackburn 1984). Table 8 shows minimum temperatures in December 1980 and January 1981 recorded in four apple growing regions of eastern Canada. Agriculture Canada survey results also included in Table 8 indicate that many trees were killed. There was a suggestion that a heavy fruit load in the 1980 crop year in eastern Ontario reduced carbohydrate reserves, thus reducing the hardiness of some trees, particularly Northern Spy. Late-maturing cultivars experienced more damage than early-maturing ones. In Quebec, estimates from surveys suggest that 25–30% of the apple trees either died or were severely injured.

The Annapolis Valley of Nova Scotia has experienced major freezes. For example, severe damage in 1945 to apple blossoms lowered yield causing over $4 M loss (1945$) to the apple growers of Nova Scotia (Brown and Baier 1970a).

The New Brunswick apple industry was affected by winter injury in 1979/1980 as well as 1980/1981 as reported in provincial surveys (Estabrooks et al. 1980; Estabrooks and Reed 1981). Minimum temperatures of −30°C were recorded at Fredericton on 21, 22 and 26 Dec. 1979. Winter injury was largely confined to the rootstock. In 1980/1981, however, when temperatures of −31°C and −35°C were recorded (Table 8), Estabrooks and Reed (1981) reported that approximately 8% of the total number of orchard trees in New Brunswick were killed. The main cultivars affected were McIntosh (66%) and Cortland (11%). For rootstocks, 46% of trees on *Malus Robusta* 5 were killed.

SMALL FRUITS. The strawberry is a semi-hardy evergreen that is widely grown despite its low tolerance to cold temperatures. These plants require the protection of snow and other covers, usually straw mulch, to survive the cold extremes of the Canadian climate. Open strawberry blossoms can only withstand temperatures slightly below 0°C (Edey 1977). In Eastern Canada, spring frosts are not usually a major factor affecting potential strawberry yields. Losses, when they do occur result from damage to the primary blossoms. Sig-

Table 8. Apple tree losses in Eastern Canada resulting from minimum temperatures in December 1980 and January 1981

	Min. temp. (°C)		
Region†	Dec.	Jan.	No. trees killed
Eastern Ontario	−30	−37	56 128‡
Quebec	−33	−36	362 702§
New Brunswick	−31	−35	22 274‡
Nova Scotia	−23	−24	25 419‡

†Smithfield, Ont.; Rougemont, Que.; Fredericton, N.B.; Kentville, N.S.
‡Converted to standard trees.
§Excludes semi-dwarf and dwarf trees covered by provincial crop insurance.
Source: Inspection reports for apple surveys from the Eastern Canada Apple Industry Compensation and Re-establishment Plan.

nificant yield losses can only be expected if greater than 20% of their blossoms are damaged, but this is quite infrequent in the established production areas.

Raspberries bloom relatively late and usually escape frost injury. Where snow cover is insufficient there is usually some loss of canes and/or flower buds due to subzero winter temperatures. Injury to the buds near the snow line is common. Sometimes the flower buds expand in late winter or early spring in response to exceptionally mild weather and then are destroyed by freezing temperatures that follow (Brown and Baier 1970b). Latham is one of the more hardy cultivars. In New Brunswick most cultivars lack sufficient hardiness for commercial production and the risk of some loss is very high, estimated to be 20%, 9 yr in 10 (Brown and Baier 1970b).

Grape losses can result from winter freezes, late spring frosts and occasionally early autumn freezes. Young grape shoots and flower clusters are easily damaged at temperatures below −0.6°C. Sustained temperatures below −2°C in the spring can severely injure all new wood and growing points (Edey 1977). Losses from freezing temperatures occur frequently in British Columbia but only occasionally in the Niagara region of Ontario. Some losses from injury at blossom time are encountered in both Ontario and British Columbia and freeze injury to the fruit before harvesting is a problem on occasion in Ontario. Widespread injury to grapes was experienced during the 1972/1973 and 1978/1979 winters in British Columbia (Denby and Vielvoye 1979). Extensive injury and crop reduction there resulted from temperatures in the −19 to −24°C range on 6 to 8 Dec. 1972. A severe cold snap (−13.5°C at Summerland) occurred on 21 Nov. 1978. Resultant damage was extensive with more injury sustained by the main structural parts of the plants rather than to buds and cane wood. Minimums of −22.5°C were also recorded at Summerland in early January 1979, resulting in moderate to severe bud injury to tender varieties such as Himrod and to cultivars of *Vitis vinifera*. Comparatively less to no injury was recorded for most of the French Hybrids, American Hybrids, and the hardier cultivars of *Vitus labrusca* (Denby and Vielvoye 1979).

Blueberry is subject to winter injury (dieback), early spring freeze injury to swollen flower buds, late spring frost injury to the blossoms and freeze injury to the fruit. In the Lake St. Jean area of Quebec, for example, about 50% of the 1968 crop was destroyed as a result of dieback and it is estimated that this can be expected about once every ten years (Brown and Baier 1970b). Injury from freezing temperatures has reduced potential lowbush blueberry production in New Brunswick and Nova Scotia. For example, winter damage reduced the 1969 crop by 50%, while frost at blossom time in 1968 destroyed the crop in much of eastern Canada (Brown and Baier 1970b). Cultivated highbush blueberry production has increased in southern Ontario from nil ten years ago to several hundred hectares. There is no record of losses from low temperatures so far.

CONCLUSIONS

Crop loss from freeze injury is one of the impediments that reduces competitiveness of Canadian agriculture. These losses result from periodic damage to most annual and some perennial crops during the growing season when temperatures fall below 0°C and to perennial crops from subfreezing winter temperatures. Growers should be made more aware of the risk of freeze damage especially where protection practices are economically feasible.

Information from a survey taken in 1969, from indemnities paid by provincial Crop Insurance Commissions since 1974, and from personal communication with certain scientists provides the following conclusions:

(1) Spring grain losses from freeze damage occur about once every 3–4 yr in Saskatchewan, less frequently in Alberta (except the Peace River region), Manitoba and the northern clay belts in Ontario and Quebec, and seldom in the remainder of eastern Canada. The frequency of losses of canola on the Prairies has been similar to cereals over the past 12 yr.

(2) During the past 20 yr availability of short-season corn and soybean cultivars has expanded the production of these crops to areas with fewer than 2300 heat units. This has resulted in frequent crop losses from fall freezes in those areas.

(3) Loss of vegetable crops from freezing seldom occurs because of the well-established cultural practices developed over the years, such as planting after the danger of last spring frost occurrence, and freeze protection practices are used when necessary since they are economically feasible.

(4) Forages and winter annuals are killed more frequently by smothering and desiccation from ice sheet formation than from low winter temperatures (−25°C or lower) when there is a lack of snow cover. Further setbacks of these crops occur from spring frosts.

(5) Major declines in tender fruit production occur once or twice every 5–10 yr depending on type of fruit and location and are usually associated with either a severe winter with minimum temperatures of −25°C or lower, or a late spring frost during bloom.

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