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ORIGINAL PAPER

An indicator of freeze-kill damages to fruit trees during flowering

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Abstract

This paper demonstrates the use of climatological data and published information to develop a thaw-freeze/freeze-kill indicator for fruit trees during flowering. In fruit-producing regions, when budding and flowering occur before the last spring freeze, a freeze-kill event can cause substantial losses. As spring onset is occurring earlier with climate change, thaw-freeze events have the potential to become more of a hazard both in terms of current production and in terms of potential adaptation strategies. To model the spring thaw-freeze and its magnitude or intensity, we proposed an indicator based on the accumulation of daily minimum temperature between successive freezing dates and its maximum value over the spring. This indicator was tested on apple and peach production in southern Ontario, Canada, using data from eight climate stations in southern Ontario. The indicator showed promise in its utility in that its magnitude was greater when freezing occurred after blooming and it was demonstrated to be correlated to the estimated blooming dates of apple and peach fruits grown in southern Ontario. The annual series was shown to fit the generalized extreme value distribution thereby allowing the extreme risk to be modelled and the return period to be calculated. It was also shown that the reported thaw-freeze events that caused significant apple and peach losses had a return period on the order of 10 years.

Keywords Climate change · Spring · Freeze-kill · Fruit production · Return period · Flowering · Blooming

Introduction

The degree of agricultural productivity of a crop is essentially the result of the right combination of climate, soil and management regime. If any of these change beyond a certain tolerance for the crop, then the productivity is reduced. Since the 1960s, there has been a well-documented change in spring onset across the northern hemisphere where this onset occurs earlier and earlier with each decade (e.g. Schwartz 1993; Schwartz et al. 2006; Hayhoe et al. 2007; Sanders-DeMott et al. 2018). In order to investigate the impact of climate change on fruit production, spring onset has been characterized using two indices: first leaf date (fld) which is the general onset of growth in grass and shrubs and can be considered early spring; and first bloom date (fbd) which is when the flowers start to bloom beyond the bud stage and are then vulnerable to freezing temperatures.

As a consequence of climate change, for the 1960–2000 period, the fld across the northeast USA has advanced by 2.1 days/decade and the fbd by 1.2 days/decade (Hayhoe et al. 2007). Schwartz et al. (2006) have shown that the last spring freeze of either − 2.2 °C or lower temperatures has also become more variable and since the onset of spring starts earlier, plants are now more susceptible to frost damage due to synoptic events. A key risk to plants therefore was when blooming occurred before the last freeze date (lfd) such that buds and new growth were killed (Rea and Eccel 2006; Palmer et al. 2003; Faust et al. 1997; Balandier et al. 1993). The longer the period between fbd and lfd, the more vulnerable the budding and flowering stages are to freeze-kills.

Freeze-kills can cause substantial losses. The reinsurer Munich RE (Faust and Herbold 2018) reported that despite a warming climate, the last freeze can occur after tree blooming causing significant losses to the agriculture industry. In 2017 such losses in Europe amounted to €3.3bn. The media have also reported on such impacts for nut and fruit growers in the USA. For example, Higgins (2019) reported in the Washington Post that spring freeze-kills were increasing in frequency, sometimes occurring in consecutive years, with

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associated large losses across the USA since 2002. Catastrophic losses were reported by apple producers in the northeastern USA in 2012. This phenomenon also impacted the fruit production industry in Ontario in 2012 when record warm periods in March lasting approximately two weeks were followed by freezing temperatures ($T_{\min} < 0$ °C) near the end of the month resulting in bud kills. Apple production experienced losses of up to 80% for the entire industry (Ontario Apple Growers 2013; OMAFRA 2019a) and peach production saw losses of 15% (Ontario Tender Fruit Producers' Marketing Board 2014; OMAFRA 2019b). Similarly, in 2015, a nighttime frost occurred on May 22–23 which impacted the production of apples (Ontario Apple Growers 2015) and peaches (Ontario Tender Fruit Growers 2016). The impact resulted in reported losses of 30% for apples (OMAFRA 2019a) and 12% for peaches (OMAFRA 2019b).

It is anticipated that with climate change and the resulting earlier onset of budding and blooming combined with greater variability in temperature extremes there is a potential for freeze-kill events to occur with varying frequency and severity. This phenomenon can be considered a spring thaw-freeze event and the magnitude and potential for damages are a function of the intensity and duration of the thaw. It should be noted that the frequency and severity of such events vary by region, latitude, altitude and the progression of time. Faust and Herbold (2018) reported such variability when reviewing the large-scale spring freeze-kill of fruit experienced in Europe in 2017. These events will have serious consequences for agriculture production and sustainability especially if production intensifies and expands northwards. Our study examines the recurrence of thaw-freeze events associated with changing climate on apple and peach production at eight locations in southern Ontario, Canada. We show this by using readily available standard climate data and agroclimatic metrics of apples and peaches to evaluate the crop-climate relationship. The approach of identifying environmental constraints in order to improve crop performance has been a long-term objective at Agriculture and Agri-Food Canada (e.g. Baier et al. 1976).

Methodology

Study area and climate data

The fruit-producing region in Ontario, Canada covers much of southern Ontario (Fig. 1). It stretches from the cities of Windsor in the west to the Ottawa region in the east and is bounded by the north shores of Lake Erie and Lake Ontario, and the south shores of Lake St. Clair and Lake Huron and the Georgian Bay lake. It therefore covers a large geographical area of approximately 800 km × 270 km with a potential to encompass varying climate impacts. Apple production covers much of this region while peach production is limited to the warmer southern areas from Windsor to Toronto. Therefore, the data used in the analysis for peach consisted of these four southern stations while that for apple used all eight stations. It should be noted that approximately 70% of the annual apple production occurs in the peach-growing region of Ontario (OMAFRA 2019a).

Eight Environment and Climate Change Canada (Government of Canada 2019) climate stations located in the fruit-growing region of Ontario were selected based on the availability of daily meteorological data from 1989 to 2018. These are airport-based stations, going from west to east (Fig. 1): Windsor (Climate ID 6139525 (1950–2014) and 6139530 (2014–2018)), London (Climate ID 6144475 (1950–2002) and 6144478 (2002–2018)), Hamilton (Climate ID 6153194 (1960–2011) and 6153193 (2011–2018)), Toronto (Climate ID 6158733 (1950–2013) and 6158731 (2013–2018)), Collingwood (Climate ID 6111792 (1995–2018), Peterborough (Climate ID 6166418 (1969–2005), 6166420 (2004–2010) and 6166415 (2010–2018)), Brockville (Climate ID 6100971 (1966–2018)) and Ottawa (Climate ID 6106000 (1950–2011) and 6106001 (2011–2018)).

Over the years, a number of stations upgraded and/or re-sited their equipment necessitating their Climate IDs to change. Instruments at Hamilton and Peterborough were re-sited approximately 800 and 900 m, respectively, from the previous location. All other stations' equipment did not change location. When joining the data, we examined the variances of the data preceding the join-date and the data following the join-date to determine whether there were any significant differences between them based on the F test at $\alpha = 0.05$. We adapted the joining method described by Vincent and Gullet (1999) by limiting the data for the F test to 15 days before and after the join-dates plus the 30 days that bracketed the join-dates in the previous and following years. This resulted in two 45-day data sets of pre and post join-dates that covered a 3-year period centred on the join-date. Testing was limited to this 3-year span as longer data sets before and after the join-dates began failing the requirement for normality for the F test. Only one join-date indicated a significant difference in the variances of the pre and post data sets. This occurred for the Peterborough station that required to be combined on 2005-12-31/2006-01-01. The reason for the difference in variances was that the pre join-date data had a significantly colder winter than the post join-date data. This was observed at all eight stations in our study. Testing this join-date for the other stations also resulted in significant differences in the variances of the pre and post join-date data despite these stations having contiguous data over this period. For the purpose of this study, it was assumed that data from the earlier and subsequent stations could be combined with minimal bias.

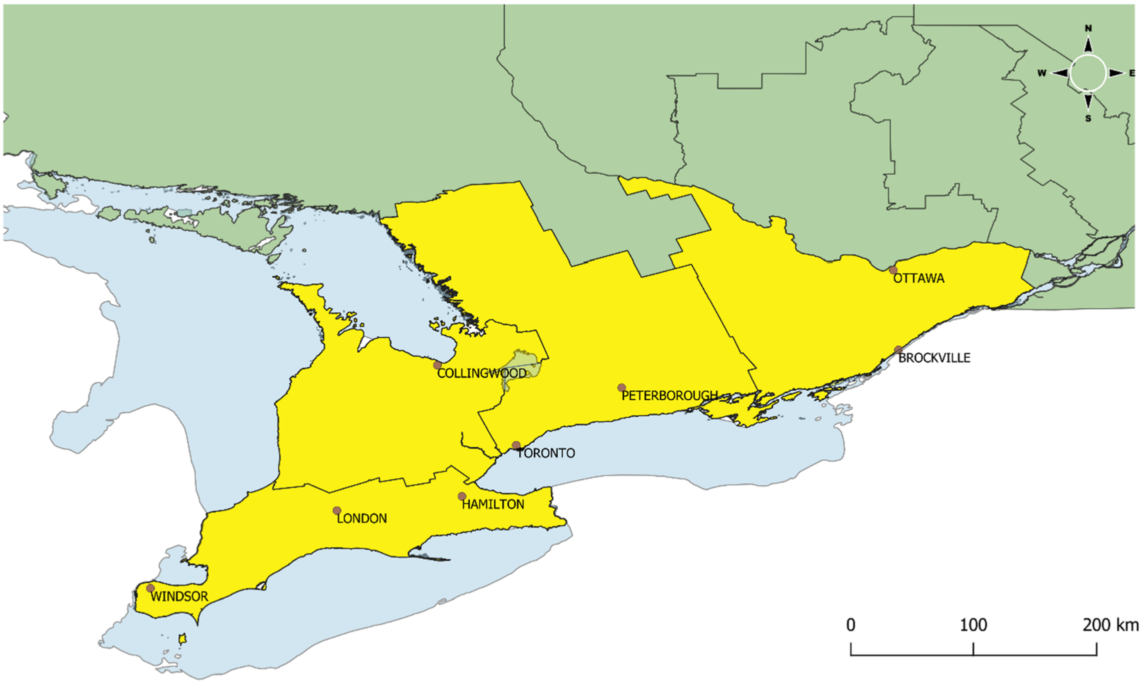


Fig. 1 Fruit-producing region of southern Ontario (yellow) and the eight climate stations

Daily minimum air temperature, T_{min} data, for March to May over the period 1989 to 2018 were used in this analysis. Missing data was limited to ≤ 1.4% for all stations (missing data for daily maximum air temperature $T_{\mathrm{max}} \leq 1.7\%$ over this data period). Missing data was treated by listwise omission which tends to lead to unbiased regression. T_{min} was selected because it corresponded to the observed freezing reported by the producers in 2012 (Ontario Apple Growers 2013; Ontario Tender Fruit Producers' Marketing Board 2014) and 2015 (Ontario Apple Growers 2015; Ontario Tender Fruit Growers 2016). This resulted in the reported losses as illustrated in Fig. 2 (OMAFRA 2019a, 2019b). Mean and maximum air temperatures did not indicate freezing temperatures that corresponded to the reported damaging events at any of the stations used in our analysis.

$\mathrm{DDT}_{\mathrm{min}}$ and spring blooming

We propose that a degree day based on the daily minimum air temperature T_{min} ($\mathrm{DDT}_{\mathrm{min}}$) and its annual (block) maxima over the spring be used as an indicator to model the occurrence of thaw-freeze events. We took the concept of the growing degree day to define $\mathrm{DDT}_{\mathrm{min}}$ with the T_{min} base temperature set as 0 °C which best corresponded to the reported freeze-kills. We also relaxed the bloom freezing threshold to be equivalent to the base temperature of 0 °C. Therefore, $\mathrm{DDT}_{\mathrm{min}}$ was calculated as the annual maximum of the sum of contiguous days of $T_{\mathrm{min}} \geq 0$ °C. The magnitude of $\mathrm{DDT}_{\mathrm{min}}$ can be considered an indicator of the energy input for growth and as such the level of vulnerability (damage severity).

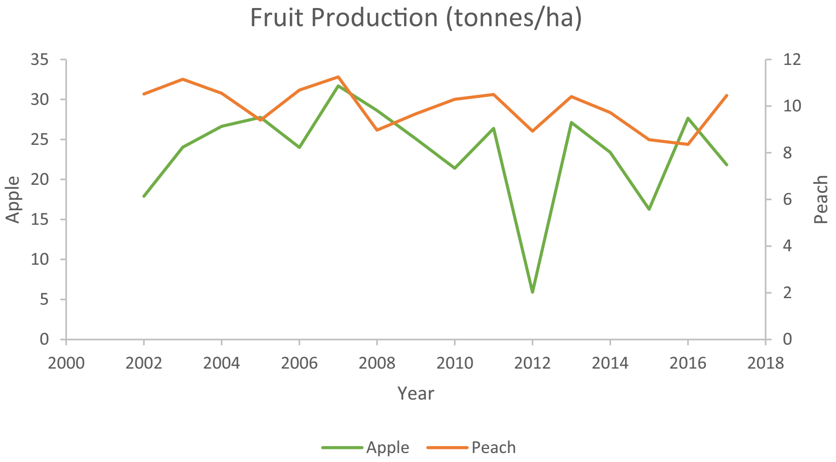


Fig. 2 Average market production of apples and peaches in tonnes/ha in Ontario, Canada, for the period 2002–2017 (OMAFRA 2019a, 2019b)

It was also necessary to determine whether an increasing magnitude of $\mathrm{DDT}_{\mathrm{min}}$ correlated with earlier blooming and therefore freeze-kill risk. Data, on the onset of the critical flowering stage, were unavailable for the fruits studied in the growing region of Ontario. Such data are important, as the occurrence of the date before the last freeze date, determines the risk due to frost kill. Phenological fruit tree models based on climate variables have been developed to estimate the various phenological stages of fruit trees such as the onset of blooming. Field and controlled laboratory studies were used to develop these models. Key to the onset of blooming for temperate fruit trees is the need by the tree to fulfil a certain level of chilling over the fall and winter to enable it to emerge from dormancy followed by warming over the spring to produce new growth. There are three main methods of estimating the chilling requirements which are based on the number of chilling hours accumulated by the tree during fall and winter. Chilling hours (CH) (Weinberger 1950) is the simplest method which tabulates the hours between 0 and 7.2 °C. However, it does not consider the negative effects of high winter temperatures on the tree phenology (Guak and Neilsen 2013). The use of chilling units (CU) based on the Utah model by Richardson et al. (1974) is an attempt to overcome the limitation of the chilling hour approach by employing either a positive or negative accumulation based on different temperature ranges. The third model is the Dynamic model (Fishman et al. 1987) that accumulates chilling portions (CP) based on complex temperature duration and intensity functions. The Dynamic model is currently considered the most reliable model. Unfortunately, there is no conversion between the three chilling metrics. Once the chilling requirement has been satisfied, the heating requirement begins and is achieved through the accumulation of growing degree hours (GDH) calculated according to Anderson et al. (1986). Each phenological stage requires a certain accumulation of GDH, and for this study, we were interested in the GDH needed for blooming.

To estimate the flowering dates for apple and peach, the chilling and heating phenological model chillR (v0.70.21.3) (Luedeling 2019; Luedeling et al. 2013) developed using the R statistical tool (R Core Team 2019) was used. The chilR model calculates the hourly chilling and heating requirements by estimating the hourly temperatures from the daily temperature extremes, based on the known sine function for diurnal temperature progression, geographic latitude and day of year. Luedeling (2019) has recommended the use of CP over CU and CH with CH resulting in the greatest uncertainty in estimating chilling needs. We therefore modelled flowering dates based on CP and CU data. Calculating CU, CP and GDH for each year required daily T_{min} and T_{max}. Since apple and peach fruit yield data were only over the period 2002–2017, these chilling and heating requirements and their respective fulfilment dates were calculated for these years for each type of fruit.

Literature-based CU, CP and GDH presented in Table 1 were used to initialize the model simulations and provide a range of potential blooming dates for each fruit. Guak and Nielsen (2013) reported that for apple cultivar Gala in B.C., Canada, CU ranged from 673 to 1084 to fulfil dormancy. Palmer et al. (2003) noted that most apple cultivars in North America needed about 800–1200 CU. For the apple-growing region in South Africa, Tharaga (2014) reported a CU range of 800–1000+ for cultivars Fuji, Golden Delicious and Royal Gala that are also grown in Ontario, and other cultivars that ranged from 450–800. No range in GDH was given by these sources. Funes et al. (2016) gave means and their standard deviations of CP for a number of apple cultivars grown in northeast Spain that ranged from 62.5 ± 5.6 to 68.4 ± 5.9 and GDH that ranged from 7416 ± 687 to 10273 ± 1032. For Golden Delicious apples grown in northern Italy, Rea and Eccel (2006) suggested that the required GDH ranged from 7100 to 9350. These GDHs reported by Funes et al. (2016) and Rea and Eccel (2006) were the GDHs needed to bring approximately 50% of the flowers to bloom. Based on this literature data we assumed a range of 450–1100 CU, 56.9–74.3 CP and 7100–11304 GDH for apple. The literature also did not indicate any correlation between chilling requirement and heating requirement magnitudes other than in general, cultivars that grew in colder climates had greater chilling and heating requirements to mitigate cold-related damage. The blooming modelling for apple was therefore initialized with the lower and upper CP and CU chilling and GDH heating requirements to give a combination of potential dates where 50% of the flowers had bloomed. These modelling scenarios were identified as aS1CP (56.9 CP; 7100 GDH), aS2CP (74.3 CP; 11304 GDH), aS1CU (450 CU; 7100 GDH), and aS2CU (1100 CU; 11304 GDH). For peach (Table 1), Tharaga (2014) reported that four cultivars grown in South Africa required 450–600 CU. Razavi et al. (2011) cited that most commercial cultivars needed 650–900 CU and popular Italian grown cultivars needed 806–925 CU. Their study's cultivars grown in Iran were found to need 746–868 CU and a corresponding 4099–4543 GDH for 50% of flowers to bloom. Based on these reported chilling and heating needs we assumed ranges of 450–925 CU and 4100–4545 GDH to estimate the blooming of peaches in Ontario. The modelling scenarios were thus identified as pS1 (450 CU; 4100 GDH) and pS2 (925 CU; 4545 GDH).

The estimated blooming dates over the period 2002–2017 were compared with the last $T_{\mathrm{min}} < 0$ °C date to gauge freeze-kill potential. We must note that there can be a large degree of uncertainty in predicting blooming dates as many other factors contribute to the actual dates (Luedeling 2019). For example, chilling and heating requirements differ for various cultivars as seen above; different nutrient and moisture regimes also influence blooming; local topology (slope, aspect and altitude) induced microclimates affect GDH needs (Rea and Eccel

Table 1 CU, CP and GDH used to initialize chillR simulations of potential blooming dates of apple and peach. The values with ± are the standard deviations of their means; the min and max values included these means with the standard deviations

Fruit	Cultivar	CU	CP	GDH	Geographic region	Reference
Apple	Most	800–1200			North America	Palmer et al. (2003)
	Braeburn	800–1000+			South Africa	Tharaga (2014)
	Fuji	800–1000+				
	Golden Delicious	800–1000+				
	Royal Gala	800–1000+				
	Star King	800–1000+				
	Pink Lady	450–800				
	Granny Smith	< 800				
	Gala	673–1084			BC Canada	Guak and Nielsen (2013)
	Golden Delicious			7100-9350	Northern Italy	Rea and Eccel (2006)
	Brookfield Gala		62.5 ± 5.6	9229.7 ± 881.8	Northeast Spain	Funes et al. (2016)
	Granny Smith		63.9 ± 5.7	8930.1 ± 1072.0		
	Fuji Chofu 2		64.0 ± 5.2	9025.2 ± 561.2		
	Golden Smoothee		65.0 ± 6.9	10144.5 ± 1366.6		
	Early Red One		65.5 ± 6.1	9199.9 ± 1019.5		
	Red Chief		66.4 ± 5.8	9076.2 ± 1135.8		
	Apovo		66.4 ± 7.8	7416.2 ± 687.4		
	Golden Reinders		68.4 ± 5.9	10272.5 ± 1031.8		
	Min	450	56.9	7100		
	Max	1100	74.3	11304.3		
Scenarios	Based on Min	aS1CU	aS1CP			
	Based on Max	aS2CU	aS2CP			
Peach	Transvalia	450–600			South Africa	Tharaga (2014)
	San Pedro	450–600				
	Bonnigold	450–600				
	Bokkeveld	450–600				
	Talana	450–800				
	Study's 5 cultivars	746–868		4099–4543	Iran	Razavi et al. (2011)
	Most commercial	650–900			Global	Razavi et al. (2011)
	Italian	806–925			Italy	Valentini et al. (2004) in Razavi et al. (2011)
	Min	450		4100		
	Max	925		4545		
Scenarios	Based on Min	pS1				
	Based on Max	pS2				

2006); and antecedent conditions (e.g. prior year's drought or high temperatures, warm/cold winters) are known to affect bud development and hence blooming (Caprio and Quamme 1999). Therefore, to estimate the potential for freezing damages to occur after blooming, we relaxed this criterion to be if either of these occurred within 10 days of each other, i.e. (date of last $T_{\min} < 0$ °C) − (date of bloom) $< \pm 10$ days. This difference was then compared with $\mathrm{DDT_{min}}$ to determine whether there was either any coincidence or correlation with thaw-freeze events and hence $\mathrm{DDT_{min}}$ as a potential freeze-kill indicator. The period in which $\mathrm{DDT_{min}}$ was assessed in this comparison with freezing after blooming was March to May in order to consider the critical blooming times.

$\mathrm{DDT_{min}}$ and its return period

The time series of $\mathrm{DDT_{min}}$ annual maxima can be analysed using generalized extreme value (GEV) analysis which can then provide return frequencies of the different intensities in $\mathrm{DDT_{min}}$; which in turn can help manage the risk of potential freeze-kills. The GEV is essentially composed of a set of extremal distributions which are the Gumbel, Frechet and Weibull distributions, depending on the shape parameter $\xi = 0$, $\xi > 0$ and $\xi < 0$, respectively. The cumulative distribution function CDF of the GEV is defined as:

$$CDF_{\xi,\sigma,\mu}(x) = \begin{cases} \exp\left(-\left(1+\xi\left(\frac{x-\mu}{\sigma}\right)\right)^{-\frac{1}{\xi}}\right), & 1+\xi\left(\frac{x-\mu}{\sigma}\right) > 0 and \xi \neq 0 \\ \exp\left(-\exp\left(-\frac{x-\mu}{\sigma}\right)\right), & \xi = 0. \end{cases}$$

Here, σ is the scale parameter and μ is the location parameter. Model parameters of μ, σ and ξ were estimated using the method of maximum likelihood. From here on, the annual maxima of DDT_{min} will simply be referred to as DDT_{min}. The return period (RP) of a given $x = DDT_{min}$ can be found using $RP = 1/(1 - CDF(x))$. The RP is the recurrence interval between extreme events and is the reciprocal of the expected frequency. The R statistical tool (R Core Team 2019) package *ismev* (v1.42) (Gilleland 2018) was used to estimate the GEV parameters, the best fit distribution and the RPs. Daily T_{min} for the period 1989–2018 over the corresponding March to May months for the eight stations were analysed to investigate the magnitude and frequency of the observed DDT_{min} for apple and data from the four southern stations of Windsor to Toronto were used for peach.

Results

Comparing blooming date with last date of $T_{min} < 0$ °C

The last date of $T_{min} < 0$ °C over the 2002–2017 apple yield data period ranged from early April to late May. For Windsor, the last date of $T_{min} < 0$ °C ranged from April 7 to April 29. For London and Hamilton it was April 14 to May 23; Toronto it was April 10 to May 20; Collingwood it was April 18 to May 13; Peterborough it was April 28 to May 28; Brockville it was April 11 to May 12; and Ottawa it was April 12 to May 23. Modelled apple blooming dates (where approximately 50% of the flowers have bloomed) according to chilling and heating requirement scenarios aS1CP and aS1CU showed that blooming had occurred either before or around the time of the last $T_{min} < 0$ °C for the Windsor, London, Hamilton and Toronto stations in 2012 where aS1CP and aS1CU either approached or overlapped the last day of $T_{min} < 0$ °C (Fig. 3). Recalling that 2012 was the year in which freeze-kill resulted in an 80% loss in apple yield for all producers compared with 2011, no such potential was predicted for the stations of Collingwood, Peterborough, Brockville and Ottawa in 2012. For the 2015 crop year in which freeze-kill was reported to have decreased apple yields by 30% from the previous year, blooming potentially occurred before the last $T_{min} < 0$ °C for London, Hamilton, Peterborough and Ottawa. Modelled blooming dates based on scenarios aS2CP and aS2CU did not indicate any potential freeze-kills as they were predicted to occur significantly after the last day of $T_{min} < 0$ °C (Fig. 3). This suggested that the chilling and heating requirements of aS1CP and aS1CU may better represent those of the apple cultivars planted in the region than aS2CP and aS2CU.

For peaches, there were only four stations that represented the growing region in southern Ontario and these were Windsor, London, Hamilton and Toronto. Peaches were not grown north of this subregion. The modelled blooming dates (also where approximately 50% of the flowers have bloomed) according to chilling and heating requirement scenarios pS1 and pS2 showed that blooming had occurred either before or around the time of the last $T_{min} < 0$ °C for the Windsor, London, Hamilton and Toronto stations in 2012 and 2015 when peach yields were reduced by 15% and 12% from the previous year, respectively (overlap of blooming dates with last $T_{min} < 0$ °C in Fig. 4). Both pS1 and pS2 predicted blooming significantly before $T_{min} < 0$ °C dates in 2012 by up to 40 days in advance and up to 17 days for London and Hamilton in 2015. This suggested that the chilling and/or heating requirements used in these two scenarios may have been too low for Ontario and therefore easily fulfilled. These chilling and heating requirements were those of peach varieties grown in South Africa (Tharaga 2014), Iran (Razavi et al. 2011) and Italy (Valentini et al. 2004).

Relationship between DDT_{min} and freeze-kill events

DDT_{min} over the period March to May from 2002 to 2017 were calculated and compared with the days between the last freeze date and blooming, i.e. (date of last $T_{min} < 0$ °C) − (date of bloom). In the case of apple, the mean difference based on blooming scenarios aS1CP and aS1CU was used. Overall as DDT_{min} increased, it appeared that blooming was occurring increasingly earlier than the date of last $T_{min} < 0$ °C. Therefore, there was a moderate to high negative linear correlation (r ranging from − 0.63 to − 0.91) between DDT_{min} and the number of days between the last freeze and blooming (Fig. 5 where r^2 is given). The linear model fit ranged from moderate ($r^2 = 0.40$, Collingwood) to good ($r^2 = 0.82$, London) with the majority having a reasonable to good fit (r^2~0.63 to 0.82). When freeze-kills were recorded in 2012 and 2015 (Fig. 6) there was a moderate correlation with $r = -0.66$ and the majority (~ 63%) of the difference (date of last $T_{min} < 0$ °C) − (date of bloom) was < 10 days.

The mean of the difference between last freeze date and blooming scenarios pS1 and pS2 was used for peach. There was a strong inverse relationship between DDT_{min} and the difference between last freeze date and blooming such that r ranged from − 0.77 to − 0.86 (Fig. 7). The corresponding fit by the linear model was considered reasonable for all stations.

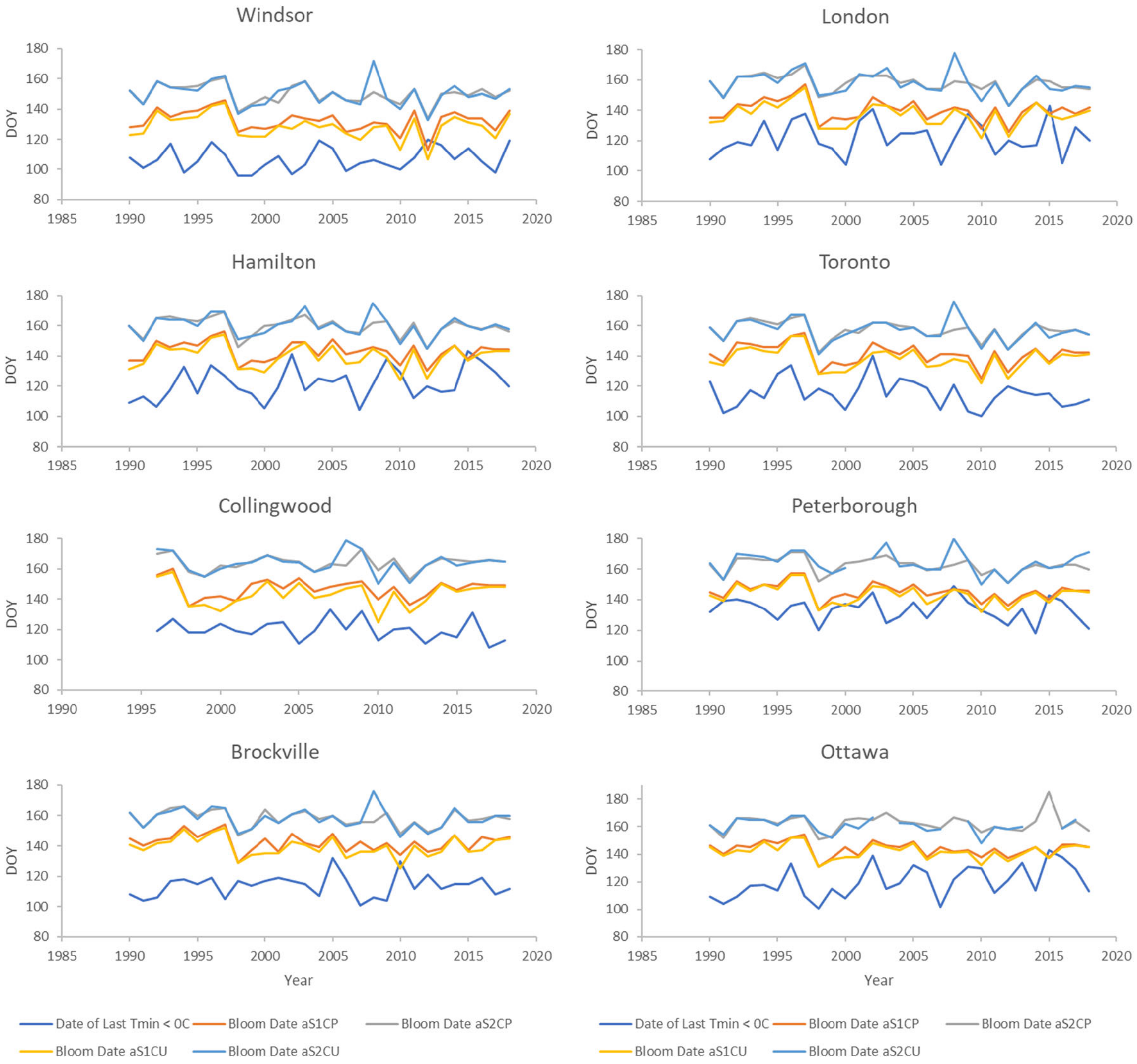


Fig. 3 Apple: modelled bloom dates (day of year, DOY) according to chilling and heating requirement scenarios aS1CP, aS2CP, aS1CU and aS2CU and date of last $T_{min} < 0$ °C. Bloom dates that were < 10 days of the last $T_{min} < 0$ °C were considered to potentially result in a freeze-kill

Focussing on the freeze-kills of 2012 and 2015 it was found that the correlation between DDT_{min} and the number of days between the last freeze and blooming was moderate ($r = -0.57$, Fig. 8) and it can be seen that DDT_{min} was associated with predicted blooming occurring before the last freeze date (negative values).

DDT_{min} and its return period

A chi-square goodness of fit test was performed on the annual DDT_{min} maxima and it was determined that the data from all stations were from the GEV distribution at the $\alpha = 0.05$ level of significance. The plot of DDT_{min} and its RPs for the stations are shown in Fig. 9 along with the best-fit regression curves corresponding to the apple and peach growing regions' data. Both the apple and peach regions' regression curves were generally coincident with slightly larger DDT_{min} occurring for the peach-growing region corresponding to the warmer climate. These regression equations are useful in estimating RPs for a given DDT_{min} for peach and apple freeze-kill risk. The magnitudes of DDT_{min} and their RPs for 2012 and 2015 were compared with those excluding the freeze-kill years (Table 2). The mean DDT_{min} of the freeze-kill years for the apple and peach growing regions were significantly greater in magnitude (at least 60% greater) than those calculated for the non-freeze-kill years and the median was more than doubled that of non-freeze-kill years. Overall the freeze-kill years' $DDT_{min} > 75$ °C d while for non-freeze-kill years it was < 52 °C d. Their respective mean and median RPs as calculated from the stations and the RPs estimated by the regression equations also highlighted this difference such that non-freeze-kill period had significantly shorter RPs (by at least half and hence twice as frequent) by comparison. RPs were generally on the order of 10 years for the freeze-kill years and approximately 3 years for non-freeze-kill period. The RP estimated by the regression equations were typically lower than

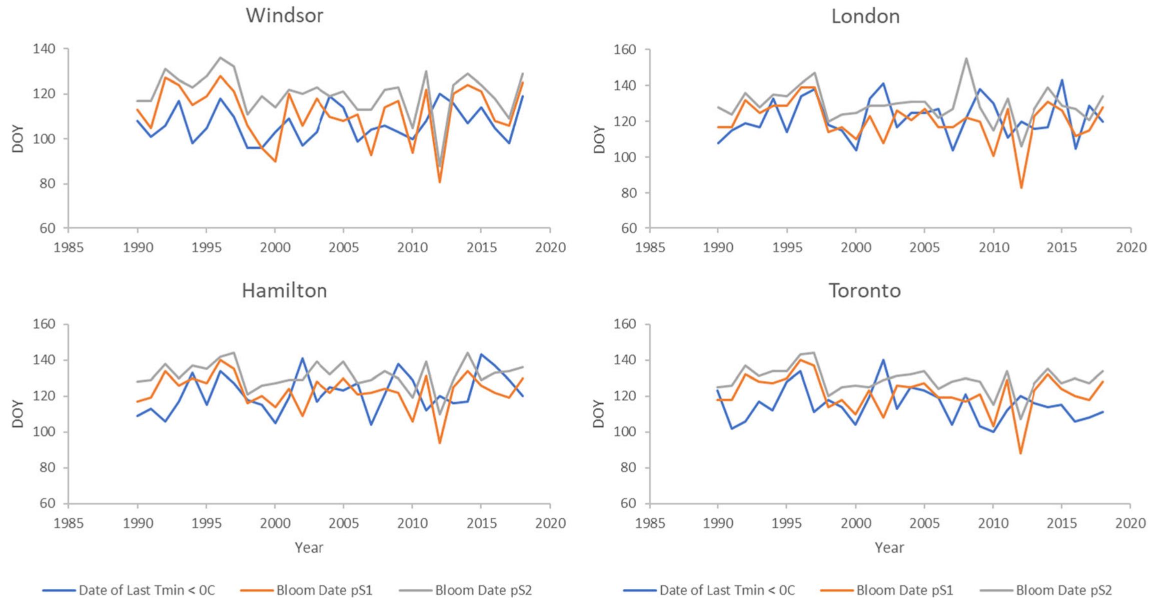


Fig. 4 Peach: modelled bloom dates (day of year, DOY) according to chilling and heating requirement scenarios pS1 and pS2 and date of last $T_{\min} < 0$ °C. Bloom dates that were < 10 days of the Last $T_{\min} < 0$ °C were considered to potentially result in a freeze-kill

the mean and median RPs. Mean $\mathrm{DDT}_{\min}$ in 2012 was approximately 15% less than that in 2015 for the apple-producing region however the apple losses were significantly more in 2012 at 80% than in 2015 at 30%. For the peach-producing region, the difference in $\mathrm{DDT}_{\min}$ between the two years was approximately 5% with comparable peach losses of 15% in 2012 and 12% in 2015. Apple losses in the peach-producing region were similar to the apple region production losses during these 2 years as 70% of apple production also occurred in the peach region.

Discussion

The question of whether the intensity of $\mathrm{DDT}_{\min}$ could be used as an indicator to freeze-kill was evaluated by its correlation to floral blooming occurring before the last freeze. This analysis was conducted for all eight stations for apple and four of the southern stations for peach. There was a consistent moderate to high inverse correlation between $\mathrm{DDT}_{\min}$ and the number of days between blooming and the last freeze date for the fruit crops. The earlier that blooming was estimated to occur before the last freeze date (assumed as $T_{\min} < 0$ °C) the greater the magnitude of $\mathrm{DDT}_{\min}$. This stands to reason as all of these metrics were determined using daily $T_{\min}$ and if an extended thaw occurred it could result in the emergence from winter dormancy and the initiation of flowering. The analysis was done for the 2002 to 2017 period corresponding to the period with available yield data, and during this period the majority of years did not report notable freeze-kill events. The $T_{\min}$ threshold for calculating $\mathrm{DDT}_{\min}$ was ≥ 0 °C and this could have captured events where non-critical freezing occurred. For example, for apple, this threshold would exclude temperatures of − 3.9 °C (a critical temperature where 90% of the bloom would be killed (Palmer et al. 2003)), short-duration freezing temperatures where bloom survivability may be higher, and where management practices mitigated freezing damage. These two latter cases would not result in either reported losses or reported mitigation measures with attribution to such weather-related events. When focussed on the reported freeze-kill years of 2012 and 2015, the analysis indicated moderate to high inverse correlations between $\mathrm{DDT}_{\min}$ and the number of days between blooming and the last freeze date for the fruit crops. The greatest uncertainty comes from estimating blooming as chilling and heating requirements were specific to the fruit species, their cultivars and the geographic region of cultivation. Such data were lacking for Ontario, and instead, international data were relied upon. Improvements in the estimation of when 50% of the flowers have bloomed either through direct observation or improved modelling would help in building confidence in the use of $\mathrm{DDT}_{\min}$.

The analysis of $\mathrm{DDT}_{\min}$ showed that despite a lower magnitude in 2012 compared with that in 2015 (Table 2), apple losses were significantly higher in 2012 than in 2015 while the same was not true for peach. In 2012, the time series of $T_{\min}$ between March and May was atypical and $\mathrm{DDT}_{\min}$ occurred in March followed by many instances of freezing and thawing during April which was reported as a freeze-kill (Ontario Apple Growers 2013; and Ontario Tender Fruit Producers' Marketing Board 2014). $T_{\min}$ time series of 2015 was more typical of the period 2002 to 2017 where it increased steadily over the spring months and $\mathrm{DDT}_{\min}$ occurred from end of April to mid-May ending with a freeze-kill on May 22-23

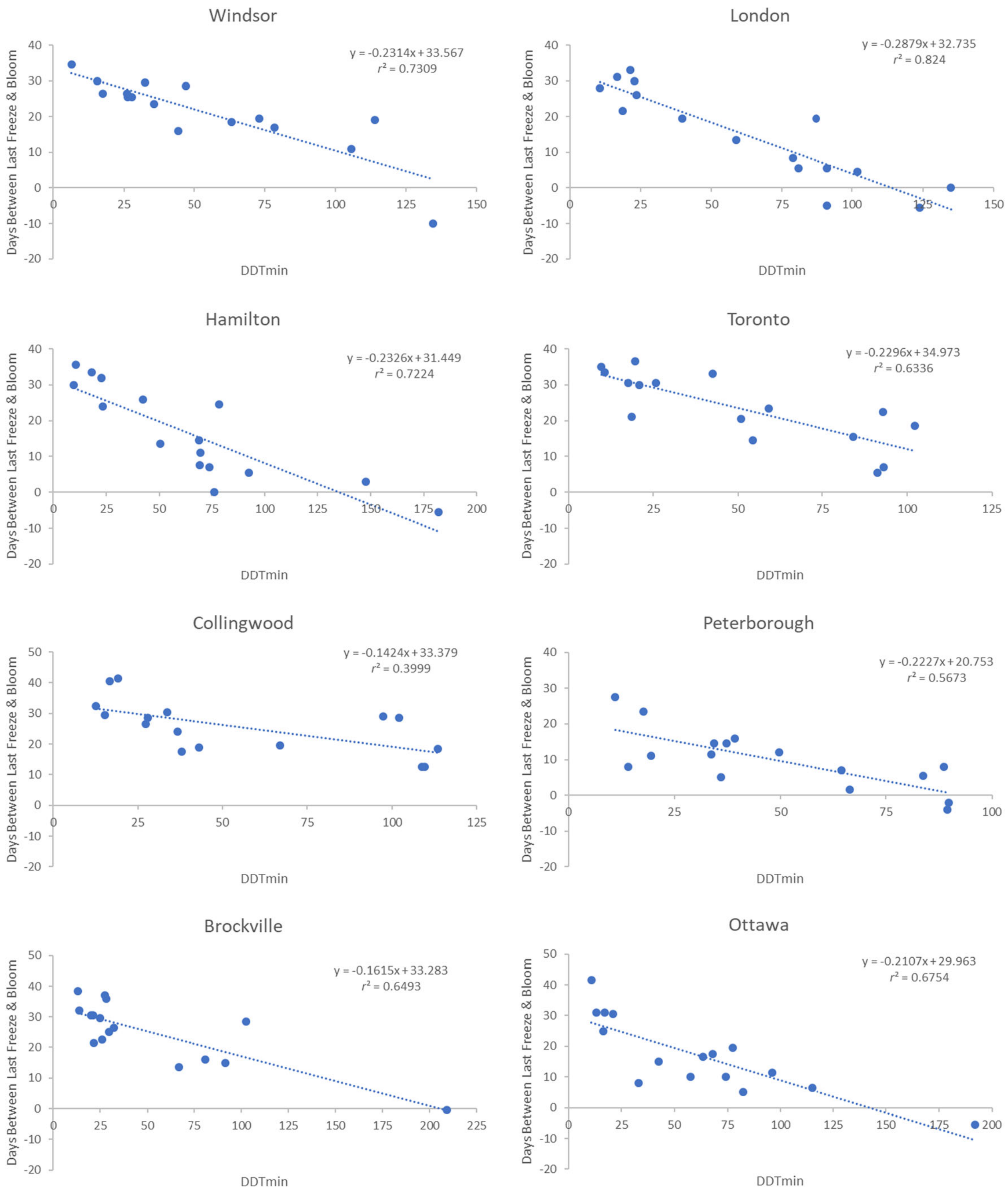
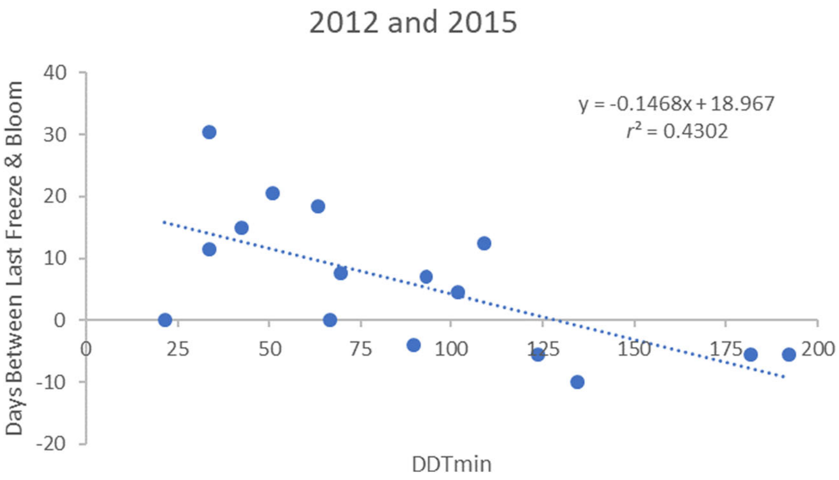


Fig. 5 Apple: plots of $\mathrm{DDT}_{\min}$ vs. Days between last freeze (date of last $T_{\min} < 0$ °C) and bloom date; the more negative the value, the earlier blooming occurred

(reported by Ontario Apple Growers 2015; and Ontario Tender Fruit Growers 2016) (see Fig. 10). Due to the lower GDH requirement of peach, chillR predicted peach to bloom earlier than apple by about 15 days. In 2012, peach blooming occurred on April 5 during a series of freeze-thaw cycles while apple blooming occurred after the freeze-thaw series on May 2 followed by continued warming (Fig. 10). In 2015, both apple and peach bloomed during the $\mathrm{DDT}_{\min}$ period. Despite an uncertainty in the actual timing of blooming as they were modelled, the $\mathrm{T}_{\min}$ data and reported losses suggested that apple buds may be more sensitive to an early warming (early $\mathrm{DDT}_{\min}$) followed by a series of freezing and thawing than normal warming (later $\mathrm{DDT}_{\min}$) followed by a single freeze event. Peach on the other hand was not as sensitive to varying sequences of thawing and freezing nor as sensitive as apple. This timing of $\mathrm{DDT}_{\min}$ is significant and a current limitation. To further improve the utility of $\mathrm{DDT}_{\min}$, an expanded data set and additional analysis would therefore be needed to explore

Fig. 6 Apple: plot of DDT$_{min}$ vs. Days between last freeze (date of last $T_{min} < 0$ °C) and Bloom date for 2012 and 2015, for eight stations; the more negative the value the earlier blooming occurred



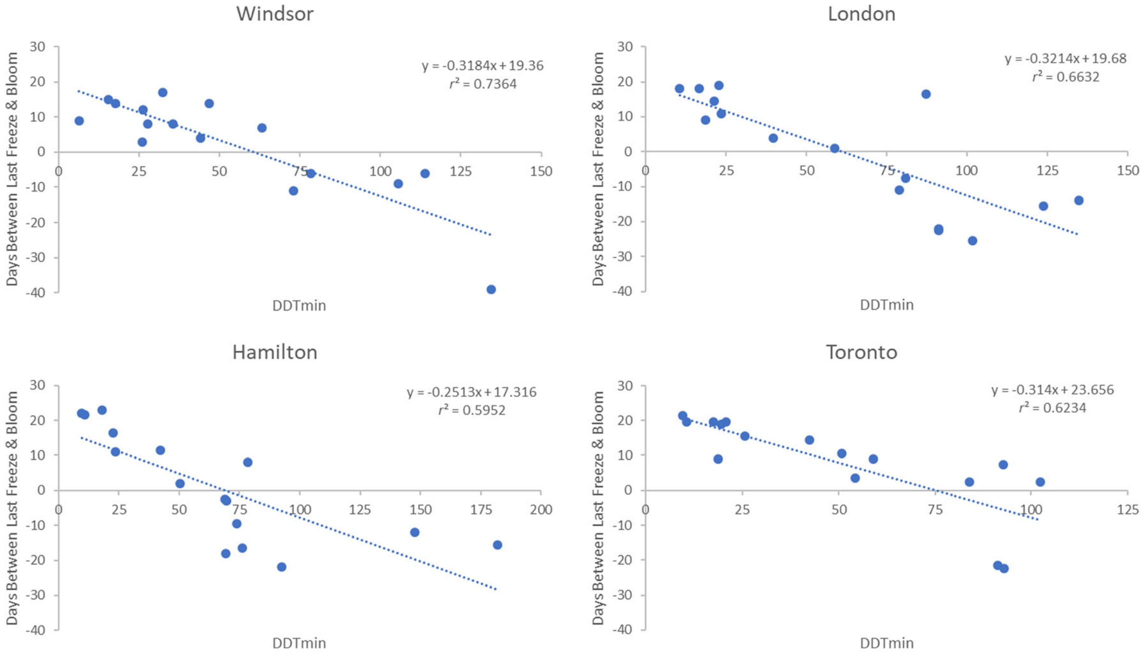


Fig. 7 Peach: plots of DDT$_{min}$ vs. Days between last freeze (date of last $T_{min} < 0$ °C) and bloom date; the more negative the values, the earlier blooming occurred

Fig. 8 Peach: plot of DDT$_{min}$ vs. Days between last freeze (date of last $T_{min} < 0$ °C) and bloom date for 2012 and 2015, for four stations; the more negative the values the earlier blooming occurred

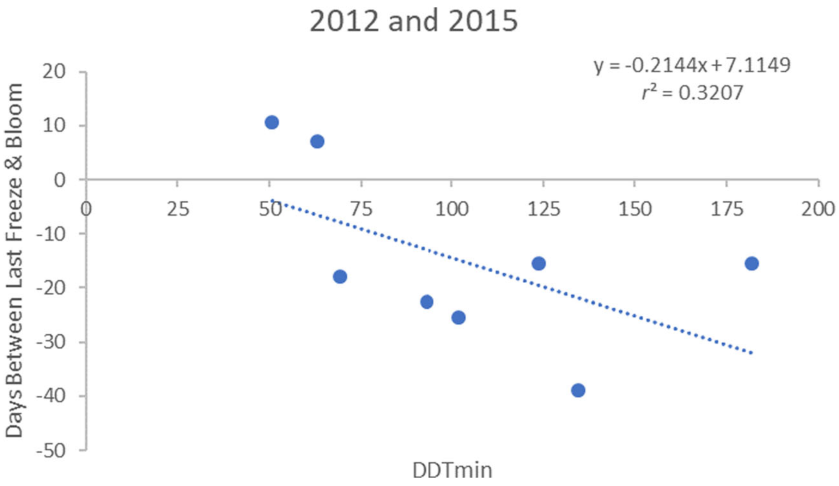


Table 2 DDT$_{min}$ and their return periods (RP) for years in which there were reported apple and peach freeze-kills compared with those with no freeze-kills over the crop reporting period 2002–2017. Data presented for all eight climate stations and four stations Windsor to Toronto corresponding to apple and peach growing regions, respectively; mean with their standard error (SE); RP of regressed mean and median DDT$_{min}$ according to RP = exp((DDT$_{min}$ − 6.3665)/40.097), r^2 = 0.95 for apple and RP = exp((DDT$_{min}$ − 7.7631)/40.185), r^2 = 0.96 for peach

Year (fruit region)	DDT$_{min}$ (°C d)		RP (years)			
	Mean ± SE	Median	Mean ± SE	Median	Regressed mean	Regressed median
2012 (apple)	81.3 ± 11.4	81.3	10.2 ± 3.0	7.6	6.5	6.5
2012 (peach)	99.7 ± 11.6	97.5	13.5 ± 4.9	9.5	9.8	9.3
2015 (apple)	94.5 ± 21.6	76.3	11.0 ± 3.8	6.1	9.0	5.7
2015 (peach)	104.9 ± 26.1	93.5	12.0 ± 5.4	7.5	11.2	8.4
Other years (apple)	50.9 ± 3.5	37.5	5.2 ± 0.8	2.1	3.0	2.2
Other years (peach)	51.1 ± 4.7	42.4	4.5 ± 0.6	2.5	2.9	2.9

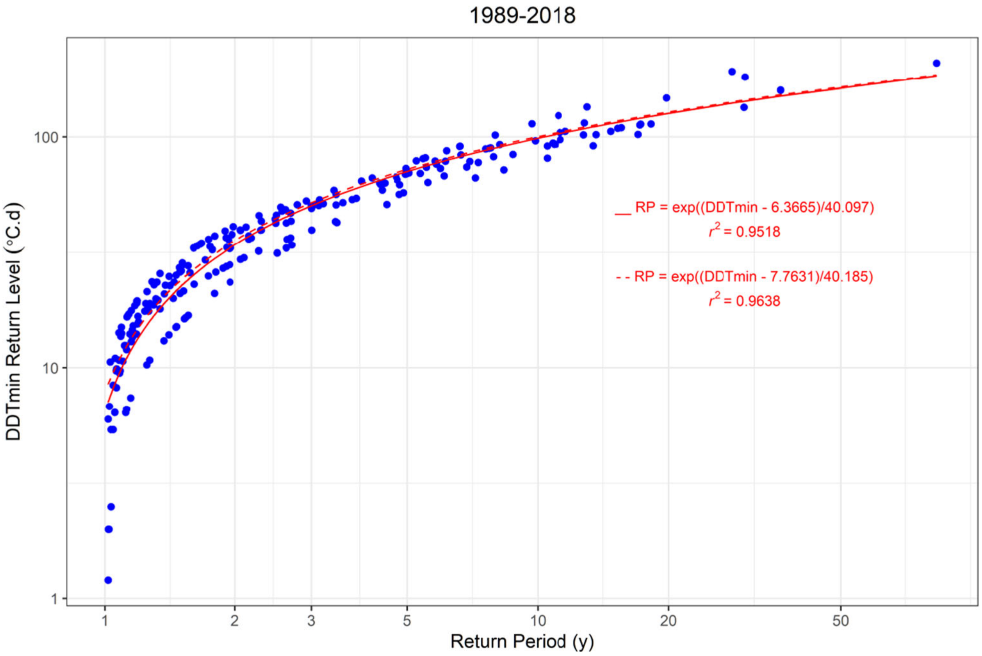


Fig. 9 DDT$_{min}$ and its RP for the stations Windsor, London, Hamilton, Toronto, Collingwood, Peterborough, Brockville and Ottawa for the period 1989–2018; solid regression curve represents all eight stations for apple; dashed curve represents four stations from Windsor to Toronto for peach

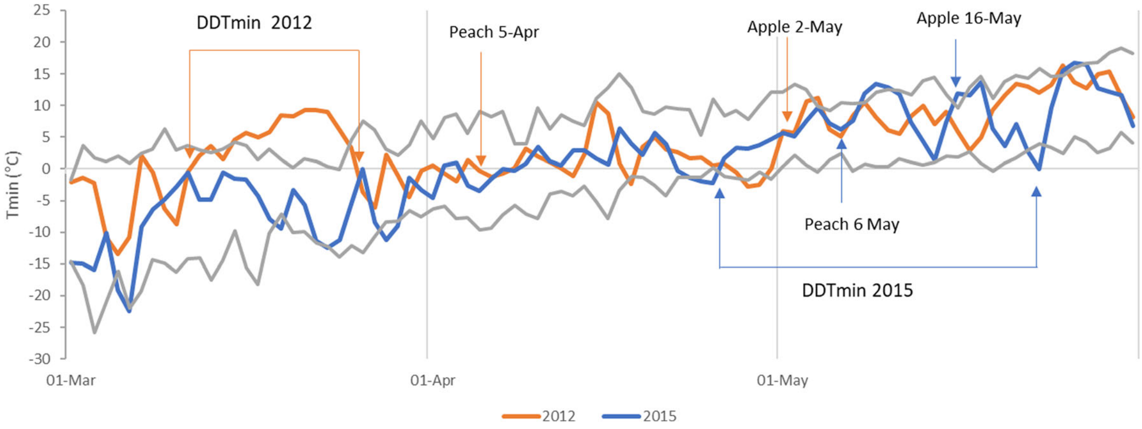


Fig. 10 T_{min}, averaged for the eight stations used in the analysis from March to May for years 2002 to 2017. The grey time series are the upper and lower limits of T_{min} excluding 2012 (orange) and 2015 (blue); time series for the four stations Windsor to Toronto representing the peach-growing region were nearly identical

the relationships with its timing, type of fruit (as it relates to blooming), and associated magnitude of loss/damage.

We can also estimate the probability of an event with a given RP occurring at least once in an N-years period by $p = 1 - (1 - 1/\mathrm{RP})^N$. This probability of a given $\mathrm{DDT}_{\mathrm{min}}$ to reoccur can be used to inform changing risk management strategies as time evolves. For example, the 2012 $\mathrm{DDT}_{\mathrm{min}}$ with a mean RP of 10.2 years and median of 7.6 years would have a $p = 0.56$ and 0.68 of occurring at least once, respectively after eight years in 2020; and $p = 0.75$ and 0.84, respectively after 13 years in 2025. It shows that the 2012 event has a fairly high probability of recurrence and we note that the two significant freeze-kill events occurred within four years of each other.

In conclusion, $\mathrm{DDT}_{\mathrm{min}}$ is a promising indicator of large magnitude thaw-freeze events that led to significant freeze-kill losses for apple and peach crops and is a mean of estimating the severity. Such events are extreme and, by definition, occur infrequently and can be described by the GEV distribution. Although there were only two extreme thaw-freeze events that led to significant losses, these events and losses occurred across the entire fruit-producing region of southern Ontario. Eight stations recorded these thaw-freeze events and all producing counties reported significant losses due to these events. Smaller magnitude $\mathrm{DDT}_{\mathrm{min}}$ tended to occur frequently without any freeze-kill losses while the significant ones had a recurrence on the order of 10 years. As the mean global air temperature increases and its variability increases, atypical warming can occur as seen in 2012 for the study region. This poses a significant risk to fruit producers when yields can be impacted by a loss of up to 80% for the entire apple-producing industry. It poses a challenge for current production areas and should be considered when planning for adaptation strategies such as expansion to more northern regions. Although this study focussed on the fruit-growing region in southern Ontario, the approach can be applied to other regions where spring freeze-kill can impact fruit production. For Canada, this includes regions in the provinces of British Columbia, Quebec, New Brunswick, Nova Scotia and Prince Edward Island; and globally at higher latitude and/or altitude fruit-producing regions.

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Data availability All data are publicly accessible and methods of analysis and software are described in the manuscript.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests. The authors have no conflicts of interest to declare that are relevant to the content of this article. Partial financial support was received from the Sustainability Metric Project of the Science and Technology Branch of Agriculture and Agri-Food Canada.

Code availability R packages noted in the manuscript were used to analyse data and then further explored and visualized using Excel.

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