Climate change and future overwintering conditions of horticultural woody-plants in Finland

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Climate in Finland offers challenging conditions for commercial horticulture. The short and insufficient growing season together with risky overwintering strongly limits species suitable for cultivation. The aim of this study was to examine the climatic conditions around Finland in the aspect of horticulture, focusing on processes relevant to woody plants and species with photoperiod controlled growth cessation, and how these conditions may be expected to change due to the projected global warming. For this, a set of temperature-related indices and threshold events were used. These indices represent the severity of coldness during winter, wintertime thaws, and frost events close to the onset and ending of the growing season. The combined results of 19 GCMs (General Circulation Model) from the CMIP3 (Coupled Model Intercomparison Project 3) multi-model data set under SRES-B1 and SRES-A2 (Special Report on Emission Scenarios) emission scenarios were used to produce the future projections. By mid-century our results suggest wintertime conditions with reduced cold stress, caused by less frequent and shorter periods of severe frost together with a rise in the extreme minimum temperature. Conversely, an increase in the number and intensity of wintertime thaw events leads to a higher risk in overwintering. Also the risk of spring frost damage is projected to decrease slightly, and the conditions for cold hardening process to improve, as the first autumnal frosts occur later.

Introduction

In the present climate, with cold winters and short summers, commercial horticulture in Finland is challenging. At the border between maritime and continental climates, winters are characterized by large variations, including occasional thaw periods and cold-air outbreaks. For many species the growing season is insufficient in length. These factors generate a strict framework for Finnish horticulture, making Finland one of the northernmost countries with commercial production. Horticulture at high latitudes is one of the fields of agriculture that are expected to benefit from climate change (Marttila *et al.* 2005). By the last decades of the 21st century, the annual mean temperature in Finland is projected to rise by about 2 to 6 °C (Jylhä *et al.* 2009) relative to the reference value (calculated over the period 1971–2000), which is roughly double the global average increase (IPCC 2007). Warming is projected to be considerably stronger in winter than in summer and slightly larger for cold extremes than for mean temperatures (Kharin *et al.* 2007, Kjellström *et al.* 2007). Obviously, as a direct response to the rise in

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temperature, the growing season will lengthen along with an increase in the number of accumulated growing degree-days. Also overwintering of perennial plants could be altered by milder winter temperatures with less severe frost events. If realized, these changes would enable an extension of the regions where current species and varieties are cultivated, and open the way for the introduction of new species and varieties with increased crop potential.

There are also some potential risks arising from a warming climate. These include problems with overwintering as thaw periods become more frequent and longer, thus modifying cold hardiness of plants. Severe freezing temperatures may still occur during cold-air outbreaks from the Arctic or Siberia. There are also significant changes projected for snow cover with less snow in future, especially around the northern Baltic Sea (Jylhä *et al.* 2008). Since snow cover acts as an efficient insulator, a reduction increases the exposure of tender roots and low-lying bushes to low temperatures. Late spring and early summer frosts during bloom can cause significant losses to annual yield and, therefore, have a large economical impact on horticulture (Snyder and de Melo-Abreu 2005). The risk from late spring frost is speculated to increase in Finland (Marttila *et al.* 2005). One more adverse outcome from climate change, including generally wetter and warmer conditions during winter, is improved living conditions for numerous pests, pathogens and weeds (Hildén *et al.* 2005). Aforementioned factors will probably increase the use of pesticides in future; this would be a major drawback, as relatively low levels of their current usage are one of the advantages of Finnish horticulture.

The aim of this study is to examine climatic conditions related to horticulture in Finland, focusing on temperature-related factors and overwintering, and how these conditions might change due to projected warming. We choose a similar approach to that of Rochette *et al.* (2004) and Winkler *et al.* (2000), by using a group of agro-climatic indices and threshold events to describe conditions relevant to the risks related to overwintering. The methodology dovetails well with our more general study on climatic conditions, with no relationship to any specific species.

However, it is important to point out some of the limitations of the chosen approach. Indices used in this study are based on knowledge on the behavior of fruit trees, and more generally on woody plants. Indices are not relevant to some other horticultural crops, mainly herbs and grasses which behavior can differ significantly from that of woody plants. The indices are also simple to calculate when making future projections based on climate model data. Kaukoranta *et al.* (2010) executed more species-specific, in this case apple, study about future climatic potential and risks in Finnish horticulture. A species-specific approach would require indices that are individually developed and tested for each species, and even cultivar, in question.

The use of indices and threshold events is supported by more quantitative information about the relationships between weather conditions and winter damage, mostly concentrated on apple trees. Lindén (2001) studied these relationships for Finnish apple orchards, using historical records of winter injuries. Together with a Canadian study (Caprio and Quamme 1999), also at the northern fringe of apple production, Lindén (2001) concluded that winters with wide-ranging winter-injuries are best characterised by mid-winter severity. In years with winter-injury, the average monthly minimum temperatures in southwestern Finland were –22 °C for December and –29 °C for February, similar to those for Canada (Caprio and Quamme 1999). However, Lindén found no connection between winter-injury and the occurrence of rapid temperature drops. In Canada, damage was found to occur (Coleman 1992) when the daily temperature drops rapidly from above zero to below –20 °C.

In this paper, we describe the climatic indices and threshold events relevant to Finnish horticulture and outline the plant physiology and phenology related phenomena behind these indices. We also present the observations and climate model data used in this study, together with the methods used to construct the future projections for these indices and events. This study was made in the context of the ILMASOPU (Adaptation of Finnish agri-food sector to climate change) project, which aims to comprehensively estimate the potential of the Finnish agri-food sector in the future.

Material and methods

Indices

Indices are commonly used to describe the effect of climate, its variability and impacts of future climate change on different sectors of society (e.g. Persson *et al.* 2007). In this study, we used similar agro-climatic indices to those that Rochette *et al.* (2004) used to investigate the impact of climate change on overwintering of fruit trees in Canada. We modified them slightly so as to make these indices more suitable for our data and Finnish practices. This included the usage of the observed minimum air temperature at the ground level (T_g), for spring and autumn frosts, instead of using minimum temperatures at the standard height of 2 meters. These indices are defined in Table 1.

Winter indices

The current winter climate over large parts of Finland is severe enough to cause some winter damage even to well-adapted fruit and berry species with a high tolerance for freezing temperatures. Perennial plants have two methods to tolerate freezing temperatures: intra- and extracellular (Sakai and Larcher 1987). Both methods have the same goal: to avoid ice formation inside cells.

During the autumnal hardening process, the plant cell-content can reach a state of supercooling via desiccation. Supercooling can extend to an even deeper stage during winter, thanks to the formation of extracellular ice. The potential formation of extracellular ice desiccates the cell content even further, since the difference in saturation vapour pressure between ice and liquid water results in the preferential evaporation of water through the cell membrane towards extracellular ice (Snyder and de Melo-Abreu 2005). When a frost period is prolonged and the extracellular ice continues to grow, frost damage may occur if the cell content is desiccated too much. Damage is caused by the collapse of the cells, or by excessive ice formation causing damage to the structure of the cells. Hence, plants can tolerate briefly (up to a few hours) intense freezing

Table 1. Indices and threshold events used. Associated descriptions and units are also introduced. T_m, T_n and T_g stand for daily mean temperature, daily minimum temperature and daily ground level minimum temperature, respectively.

Season	Indices or threshold	Description	Unit
Winter	CDD_-15	Sum of cold degree-days: $T_m < -15$ °C from 1 Aug. to 31 Jul.	Kelvin days (Kd)
	AMT	Lowest T_n from 1 Aug. to 31 Jul.	°C
	L_-15	Date of last occurrence of $T_n \leq -15$ °C after 1 Jan.	Date
	THAW	Sum of degree days: $T_m > 0$ °C from 1 Jan. to L_-15	Kelvin days (Kd)
Autumn	FAF_-2	Date of first autumnal frost $T_g \leq -2$ °C since 1 Aug.	Date
Spring	SGS	Start of the growing season: date of first 5-day spell with $T_m > 5$ °C	Date
	LSF_-2	Date of last spring frost $T_g \leq -2$ °C	Date
	T_SUM_5	Sum of degree-days: $T_m > 5$ °C from SGS to LSF_-2	Kelvin days (Kd)

via supercooling, but continuous milder freezing over a few days is more likely to result in excessive extracellular ice and subsequent cell damage. Therefore, two indices are required to adequately represent the coldness of winter climate. We used the same two indices as Rochette *et al.* (2004) to describe the stress caused to plants in winter by freezing temperatures. Conditions with prolonged or frequent, relatively severe freezing temperatures were expressed with the index CDD_–15 (Kd; for indices and their units *see* Table 1), which consists of cumulative cold degree-days below –15 °C. Temporary cold tolerance of plants is defined by the stage of deep supercooling. Here, we present the absolute minimum temperature of the winter (ATM) as an indicator of the risk of frost injury related to temperature drops below the level of crop specific temporary cold tolerance.

The hardiness of plants to cold fluctuates during the winter depending on environmental temperatures. Substantial exposure to warm conditions can result in a loss of hardiness. If the level of hardiness reduces during a thaw, the risk of damage due to subsequent exposure to severe freezing is increased. To express this, we again used a similar index to Rochette *et al.* (2004): the THAW index (Kd) consists of degree-days above 0 °C between the start of the year and the last occurrence of –15 °C or below (date of L_–15) during the winter in question. It should be noted that the THAW index does not consider whether a severe freeze occurs immediately after a thaw event, which is when damage is most likely to happen, it merely describes the potential for risk whenever a severe freeze follows a thaw.

Autumnal and spring indices

For many woody plants growing at high latitudes, the shortening of the daytime (i.e. photoperiod) in autumn controls the cessation of growth and the start of the hardening process (Sakai and Larcher 1987). However, some exceptions exist; for example, for apple and pear trees it is the decreasing autumn temperatures that induce growth cessation (Heide and Prestrud 2005). Hardening is an important element of successful overwintering and it proceeds with declining temperatures. In ideal conditions for this process, temperatures range between 0 °C and 5 °C. If the period between the dates of cessation of growth (specific for every species, variety and geographical origin of the plant), and the first frost of the autumn is too short, hardening may be inadequate. Thus, the longer the frost-free period after cessation of growth, the better the conditions are for the hardening process. To describe conditions for autumnal cold hardening of woody plants, we take the date of the first moderate frost since the start of August, where daily ground level minimum T_g ≤ –2 °C (date of FAF_–2). We ignore weaker frosts because, according to Solantie (1987), these may currently occur throughout the whole year in Finland, except in the archipelago and areas dominated by lakes. Also, species growing in temperate zones do tolerate mild frost.

After the onset of spring, the level of hardiness to cold drops steadily as the environmental temperatures rises. During the early part of the growing season, as the developmental stage of flower buds progresses, the risk of frost damage rises gradually (Proebsting and Mills 1978). Generally, for most fruit trees in temperate zones, a 30 minute exposure to temperatures of –2 °C at full bloom destroys 10% of the flowers and exposure to –5 °C, 90% (Rochette *et al.* 2004). Therefore, the repercussions from frost events during the growing season will be more severe the later they occur. We measure the sensitivity of horticulture to late spring frost with accumulated effective degree-days, as degree days are an indicator for a plant's stage of development.

We describe the relationship between the last spring frost and the accumulated effective degree-days with the index T_SUM_5 (Kd), which consists of the cumulative number of degree-days above 5 °C during the period between the start of the growing season and the last spring-frost. We assume the start of the growing season (SGS) to be equal to the start of the thermal growing season. For the latter we used the first five-day spell with T_m (daily mean temperature) remaining above 5 °C (e.g. Carter 1998). According to Walther and Linderholm (2006), growing season indices vary, but the 5 °C T_m threshold is widely accepted, in particu-

lar for mid and high latitudes. It is also assumed that ground is snow free during the SGS. For the last spring frost (LSF_–2) we take the date of the last moderate frost (daily minimum $T_g \le -2$ °C), again because of the slight frost tolerance of fruit trees growing on higher latitudes, even at full bloom. Thus, a larger value of T_SUM_5 represents a greater vulnerability to late spring frosts.

Climate data

Our study covers the main agricultural areas of Finland except the Åland Islands: Lapland was also excluded because of its clearly unsuitable climate for commercial horticulture. Our indices were evaluated for three 30-year periods, 1971–2000, 2010–2039 and 2040–2069, using temperature data from both observations and climate models.

Weather stations and observational data

Two criteria were used for selecting weather stations. Firstly, complete or nearly complete daily air-temperature observations, including ground-level temperature measurements for the period 1971–2000, were required. Secondly, the selected stations had to cover the different hardiness zones of fruit trees in Finland, as defined by Solantie (2004). Five weather stations, which complied with the criteria, were chosen (Fig. 1 and Table 2). Three of the selected weather stations (numbers 1, 3 and 5 in Fig. 1) are located at research stations of the Agrifood Research Finland and the remaining two stations represent the Finnish lake district (number 2), and the eastern, more continental part of Finland (number 4).

Daily observations were extracted from the climate database of the Finnish Meteorological Institute, of which ca. 3% was missing, mainly T_g. However, only a small fraction of the missing T_g values was relevant to LSF_–2 and FAF_–2; these were estimated using a typical, weather-station and season-dependent, difference between daily minimum temperatures measured at the height of two meters inside a screen and minimum temperatures at the ground level.
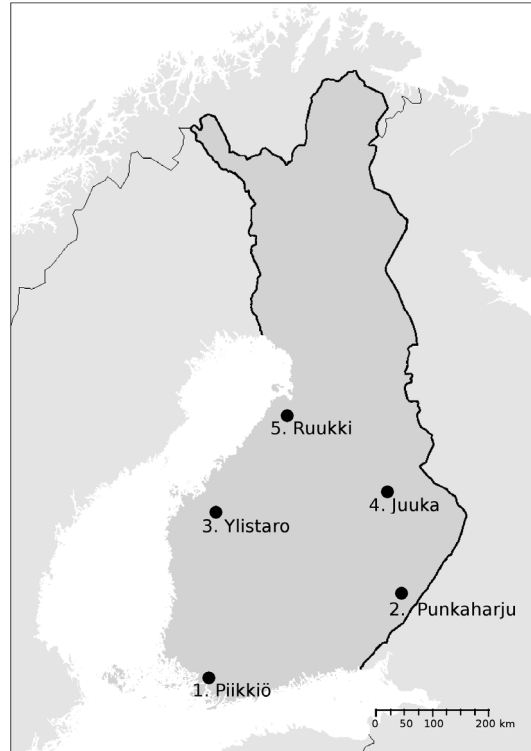

Fig. 1. Locations of weather stations used. Numbers from 1 to 5 refer to the numbers of the weather stations in Table 2.

Climate model data

Temperature change scenarios were constructed from simulations performed with 19 global climate models that were utilized in preparing the

Table 2. Station data for the weather stations used in this study and the associated hardiness zones (HZ) of fruit trees. Stations in the first column refer to locations 1–5 in Fig. 1. The lower the hardiness zone number, the better conditions are for fruit trees (Solantie 2004). Hardiness zones are determined by the combination of effective temperature sum of the growing season, length of the growing season and the level of coldest winter temperatures.

Station	Name	Lat. N	Long. E	HZ
1	Piikkiö	60°23′	22°33′	1B
2	Punkaharju	61°48′	29°19′	2
3	Ylistaro	62°56′	22°29′	4
4	Juuka	63°14′	29°14′	4–5
5	Ruukki	64°41′	25°06′	5

2007 Fourth Assessment Report of the IPCC. The data were taken from the so-called CMIP3 multi-model dataset (Meehl *et al.* 2007). The scenarios describe changes in 30-year averages of monthly mean temperatures relative to the period 1971–2000. We considered two future periods, 2010–2039 and 2040–2069, and two SRES emission scenarios, A2 and B1 (Nakićenović *et al.* 2000). For the period 2010–2039, we used only scenario A2, and for the period 2040–2069 we used both A2 and B1 scenarios. This choice was made because, according to the IPCC (2007), it is not until the mid-21st century that any differences between the emission scenarios become more significant.

Multi-model mean projections for changes in the monthly mean temperature were interpolated onto a 0.5° × 0.5° grid covering Finland (for more details, *see* Jylhä *et al.* 2009). In this study, temperature change scenarios for each of the five weather stations were extracted from the grid simply by selecting the land grid-point closest to the weather station in question. All selected grid points were within 20 km of the weather stations.

Application of model data to observations for calculating indices

Daily temperature data are required for calculating the indices used in this study. With only monthly climate model data output available, we used the so-called delta change method (e.g. Meier *et al.* 2006) to provide the daily data for the future periods. In the delta change method, the simulated climate response is connected with observations, i.e. the projected monthly mean rate of warming for a particular SRES scenario, period, calendar month and grid point is added to the daily baseline temperature observations (1971–2000) of the particular weather station considered. The main limitation of this method is its strong reliance on observations, i.e. indices calculated for future periods have the same daily and annual variability superimposed on the background as the indices calculated for the present climate. Therefore, any possible future changes in the shape of temperature distribution, e.g. extreme temperatures and daily amplitudes, are neglected in the simple delta change method.

Adding simulated monthly mean warming to daily observations could cause errors in the indices, especially those with date-dependent values, if differences between the rates of warming between consecutive months are substantial. For example at Piikkiö (station no. 1), the average warming for the period 2040–2069 in scenario A2 is 2.3 °C for October, and 3.6 °C for November. Therefore, there is a large step change in the monthly mean warming between the last day of October and the first day of November. This could affect the calculation of the dates of threshold events, such as the first autumnal frost. Cubic splines were used (Schumaker 1981) to avoid these potential step-changes and to partition a specific rate of warming to each day of the year. Monthly mean warming was attributed to the central point of the month in question before the cubic spline interpolation.

According to climate model studies, daily minimum temperatures are projected to rise somewhat more rapidly than daily mean temperatures, especially during winter and at extremely low temperatures (Hegerl *et al.* 2004, Kjellström *et al.* 2007, Lobell *et al.* 2007). An attempt to take this asymmetric warming into account was made by modifying the warming rates of daily minimum temperatures slightly relative to the coincident warming rates of daily mean temperatures. The adjustment of daily minimum temperatures was carried out by using regional climate model data produced in the PRUDENCE project (Christensen *et al.* 2007). Using data from seven regional climate models, estimates of the difference in the change in daily mean and daily minimum temperatures were made for Finland, and an almost linear relationship was found (Fig. 2). Based on these estimates we derived the following relationship:

$$\Delta T_{min} = 1.155 \Delta T_{mean} - 0.114 \qquad (1)$$

where ΔT_{min} is the increase in daily minimum temperature, and ΔT_{mean} is the increase in daily mean temperature. The additional warming of ΔT_{min} was found to be in the range 0–0.6 °C.

Although this method may appear oversimplified, we wished to take the asymmetric warming of temperature distribution into account because it could have had a notable effect on the

behaviour of late spring frosts, one of the trickiest questions related to the future climatic conditions for horticulture in northern regions.

Results

The rise in temperature, relative to the observed 1971–2000 period ranges from 0.9 °C (August 2010–2039 A2 in Piikkiö) to 4.8 °C (January 2040–2069 A2 in Ruukki). Generally, the warming is slightly stronger towards the north and more continental regions and, for the winter months (Dec., Jan., Feb.), is about twice that seen for the summer months (Jun., Jul., Aug.), with warming rates for spring (Mar., Apr., May) and autumn (Sept., Oct., Nov.) falling in between. Warming rates in scenario B1 by 2040–2069 are roughly halfway between the A2 warming for 2010–2039 and for 2040–2069.

Damages due to extreme winter cold

Extreme winter cold was examined using two indices, CDD_–15 and AMT, which describe both the duration and intensity of freezing temperatures. CDD_–15, which reflects conditions of prolonged severe frosts and the following risk for accumulation of excessive extracellular ice, is substantially reduced in the future (Fig. 3). As temperatures rise, the temperature threshold of the daily mean temperature below –15 °C is attained less frequently.

The mean accumulation of CDD_–15 is reduced from the present level (1971–2000) by approximately one-third for 2010–2039 and by half for 2040–2069 (scenario B1) at all locations. In scenario A2 (2040–2069), the mean conditions for CDD_–15 at Punkaharju (station no. 2) and Ylistaro (station no. 3) are somewhat similar to the present conditions found at Piikkiö (station no. 1), a region where commercial apple production exists today. At Piikkiö, which has the mildest winter climate amongst the stations considered here, roughly every third winter during 1971–2000 had zero or an insignificant (we used an arbitrary threshold of ≥ –10 Kd) accumulation of CDD_–15. As the temperature rises, these non-risk winters will become more and more
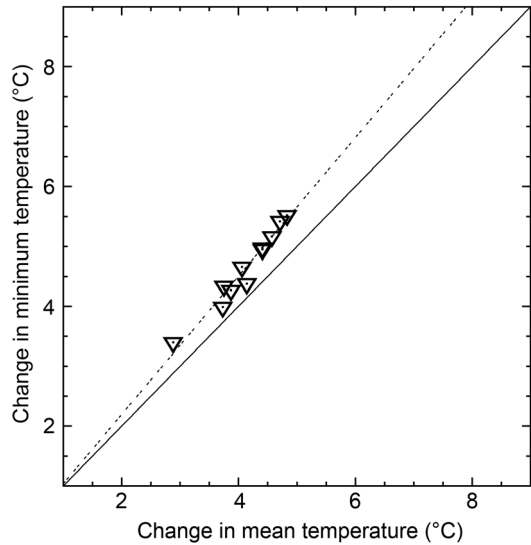

Fig. 2. Projected changes (annual average) in daily minimum temperatures *versus* projected changes in daily mean temperatures in Finland from 1971–2000 to 2070–2099. The diagonal line divides the scatter plot into two parts; in the upper part, changes in daily minimums are larger than changes in daily means and *vice versa* in the lower part. The triangular symbols depict the group of regional climate model projections produced in the PRUDENCE project (Christensen *et al*. 2007). The thin dashed line shows the linear regression fitted into model projections, expressed by Eq. 1.

common. By 2040–2069 (scenario A2), low-risk winters are predicted to occur in seven years out of ten at Piikkiö, four years out of ten at Punkaharju and Ylistaro, and every fourth year at Ruukki (station no. 5). However, at Juuka (station no. 4), which has the coldest winter climate among this study sites, some accumulation of CDD_–15 will still occur during every winter. Below –100 Kd is reached about every third winter during 2040–2069 in A2, as compared with three years out of four during the period 1971–2000.

The ATM index is much simpler because of the use of delta change method. Despite the modification of the daily minimum temperatures relative to the daily mean (Eq. 1), we were not able to systematically consider changes in the temperature distribution, especially in the tails of the distribution. Kjellström *et al*. (2007) project even larger changes in ATM than this study. The increase in ATM is more pronounced in colder regions; therefore differences in ATM between locations tend to decrease. The increase in ATM
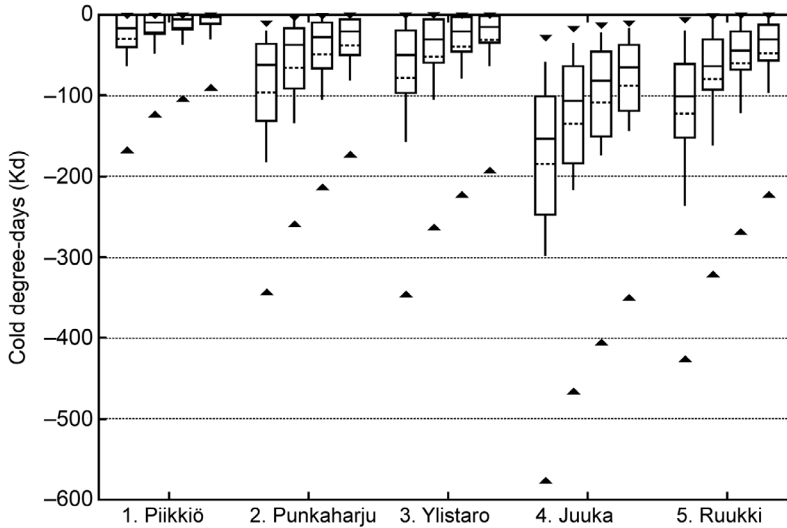
Fig. 3. Boxplots of CDD_–15 for five weather stations in Finland (*see* also Table 2 and Fig. 1). There are four boxplots shown for every station, representing indices calculated from observations from 1971–2000 (first from the left), and from future scenarios for the period/emission scenario 2010–2039 A2 (second), 2040–2069 B1 (third) and 2040–2069 A2 (fourth), respectively. Lower and upper boundaries of box indicate lower and upper quartiles; solid and dashed horizontal lines within boxes indicate median and mean, respectively; ends of vertical lines below and above box indicate 10th and 90th percentiles, respectively; triangular symbols pointing up and down indicate minimum and maximum values, respectively, of the samples.

ranges from 1.5 °C to 2.4 °C for 2010–2039, and from 2.9 °C to 4.1 °C (scenario B1) and 4.0 °C to 5.2 °C (scenario A2) for 2040–2069 (not shown). Due to this increase in ATM, the mean conditions during 2040–2069 in scenario A2 are similar to or more favourable for horticulture than the present conditions at Piikkiö for all locations except Juuka, where conditions will be similar to those currently found at Punkaharju. At Punkaharju and Ylistaro future conditions in scenario B1 will also match the present conditions at Piikkiö. With rising ATM, the present temperature level of maximum deep supercooling will be faced less and less frequently.

Conditions for hardening during autumn and dehardening during winter

A warming climate will delay the first frost in autumn, here represented with the date of the first moderate frost since the start of August (FAF_–2). A later FAF_–2 improves the conditions for cold hardening of plants by lengthening the period between the cessation of growth,

controlled by a shortening photoperiod, and FAF_–2. Currently, the mean date of FAF_–2 ranges from the latter part of August (Ylistaro, Juuka and Ruukki, i.e. stations 3–5) to the latter part of September (Piikkiö and Punkaharju, i.e. stations 1–2). The warming influence of lakes during autumn can be clearly seen in the results for Punkaharju (Finnish lake district), where the proportion of lakes within a 10-km radius around the weather station is 56%. In Punkaharju, where the autumn frost conditions are comparable to those in Piikkiö, no FAF_–2 before September was observed during the period 1971–2000. In contrast, the Ylistaro station has quite an early FAF_–2 relative to the general climatic conditions in that region. These examples emphasize the role of the local micro-climates of the weather stations when considering frosts close to the start and end of the growing season.

For the period 2010–2039, the mean FAF_–2 is expected to shift 6–11 days later, relative to 1971–2000 (Fig. 4). For the period 2040–2069, this shift increases to 11–20 days in scenario B1 and 16–22 days in scenario A2. The change in mean FAF_–2 is smallest at Juuka, with 16
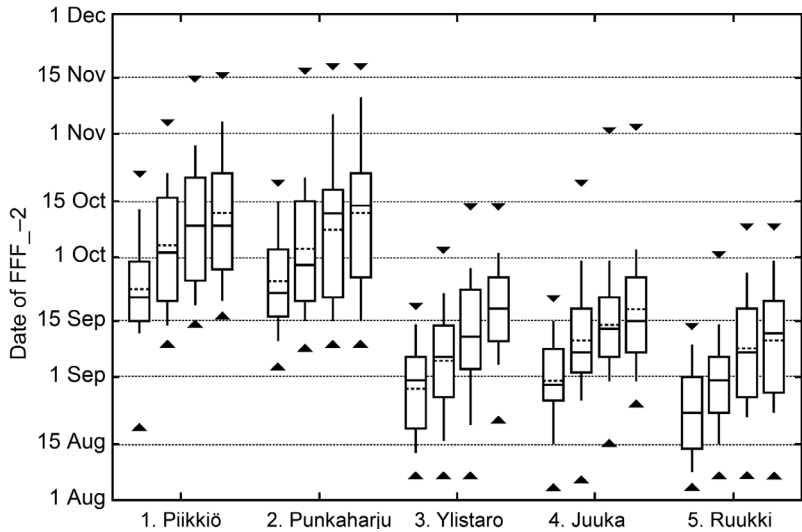
Fig. 4. Same as Fig. 3 but for FAF_–2, representing the date of the first moderate autumnal frost.

days, and greatest at Punkaharju and Ruukki (22 days). There seems to be no geographical pattern in the delaying of the mean FAF_–2. As a result of warming (2040–2069, scenario A2), the first moderate frost of the autumn usually occurs between mid-September and mid-October at all locations investigated here.

As mean temperatures in winter months rise, the number of days with a mean temperature above 0 °C will also increase. Thaw events can have an adverse effect on the overwintering of plants because of the possible lost of cold-hardiness and the increased risk of damage from a subsequent severe frost. Evidently, the increase in the accumulated temperature sum above 0 °C, which increases the THAW index, is partly compensated by the earlier occurrence of the last event with the daily minimum temperature ≤ –15 °C during winter (L_–15). However, projected changes in the date of L_–15 are quite moderate (not shown). On average, the changes in L_–15 relative to the period 1971–2000 are 6.6 days for 2010–2039, 7.4 days for 2040–2069 in scenario B1, and 9.6 days for 2040–2069 in scenario A2. The smallest change occurs at Ylistaro (seven days for 2040–2069, scenario A2) and greatest at Piikkiö (13 days).

In the current climate (1971–2000), the mean accumulation of THAW is fairly low (Fig. 5): 21 Kd in Piikkiö, the location with the mildest winters in this study. Winters with an insig-

nificant accumulation of THAW (about 10 Kd or less) are common, occurring every third to every second year at the locations studied here. The maximum THAW reached is 75 Kd at Ruukki. The mean accumulation of THAW will be at least doubled by the period 2010–2039 at all locations, and increases steadily as temperatures rise towards 2040–2069 for both scenarios (B1 and A2). However, Piikkiö is an exception, with apparently no difference shown in THAW between the two scenarios; this could be due to compensating factors such as the relatively large change in L_–15 between the two scenarios. The mean THAW over all locations increases from the current level of 14 Kd to 70 Kd by 2040–2069 in A2, with winters reaching 100 Kd becoming quite common, occurring roughly every third winter in Ylistaro, Juuka and Ruukki. Maxima reach 250 Kd.

There are some regional features in the behaviour of the THAW index. One is the difference between Punkaharju and Ylistaro, with THAW accumulation being clearly smaller at Punkaharju by 2040–2069. This is despite a similar mean L_–15 at both locations in the future scenarios. The clear difference in THAW is largely because of the vicinity of the open sea (the Gulf of Bothnia) at Ylistaro, resulting in more common winter thaw events.

Another regional feature of note is related to L_–15 and differences in its relative significance
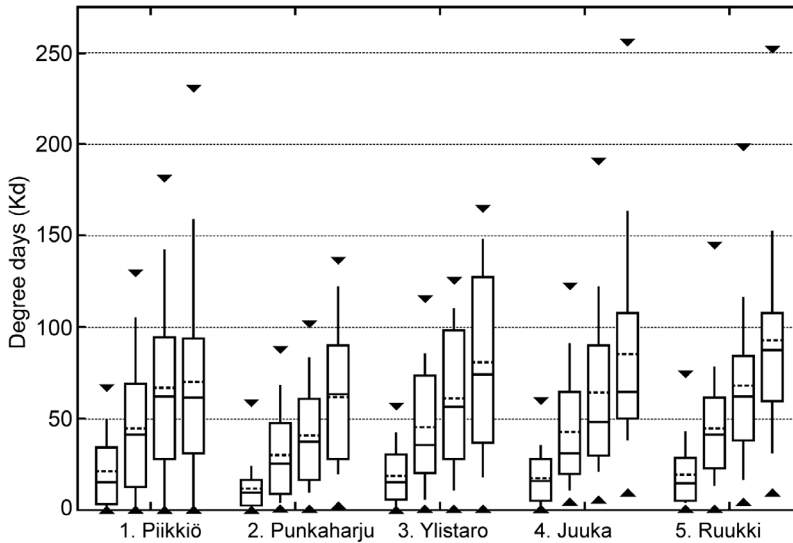
Fig. 5. Same as Fig. 3 but for THAW, representing risk of de-hardening during winter.

to the accumulated THAW index. Although there are no large differences in the projected changes of L_–15 for the period 2040–2069 (scenario A2), the effect of an earlier L_–15 on THAW is greater where L_–15 currently occurs earlier, such as at Punkaharju when compared with Juuka. The time available for the accumulation of THAW is reduced more at Punkaharju, relative to Juuka, even if the absolute change in L_–15 is the same. In scenario A2 by 2040–2069, the accumulation of THAW increases most at Ylistaro, Juuka and Ruukki and exceeds the levels of Piikkiö, the station with the largest THAW currently.

Vulnerability for spring frosts

The risk of frost damage during flowering was estimated using the T_SUM_5 index, which consists of accumulated degree-days above 5 °C between the start of the growing season (SGS) and the last spring-frost (LSF_–2). Accumulated T_SUM_5 during future periods is defined by the net effect of several factors. The net effect results from projected changes in timing of both SGS and LSF_–2, or more exactly, changes in the length of time between them. Also, the general warming of spring, and possible differences in the warming rates between the start and end of the time span in question, can also have their

own effect on the behaviour of T_SUM_5 in the future.

The projected changes in SGS are quite moderate and consistent, at least when considering medians of the 30-year distributions and the periods 2010–2039 and 2040–2069 in scenario B1 (Fig. 6). The mean values for the 30-year periods are more inconsistent because of some very early dates for SGS. These unrealistically early SGS dates (during January–February), found at all locations for the period 2040–2069 (scenario A2), and at Piikkiö as early as 2010–2039, are caused by the method used for estimating SGS. Changes in SGS by 2040–2069 in scenario A2, relative to 1971–2000, as medians of the 30-year samples, range from 11 days at Punkaharju, to 18 days at Piikkiö and suggests that, by 2040–2069 (A2), all locations will have an earlier SGS than Piikkiö has in the present climate.

Except at Punkaharju, the shift in LSF_–2 (Fig. 7) is generally smaller than for SGS. LSF_–2 is projected to occur ten to 15 days earlier than currently at all locations by 2040–2069, scenario A2. The time span between SGS and LSF_–2 changes only slightly, extending by four days at Piikkiö and Ruukki, three days at Ylistaro, a one day at Juuka, and shortening by four days at Punkaharju. There are currently large station-to-station differences in the length of the time span between SGS and LSF_–2, which will continue to be the case in the future. By 2040–
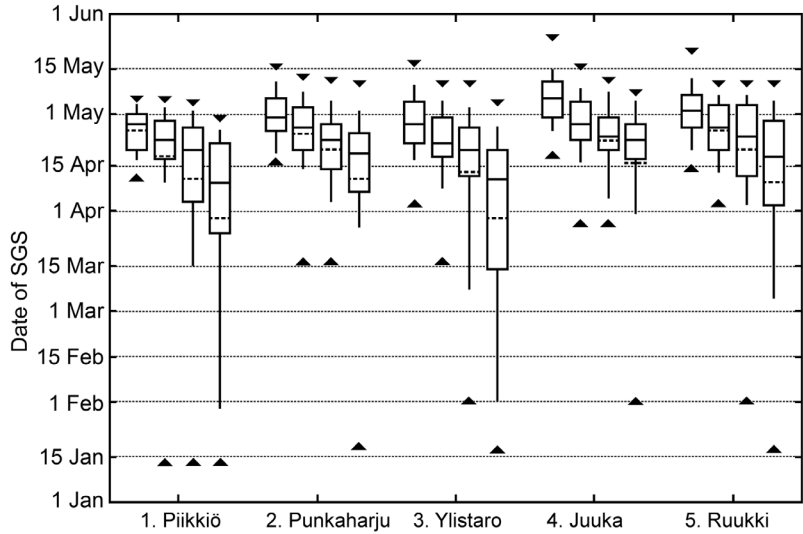
Fig. 6. Same as Fig. 3 but for SGS, representing the date of the start of the growing season.
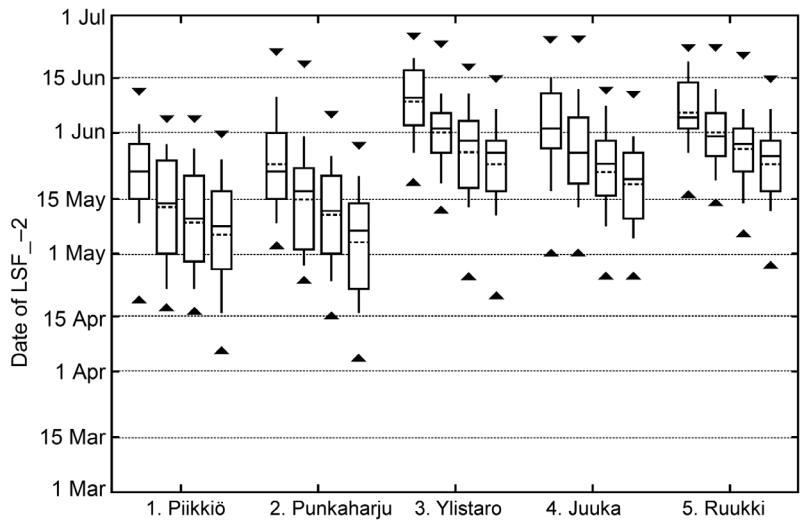

Fig. 7. Same as Fig. 3 but for LSF_–2, representing the date of the last moderate spring frost.

2069 in scenario A2, the difference ranges from only 18 days at Punkaharju to 46 day at Ylistaro. From FAF_–2, it is evident that the local climate at the Ylistaro weather station is very vulnerable to early-autumn and late-spring frosts. However, according to the FMI's weather station database, Ylistaro is found to be representative temperature-wise for wide-plain fields in the region.

The time span between SGS and LSF_–2 strongly affects the mean levels of accumulated T_SUM_5, both during the present and in the future. Punkaharju has the smallest and Ylistaro the greatest T_SUM_5 (Fig. 8). Even

though, according to our results, the time span between SGS and LSF_–2 generally increases in the future, there is a clear signal of lower T_SUM_5, implying that there is a slightly reduced risk of frost damage from late-spring frosts. By 2040–2069 in scenario A2, median values of T_SUM_5 are reduced by 25–66 Kd, relative to 1971–2000, resulting in T_SUM_5 accumulation of about 60%–75% of the current levels. A reduction in T_SUM_5, in spite of a slightly longer accumulation time span, is dominated by the earlier date of the last spring-frost. Daily accumulation of T_SUM_5 is usually substan-
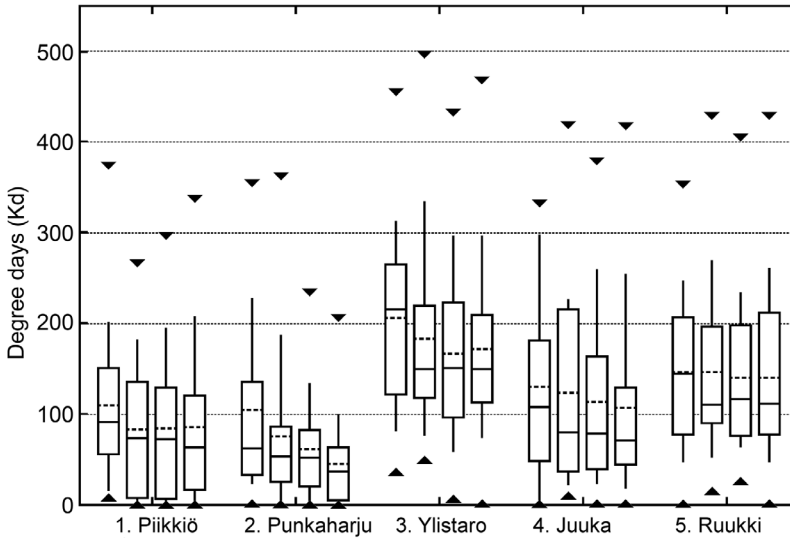
Fig. 8. Same as Fig. 3 but for T_SUM_5, representing the vulnerability for late spring frost.

tially smaller in the early stages of the growing season than the accumulation close to LSF_–2. An earlier SGS and generally warmer spring are therefore not able to compensate for the effect of earlier LSF_–2 on accumulated T_SUM_5. In fact, the correlation coefficients between LSF_–2 and T_SUM_5 are quite large, ranging from 0.71 (Ruukki; 2040–2069, A2) to 0.87 (Juuka; 2040–2069, B1).

According to our results, the upper tails (maxima and 90th percentiles in Fig. 8) in the distribution of the 30-year samples will not change substantially. Hence, it seems that the flaw in the description of SGS, with some unrealistically early starts of the growing season, does not have too much influence on the results of T_SUM_5 during the future periods. Even though our method for determining SGS (5 day span with $T_{mean} > 5$ °C), together with the delta change method, may occasionally result in too early SGS caused by wintertime thaw events, this does not mean that T_SUM_5 would necessarily begin to accumulate after an unrealistically early SGS.

Discussion and conclusions

The results regarding the expected rise in temperatures (ranging from 0.9 °C to 4.8 °C), are simple to interpret, especially for the winter months. Compared with the current mean condi-

tions, the warming results in more thaw days, less frequent and shorter periods of severe frost, a rise in the extreme minimum temperatures, earlier dates of the last spring-frost and later dates of the first autumn-frost.

Most of the prominent changes are projected to occur in winter conditions, with both adverse and beneficial impacts for the overwintering of fruit trees and berry bushes. Combined changes in the indices describing how cold the winter is (CDD_–15 and AMT) lead to a lower risk of winter damage for species and varieties currently cultivated and make it possible to introduce new ones. For the locations studied (Fig. 1), by 2040–2069 in scenario A2, the conditions at Punkaharju and Ylistaro will resemble the current conditions at Piikkiö, and conditions at Juuka and Ruukki will resemble those at Punkaharju. With regard to AMT, conditions in the future may be even more favourable than projected in this study, as we may have underestimated increases in extreme low temperatures. Kharin *et al.* (2007) projected the 20-year return value for the minimum temperature to increase by 6–8 °C in Finland by 2046–2065, relative to 1981–2000, whereas, in this study, the maximum increase in AMT was only 5.2 °C for the coldest day of the 30-year sample. Besides benefits gained from rising winter temperatures, however, there are also disadvantages, as the THAW index is projected to rise dramatically in the future. An

increase in THAW means that the level of cold hardiness will fluctuate more during future winters, which increases the risk of frost damage from any subsequent severe frost, although these frosts are likely to be less severe.

Temperature-wise, the most explicit improvement for horticulture is projected to take place in the conditions affecting the cold-hardening process of plants (ones with photoperiod controlled growth cessation) during autumn, the first autumnal frost (FAF_–2). For species which growth cessation is controlled by temperature (Heiden and Prestrud 2005) the response would be somewhat different. By 2040–2069 in scenario A2, FAF_–2 is projected to occur on average 16–22 days later than currently for the locations studied. The delay of FAF_–2 lowers the risk for insufficient cold-hardening which potentially occurs when the period between the photo-induced start of the cold-hardening process and FAF_–2 is too short. Thereby, risks for damages caused by subsequent frost events in late autumn and early winter are also reduced.

T_SUM_5 was used to express the risk of frost damage during bloom, which, if severe enough, can lead to significant yield losses and, therefore, have a great economical impact. Changes in both the start of the growing season (SGS) and the last spring-frost (LSF_–2) affect T_SUM_5, although LSF_–2 seems to have a larger impact. Both SGS and LSF_–2 are projected to occur roughly two weeks earlier (2040–2069 A2) than at present. Regardless of the simplifications in calculating SGS, the earlier projected onset is in agreement with other results: e.g. Karlsen *et al.* (2007), who estimate that an increase of 1 °C in spring temperatures corresponds with the SGS occurring about 5–6 days earlier (averaged over Fennoscandia). According to our results, the aforementioned advances of SGS and LSF_–2 lead to a moderate reduction in the mean levels of T_SUM_5. Hence, it seems that the risk caused by spring frosts will decrease, unlike the speculation in Finland's national strategy for adaptation to climate change (Marttila *et al.* 2005). Our results suggesting slightly reduced risk of late spring-frost damage are supported by some other studies: Bennie *et al.* (2010) predicted frost risk to decrease slightly across northwestern Europe,

and Rigby and Porporato (2008) state that spring frost-risk is sensitive to both increasing mean temperature (decreasing risk) and increasing daily temperature variance (increasing risk). Although Rigby and Porporato (2008) expect the daily variance to increase, there are in fact signs that the opposite will occur at high latitudes, with a reduction in the daily temperature range (Stone and Weaver 2003, Lobell *et al.* 2007) and enhanced warming of daily minimum temperatures relative to daily mean temperatures (Kjellström *et al.* 2007, Jylhä *et al.* 2009).

T_SUM_5 is largely controlled by the time span between SGS and LSF_–2. Furthermore, LSF_–2 (and also FAF_–2) is largely affected by small-scale characteristics of a weather-station surroundings. It is worthwhile emphasizing that commercial fruit production, especially at the northern fringes, often takes advantage of relatively small areas where conditions are best suited for production, whereas weather stations are commonly located at places representing the typical conditions for the region.

Our results are in reasonable agreement with those of similar studies investigating challenging conditions for commercial horticulture (Winkler *et al.* 2000, Rochette *et al.* 2004). Disagreements concentrate on projections of late spring-frosts and how warming will modify the net effect of advanced growing stages and spring frosts. These differences are probably partially model-related; the results of Winkler *et al.* (2000) regarding changes in spring conditions are opposite depending on which of the two GCMs in their study were used. Secondly, the results of Rochette *et al.* (2004), with regional differences in the direction of change, were based on climate change projections of a single GCM, as compared with our composite of 19 GCMs.

Our modifications to the direct GCM-projected changes in temperature include temporal downscaling of monthly values of warming rates and, based on results from regional climate models, asymmetric rise in temperatures, leading to larger increases in the daily minimum temperatures as compared with those in the daily mean temperatures. These modifications strengthen our conclusions. For comparison, we also made calculations without the aforementioned modifications and differences were generally quite

moderate, e.g. there were no sign reversals in the changes. The largest differences were found for variables that are dependent on daily minimum temperatures. For 2040–2069 in scenario A2, the mean date of the last spring-frost occurred 1–5 days earlier in our modified projections. Therefore, levels of vulnerability for the late spring-frost (T_SUM_5) deviated slightly as well. Temporal downscaling also resulted in some differences in the results for threshold events, such as the start of the growing season (SGS), but these appeared to be random.

It seems that climate change will have quite a considerable effect on Finnish horticulture, and more precisely on woody plants with photoperiod-controlled growth cessation. How to take advantage of a more efficient growing season and a milder winter, however, will not be obvious. Late spring-frosts and fluctuating temperatures during winter will continue to offer challenges, at least in regions where temperatures will still occasionally drop low enough to cause frost damages. Marttila *et al.* (2005) predicted that the cultivation of apple could possibly be expanded; perry, plum and cherry may become significant crops, and overwintering of the strawberry and raspberry should become more secure. These conclusions are supported by this study, at least when considering temperature-related factors and overwintering. Conditions in current apple production areas, represented in this study by Piikkiö, should during the 21st century extend to western coastal areas and to southeastern parts of Finland. However, it should be kept in mind that climatic conditions, and here we have only discussed temperature-related parameters, are just one of the factors regulating the future of Finnish horticulture. Adaptation to climate change also depends on internal changes within the agricultural sector and external decisions that specify agricultural policies (Hildén *et al.* 2005).

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