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Climate change and the effect of temperature backlashes causing frost damage in *Picea abies*

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Abstract

In boreal and nemoboreal forests, tree frost hardiness is modified in reaction to cues from day length and temperature. The dehardening processes in Norway spruce, *Picea abies*, could be estimated to start when the daily mean temperature is above 5 °C for 5 days. Bud burst will occur approximately after 120–170 degree-days above 5 °C, dependent on genetic differences among provenances. A reduced cold hardiness level during autumn and spring and an advanced onset of bud burst are expected impacts of projected future global warming. The aim of this study was to test if this will increase the risk for frost damage caused by temperature backlashes. This was tested for Sweden by comparing output from the Hadley Centre regional climate model, HadRM3H, for the period 1961–1990 with future IPCC scenario SRES A2 and B2 for 2070–2099. Different indices for calculating the susceptibility to frost damage were used to assess changes in frost damage risk. The indices were based on: (1) the start of dehardening; (2) the severity of the temperature backlash; (3) the timing of bud burst; and (4) the cold hardiness level. The start of dehardening and bud burst were calculated to occur earlier all over the country, which is in line with the overall warming in both climate change scenarios. The frequency of temperature backlashes that may cause frost damage was calculated to increase in the southern part, an effect that became gradually less pronounced towards the north. The different timing of the onset of dehardening mainly caused this systematic latitudinal pattern. In the south, it occurs early in the year when the seasonal temperature progression is slow and large temperature variations occur. In the north, dehardening will occur closer to the spring equinox when the temperature progression is faster.

Keywords: Frost damage; Global warming; Norway spruce; Temperature backlash

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1. Introduction

Trees are damaged by frost when the temperature falls below their hardening status. This commonly occurs after a warmer period in the spring or autumn or following a mild period at any time during the winter. Reversible frost damage requires a high energy and water consumption for repair (Larcher, 1981). Non-reversible frost damage may cause heavy needle losses, often killing seedlings that are subjected to topographic ponding of cold air and radiative cooling (Sakai and Larcher, 1987). Bark necrosis and resin flow in mature Norway spruce have been related to frost damage (Barklund et al., 1995). Until healed, such lesions render the tree susceptible to attacks by fungal pathogens (Alden and Hermann, 1971; Schoeneweiss, 1975) that may further aggravate the damage. An increased winter temperature may reduce tree growth as insufficient hardiness during the dormancy period increases the consumption of carbohydrates and water (Skre and Nes, 1996), which in turn increases the risk for frost damage caused by temperature backlashes (Barklund et al., 1995).

Climate change can reduce the resistance and resilience of an ecosystem, as the species will be less adapted to the new conditions (Larsen, 1995; Kramer et al., 2000). Uncertainties about future risk for frost damage make it difficult to estimate future forest production (Burton and Cumming, 1995; Kellomäki et al., 1995). Bergh et al. (1998) concluded that the productivity of boreal conifer forests may be overestimated by about 40% if the effects of frozen soil and the energetic costs for repairing reversible frost damage are not considered. It ought to be noted that the value of provenance transfer experiments may be limited and that such manipulations may not yield reliable results for predictions of climate change effects (Hänninen, 1996), as temperature and light conditions do not correspond in their change. Although influenced by limitations and uncertainties about the emission scenarios, climate models are important decision support for the long-term planning in forestry (Loehle and LeBlanc, 1996; Price and Flannigan, 2000). Several physiological processes influence both the probability and the severity of frost damage. It is therefore a good strategy to evaluate the effect of an expected climate change by using more than one indicator, as the reliability of the frost damage assessment increases if several indices show the same directions of change. In this paper, we have used four indices based on: (1) the start of dehardening; (2) the severity of the temperature backlash; (3) the timing of bud burst; and (4) the cold hardiness level. In effect, we will compare different parameterisations of the risk of frost damage in Norway spruce.

Various starting dates and temperature thresholds have been used for calculating the onset of dehardening and the following growth processes. The trees can have several active periods during spring and any well-defined beginning of the growing season could be difficult to determine. This was observed in a *Pinus sylvestris*/*Picea abies* forest in Norunda, southern Sweden, were periods with temperatures above 0 °C alternated with periods below 0 °C between February and April. The onset of spring recovery was predicted by the 5-day running average temperature (Suni et al., 2003). Subzero temperature could be expected to cause frost damage after the onset of dehardening, as the trees may no longer have a sufficient hardiness level (Index 1). The resulting damage of a temperature backlash will, however, be severer the longer the period after the start of activity as the trees become less hardened. This could be estimated as accumulating degree-days after the onset of dehardening (Index 2) (Lindergård, 1996).

Bud burst is under strong genetic control, and the timing can be predicted by calculating an accumulated temperature sum (Greer et al., 2001; Beuker, 1994). The calculation of temperature sums can be used to evaluate different species and phenology phenomena, as the sequence and temporal distance between predetermined thresholds remains the same from year to year (Linkosalo, 2000). Light conditions can be assumed to prevent developmental processes during autumn, before the winter solstice (Partanen et al., 1998). The accumulation of degree-days is therefore preferably calculated from a parameterised date (Linkosalo, 2000), such as the 1st of January. There is a considerable variation between different clones of Norway spruce. A linear temperature sum with a threshold of 5 °C were found to predict the date of bud burst most accurately for Norway spruce in Sweden, however, thresholds between 2 and 6 °C were not significantly different owing to the influence of uncontrolled seasonal variation (Hannerz, 1999). For the provenances most commonly used in central Sweden bud burst occurs after 120 degree-days above 5 °C and the provenances used in southern Sweden flush after 170 degree-days above 5 °C (Index 3) (Hannerz, 1994). Other thresholds have also been used; Bergh et al. (1998) used 290 degree-days above 0 °C to predict bud burst of Norway spruce in northernmost Sweden and Aber et al. (1995) approximated the onset of foliar production to 300 degree-days above 0 °C for spruce-fir forests in northern USA. Frosts episodes are particularly harmful during bud burst as the emerging shoots have a very poor frost resistance (Cannell and Sheppard, 1982). Although less frequent, temperature backlashes occurring after bud burst may thus cause more sever damage than temperature backlashes occurring close to the start of dehardening.

However, the calculation of an accumulating temperature sum does not always perform well in estimating growth initiation (Pelkonen and Hari, 1980). The ability of conifers to adjust the level of frost hardiness to the ambient temperature depends on the phenological state (Kramer et al., 2000; Greer et al., 2001). The hardiness level is less variable in autumn than in spring (Anisko et al., 1994), as the onset of hardening is initiated by shortening day length, the hardiness level advances in response to low temperatures and dehardening is prevented (Greer et al., 2001). In spring, the trees are able to both harden and deharden (Bigras et al., 2001). Even throughout the summer, cool days have been found to initiate hardening in *Picea sitchenses* with a lag phase of about 6 days (Cannell and Sheppard, 1982). A more elaborated calculation of the frost hardiness level, taking the physiological processes into account (Index 4), can therefore improve the risk assessment of frost damage.

While it is very likely that a future climate with increasing minimum temperatures will cause a shortened winter season with overall fewer cold days, fewer frost days and fewer cold waves over most land areas (Cubasch et al., 2001), the risk for frost damage, i.e., when the temperature falls below the tree hardiness status, need not per se to be lower (Kellomäki et al., 1995). The aim of this study was to assess the risk of frost damage in Norway spruce caused by temperature backlashes during spring and autumn. This was tested by using the four indices to compare the frequency and severity of temperature backlashes for the period 1961–1990 with two scenarios for the period 2070–2099.

2. Materials and methods

The Hadley Centre regional climate model HadRM3H was used in this study and the data were taken from the run 'a' in a set of three ensemble members. The output from HadRM3H has been described in a regional climate impact assessment by Hulme et al. (2002). For the period 1961–1990, the SRES common scenario (i.e., observed greenhouse gas forcing) was used, and for the period 2070–2099, the two scenarios A2 and B2 were used (Nakicenovic and Swart, 2000). In general, the greenhouse gas concentrations are higher in the A2 scenario than in the B2 scenario. For each grid cell (about 50×50 km^2), daily mean temperatures (T_{mean}) and daily minimum temperatures (T_{min}) were used to calculate the backlash indices. The change of an index value between recent and future climate was calculated as the difference in the total frequencies over 30 years between the scenarios and the SRES common period.

2.1. Definition of indices

Four different indices were used for calculating the frequency and severity of temperature backlash, indicating the risk for frost damage in Norway spruce:

Index 1: Number of temperature backlashes after the onset of dehardening processes. This was calculated over a 30-year period as the number of days with a minimum temperature, T_{min}, below 0 °C following immediately after a 5-day running average with a mean temperature, T_{mean}, above 5 °C.

Index 2: Accumulating degree-days between the onset of dehardening and $T_{min}<-2$ °C. This was calculated as a spring backlash index (SBI) according to Lindergård (1996). In this index, dehardening was considered to start when $T_{mean}>5$ °C for 4 consecutive days. The severity of a frost damage increases as the trees become less hardened. This was calculated as a daily accumulation of degrees above 5°C, based on daily mean temperatures, between the onset of

Table 1
Parameters used to calculate the cold hardiness level of Norway spruce, Index 4

Parameter	Value and unit
Daily mean temp.	°C
Daily min. temp.	°C
Desired hardiness level	*F*(daily mean temp.)
Hardiness level	minimum −2 °C, maximum −50 °C
Rate of hardening	0–1 °C/day
Rate of dehardening	0–5 °C/day
Winter dormancy	from days 260 to 355
Temperature backlash	if min. temp.<hardiness level
Start of spring/autumn	Julian days 1 and 210

dehardening and the first minimum temperature below −2 °C (Eq. (1)):

$$\mathrm{SBI} = \sum_{n=a}^{b} D\_\mathrm{acc}_\mathrm{n} \qquad (1)$$

where a is the start of vegetation period defined as 4 consecutive days with $T_{\mathrm{mean}}>5$ °C, $D\_\mathrm{acc}_n=\max(0, T_{\mathrm{mean}}-5)$, b=first day after day a with $T_{\mathrm{min}}<-2$ °C.

Index 3: Number of temperature backlashes after bud burst. The frequency of minimum temperatures below 0 °C following bud burst was calculated over the 30-year periods. The date of bud burst was calculated by an accumulation of 120 and 170 degree-days above 5 °C with the 1st of January as start date, in the text abbreviated as GDD 120 and GDD 170, respectively. The daily mean temperature was used in the calculation of the temperature sum.

Index 4: Number of days with a temperature below the hardiness level during spring and autumn. The Norway spruce cold hardiness was calculated throughout the year, using the parameters displayed in Table 1. The purpose was to estimate the frequency of potentially harmful frost episodes during spring and autumn, while accounting for hardening processes occurring in response to low temperatures after the start of dehardening in spring. The desired hardiness level was described by a sigmoidal curve of the daily mean temperature. Minimum hardiness level was set to −2 °C. Maximum hardiness level, −50 °C (Bigras et al., 2001), was targeted when the mean temperature dropped below −15 °C (Larcher, 1995). The level of hardiness was adjusted in response to the daily mean temperature. The rate of hardening, described by a sigmoidal curve, was faster at freezing temperature, and the maximum rate of hardening, 1 °C/day (Greer et al., 2001), was reached at −10 °C. The minimum rate of hardening, 0.1 °C/day, occurred during autumn at temperatures above 12 °C. This was based on the assumption that shortening of the day length induces a minimum level of frost hardiness and freezing temperature induces deeper frost hardiness (Guy, 1990; Bigras et al., 2001). Dehardening processes was described by a linear function, where the processes started above 5 °C, and the maximum rate of dehardening at daily mean temperature above 15°C was set to 5 °C day^{-1} (cf. Alden and Hermann, 1971; Larcher, 1995; Bigras et al., 2001). In the model, dehardening was prevented between Julian day 260, the autumn equinox, and Julian day 355, the winter solstice. Both hardening and dehardening was thus possible during spring. The number of events when

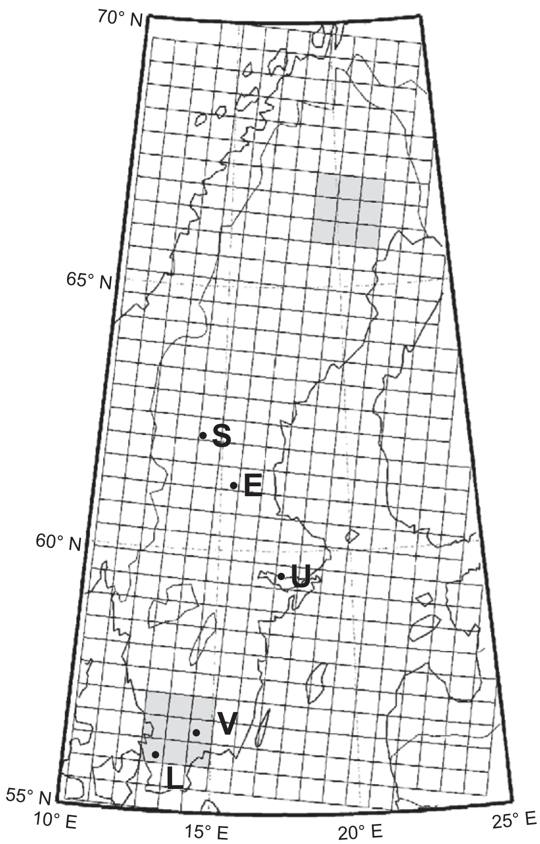

Fig. 1. The five meteorological stations; Ljungbyhed (L), Växjö (V), Edsbyn (E), Uppsala (U) and Sveg (S), together with the two 3×3 grid box areas in southern and northern Sweden, respectively.

Table 2
The mean and minimum temperature and standard deviation over 30 years for January to May, calculated with data from the HadRM3H model for the common period 1961–1990 and for scenarios A2 and B2

Month		South of Sweden			North of Sweden		
		1961–1990	Scenario A2	Scenario B2	1961–1990	Scenario A2	Scenario B2
January	T_{mean}	−0.41±4.4	3.4±3.6	1.8±4.0	−11.3±6.8	−7.1±5.7	−7.8±5.7
	T_{min}	−2.8±4.8	1.4±4.2	−0.41±4.5	−14.3±6.8	−9.5±6.0	−10.4±5.9
February	T_{mean}	0.17±3.6	3.1±3.4	1.8±3.8	−11.1±6.6	−7.8±5.8	−8.4±5.6
	T_{min}	−2.5±4.1	0.63±4.0	−0.90±4.6	−14.4±6.8	−10.6±6.1	−11.3±5.8
March	T_{mean}	1.6±3.1	4.5±2.9	3.4±3.0	−7.8±5.1	−4.1±3.9	−5.5±4.3
	T_{min}	−1.7±3.8	1.3±3.6	0.15±3.7	−11.6±5.7	−7.3±4.7	−8.9±4.9
April	T_{mean}	4.9±3.1	8.8±3.3	7.8±3.1	−2.9±4.1	2.1±4.2	1.3±4.1
	T_{min}	0.74± 3.8	4.5±3.8	3.7±3.6	−6.9±4.6	−2.2±4.1	−2.9±4.2
May	T_{mean}	10.0±2.9	14.0±3.1	13.1±3.1	4.7±3.8	10.2±3.8	8.7±3.9
	T_{min}	5.7±3.4	9.6±3.3	8.6±3.3	−0.26±3.9	5.1±3.9	3.6±4.1

the daily minimum temperature fell below the hardiness level was counted both for autumn and spring. Julian day 1 was set as the start of spring and Julian day 210 as the start of autumn.

2.2. Climate model validation

The climate model output was validated against observational data with respect to its ability to capture the timing of phenological events and the severity of temperature backlashes. The indices were calculated for both observed data from five meteorological stations: Ljungbyhed (56°05′ N, 13°14′ E), Växjö (56°52′ N, 14°48′ E), Edsbyn (61°23′ N, 15°50′ E), Uppsala (59°52′ N, 17°38′ E) and Sveg (62°15′ N, 14°18′ E) (Fig. 1), and data for the corresponding grid cells from the SRES common period. These two sets of indices were then compared using the non-parametric Mann–Whitney U-test.

The start of dehardening, the date of bud burst and the hardiness level at the 1st of January showed a clear and uniform trend from south towards north. Therefore, the earliest and latest date and the highest and lowest hardiness level were assessed by taking the mean value from a 3×3 RCM grid box area. The south area was centred at 56°5′°N 14°E and the north area at 67°N 18°E in Sweden (Fig. 1). T_{mean} and T_{min} for the south and north area, calculated with data from the HadRM3H model for the common period 1961–1990 and for scenarios A2 and B2, are given in Table 2 for January to May.

3. Results

The start of the dehardening processes, calculated for the period 1961–1990, occurred during March–April in the southern part of Sweden, and during May in the northern part (Table 3). According to scenario A2, the dehardening processes will occur about 60–70 days earlier in southern Sweden. The increase is gradually less pronounced, with a gradient towards 20 days earlier in northern Sweden. Scenario B2 indicated a similar, but

Table 3
The Julian day and standard deviation over 30 years for the start of dehardening and bud burst, together with the hardiness level, °C, at the first of January, calculated with data from the HadRM3H model for the common period 1961–1990 and for scenarios A2 and B2

Index no.	Process	South of Sweden			North of Sweden		
		1961–1990	Scenario A2	Scenario B2	1961–1990	Scenario A2	Scenario B2
1	start of dehardening	76±34	16±18	29±31	133±9	113±9	115±12
2	start of dehardening	101±23	29±29	60±40	139±9	118±9	121±12
3	bud burst after 120 GDD	139±7	110±13	119±12	146±7	142±8	150±9
3	bud burst after 170 GDD	147±7	119±10	128±10	173±7	149±7	157±9
4	hardiness level the 1 January	−30±6	−17±6	−19±5	−50±0.4	−45±6	−48±4

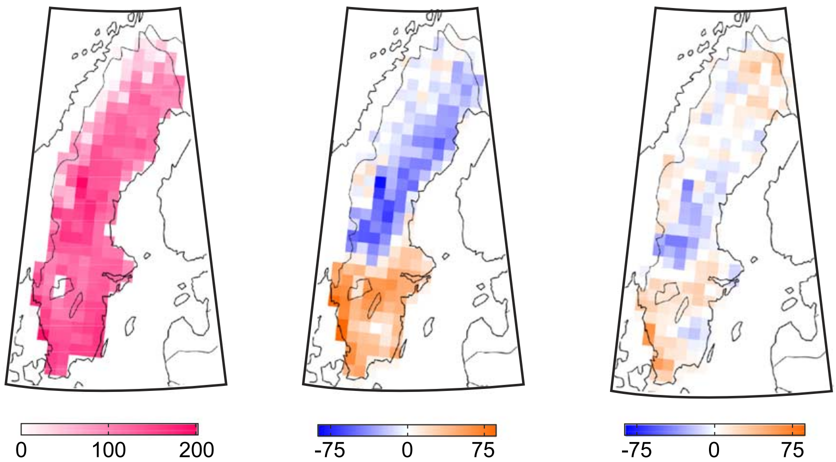

Fig. 2. The frequency of minimum temperature <0 °C after the start of dehardening, 5 consecutive days with a mean temperature above 5° for the SRES common period 1961–1990 (i) and the changes according to scenario A2 (ii) and scenario B2 (iii) for 2070–2099. Unit: number of temperature backlashes after the onset of dehardening processes.

weaker change, about 40–50 days earlier in the southern part towards 18 days earlier in the northern part. Bud burst was calculated to occur during May in southern Sweden and during June in northern Sweden during 1961–1990. According to scenario A2, both GDD 120 and GDD 170 was calculated to occur 28 days earlier in the southern part. In the northern part, however, the date for reaching GDD 120 will occur only 4 days earlier, whereas GDD 170 will be reached 24 days earlier than today. The same pattern was found in scenario B2, calculated as 19 days earlier in the south. In the northern part, bud burst after GDD 120 was calculated to occur 4 days later and GDD170 about 16 days earlier than today. In a warmer climate, the cold hardiness level in southern Sweden will be reduced, by 13 °C in

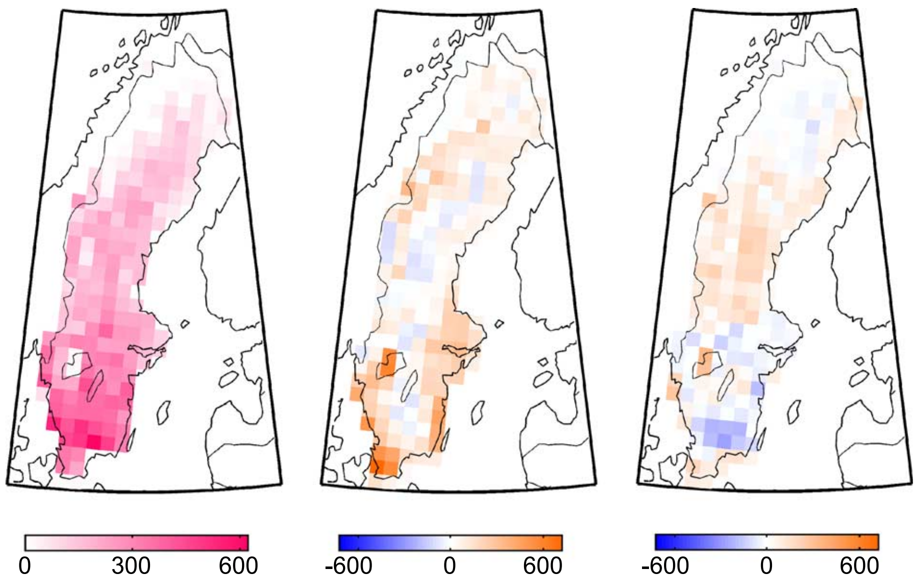

Fig. 3. The spring backlash index, mean value over 30 years for the SRES common period 1961–1990 (i) and the changes according to scenario A2 (ii) and scenario B2 (iii) for 2070–2099. Unit: accumulating degree-days between the onset of dehardening and T_{min}<−2 °C.

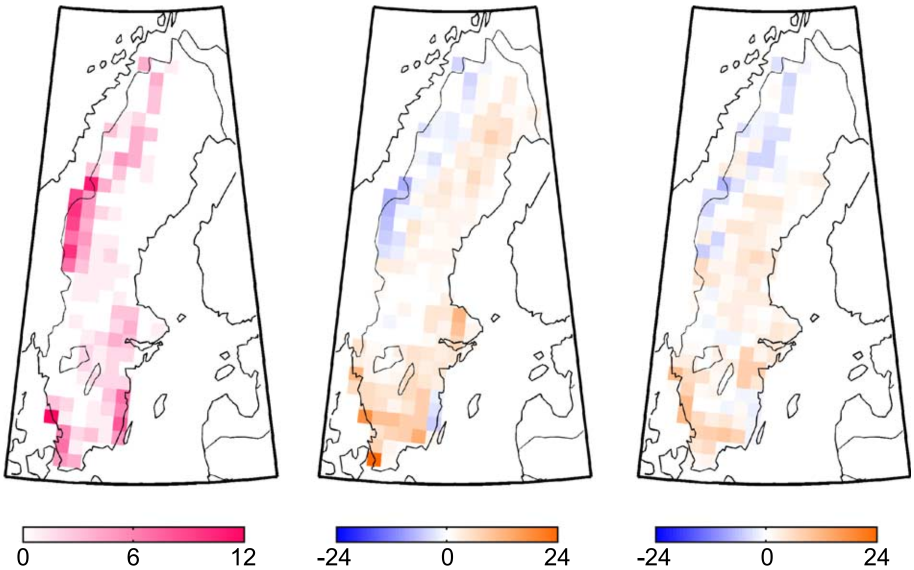

Fig. 4. The frequency of minimum temperature <0 °C after GDD 120, calculated over 30 years for the SRES common period 1961–1990 (i) and the changes according to scenario A2 (ii) and scenario B2 (iii) for 2070–2099. Unit: number of temperature backlashes after bud burst.

scenario A2 and by 11 °C in scenario B2. In both scenarios, this reduction will follow a gradient towards north where the hardiness level is almost unchanged.

The frequency of temperature backlashes after the start of dehardening, Index 1, did not differ between the northern and southern part of Sweden for the period 1961–1990. The frequency varied between three and five backlashes per year, and will increase in the southern part of Sweden according to both scenarios. The largest increase was, on average, 2.9 backlashes per year in scenario A2 and 2.1 back-

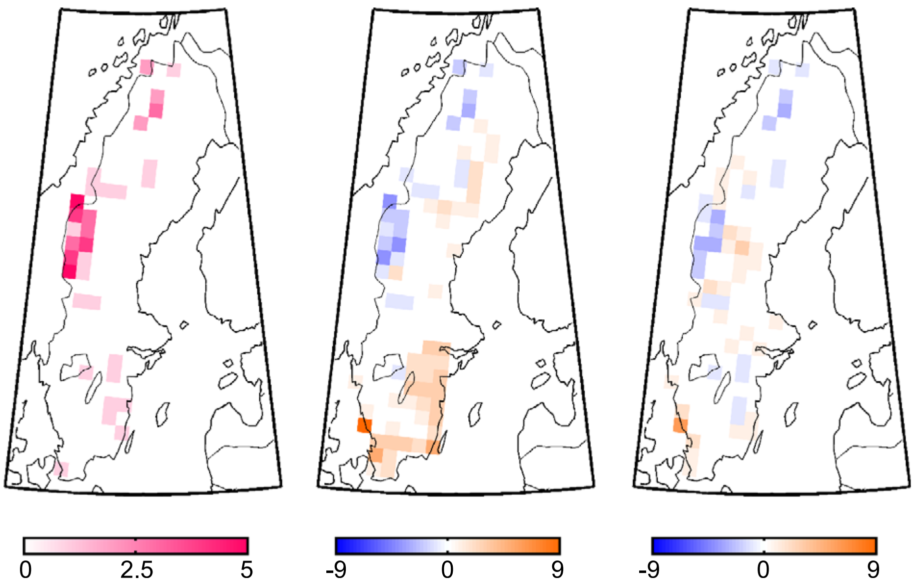

Fig. 5. The frequency of minimum temperature <0 °C after GDD 170, calculated over 30 years for the SRES common period 1961–1990 (i) and the changes according to scenario A2 (ii) and scenario B2 (iii) for 2070–2099. Unit: number of temperature backlashes after bud burst.

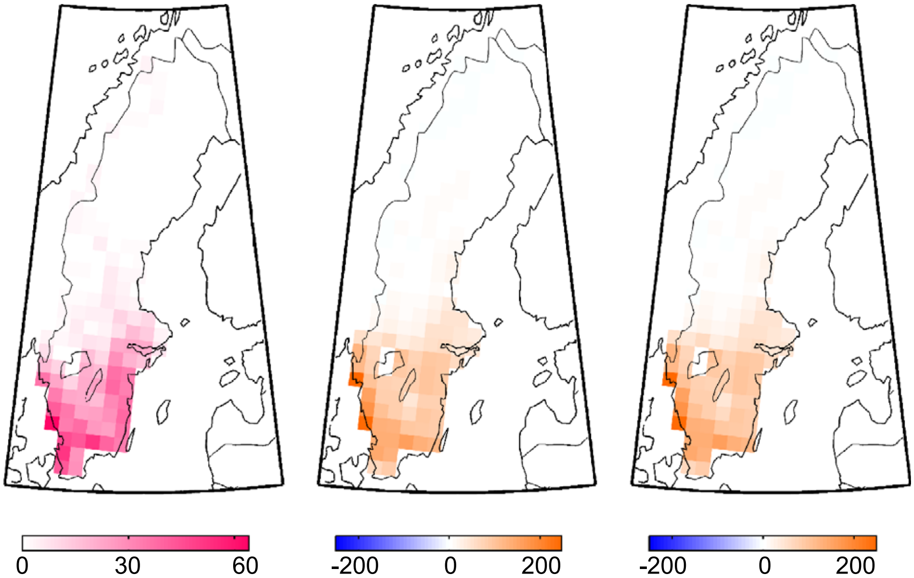

Fig. 6. The frequency of spring backlashes calculated with the cold hardiness model for the SRES common period 1961–1990 (i) and the changes according to scenario A2 (ii) and scenario B2 (iii) for 2070–2099. Unit: number of days with a temperature below the hardiness level.

lashes per year in scenario B2. Towards the central and northern part of Sweden, the index decreased. This was most pronounced at 64°N with a decrease of up to 2.7 backlashes per year in scenario A2 and 1.5 in scenario B2 (Fig. 2). The temperature backlashes were more severe in the southern part during 1961–1990 according to Index 2. The severity will increase over almost the whole country according to scenario A2, but the increase will be most pronounced in southern part. In scenario B2, an increase

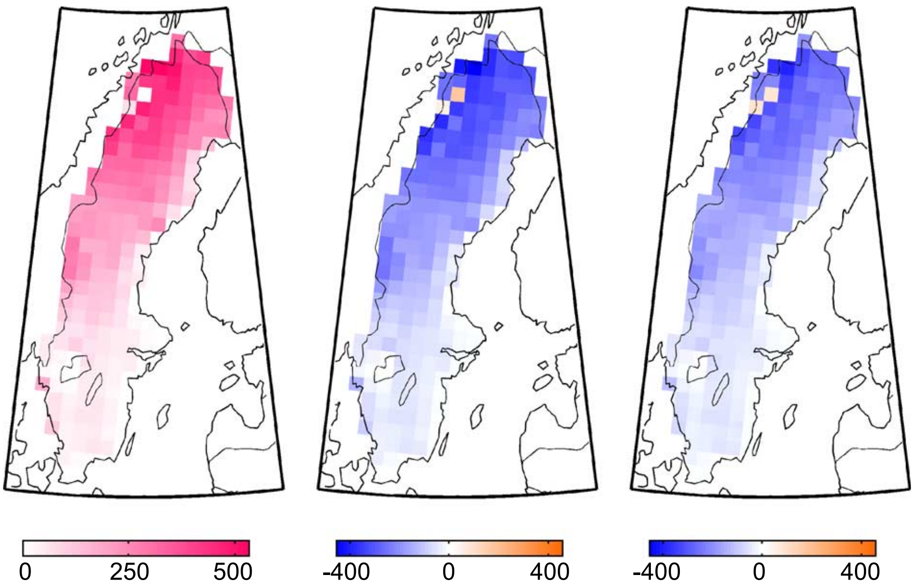

Fig. 7. The frequency of autumn backlashes calculated with the cold hardiness model for the SRES common period 1961–1990 (i) and the changes according to scenario A2 (ii) and scenario B2 (iii) for 2070–2099. Unit: number of days with a temperature below the hardiness level.

was calculated for the southerly and central part, whereas no change or even a decreased was calculated for the southeastern and northern part of Sweden (Fig. 3).

The frequency of minimum temperature below 0 °C after bud burst, Index 3, was highest in the northwestern and southern parts of Sweden during 1961–1990. It was calculated to increase in response to climate change in most parts of southern Sweden. The increase in subzero temperatures after bud burst was calculated to be gradually less pronounced towards north. Some grid cells in the northwestern and southeastern part indicated a decrease. The changes were more pronounced in scenario A2 than in scenario B2 and more pronounced for GDD 120 (Fig. 4) than for GDD170 (Fig. 5). Thus, scenario A2 for GDD 120 indicated at most an increase with 13 backlashes over 30 years, whereas scenario B2 for GDD 170 did not show any major change.

Index 4 indicated that spring temperature backlashes were most common in the southern part of Sweden during 1961–1990. This pattern was calculated to be even more pronounced by climate change, slightly more in scenario A2 than in scenario B2 (Fig. 6). During 1961–1990, on average 11 events per year could cause frost damage during autumn in the northernmost part, whereas there was almost no risk for autumn frost damage in the southern part. According to both scenarios A2 and B2, the warming will reduce the risk for autumn frost in the whole country (Fig. 7).

The timing of phenological events and the severity of temperature backlashes as calculated with data from the HadRM3H were validated against observed temperature data from five meteorological stations for the period 1961–1990 (Table 4). By using data from the HadRM3H, a later start of dehardening processes in Edsbyn and a later date for bud burst at Växjö, Uppsala, Sveg and Edsbyn were estimated. The difference varied between 3 and 9 days. The cold hardiness level at the 1st of January was generally overestimated with 3–6 °C, except in Uppsala where it

Table 4
Median values and statistical significant differences in timing of dehardening and bud burst together with the frequency and severity of temperature backlashes, calculated per year, between the four impact indices calculated for 1961–1990 with observed temperature data (obs.) and temperature data from the HadRM3H SRES model (model); n.s.=not significant

Index no.	Parameter	Ljungbyhed			Växjö			Uppsala			Sveg			Edsbyn		
		Obs.	Model	*P*-value	Obs.	Model	*P*-value	Obs.	Model	*P*-value	Obs.	Model	*P*-value	Obs.	Model	*P*-value
Timing																
1	start of dehardening	88	67	n.s.	98	101	n.s.	106	107	n.s.	122	120	n.s.	112	118	0.04
2	start of dehardening	104	102	n.s.	106	107	n.s.	116	114	n.s.	128	133	n.s.	121	127	0.02
3	date of 120 GDD	135	135	n.s.	137	142	0.002	141	145	0.02	154	160	0.0002	149	156	0.0001
3	date of 170 GDD	143	143	n.s.	145	150	0.0006	150	153	0.02	162	168	0.0003	155	164	0.0001
4	hardiness 1 January	26	29	0.02	30	33	0.01	41	37	0.0001	47	50	0.005	41	47	0.001
Freq. of backlashes																
1	+5° 5 days<0 °C	6	5	n.s.	5	4	n.s.	4	4	n.s.	10	4	0.0001	6	3	0.0004
2	spring backlash index	8.4	1.8	n.s.	5.4	5.1	n.s.	9.0	0.0	0.007	12.3	0.8	0.0001	6.6	0	0.007
3	120 GDD<0 °C	0	0	0.02	0	0	n.s.	0	0	0.0006	1.5	0	0.0001	0	0	0.01
3	170 GDD<0 °C	0	0	0.04	0	0	n.s.	0	0	0.04	0.5	0	0.0001	0	0	n.s.
4	spring backlashes	2	1	n.s.	1	0	n.s.	1	0	0.007	1	0	0.0001	1	0	0.0003
4	autumn backlashes	1	1	n.s.	0.5	1	n.s.	3	0	0.0001	9	4.5	0.0002	3	2.5	n.s.

was underestimated with 4 °C. Both the frequency and the severity of the temperature backlashes were underestimated in Uppsala, Edsbyn and Sveg. Also the frequency of temperature backlashes occurring after bud burst tended to be underestimate, except in Växjö and for GDD 170 in Edsbyn. The frequency of autumn backlashes was underestimated in Uppsala and Sveg.

4. Discussion

The risk for frost damage is affected by the timing of phenological events and this study shows that the impact is dependent on latitude. During the period 1961–1990, there was a tendency towards a larger risk for frost damage during spring in the southern part compared to the northern part of Sweden. The reversed pattern was found during autumn. A reinforcement in the north–south gradient of spring backlashes, and a reduced frequency of autumn backlashes in general, was indicated in both SRES scenarios A2 and B2. The underlying cause is that the effect on the start of the dehardening and bud burst will be more pronounced in the southern part of Sweden than in the northern part. This was also indicated by a 10 °C reduction of the cold hardiness level in the south towards no change in the north by the 1st of January. However, as seen by the difference in risk for frost damage after bud burst, Index 3, high latitude ecotypes will be more prone to spring frost injury in a warmer climate (Hannerz, 1994; Myking and Heide, 1995), as they need a smaller critical temperature sum before bud burst than southern provenances (Beuker, 1994).

During the winter, there is a strong link between variations in the atmospheric circulation and temperatures in Scandinavia (Chen and Hellström, 1999; Jacobeit et al., 2001; Jönsson and Bärring, 1994; Slonosky et al., 2001). Owing to the meandering polar front, there is an alteration between cold and warm air masses, which may produce large temperature changes. Early in the year, close to the winter solstice, the seasonal temperature progression is slow and temperature backlashes are frequent. An earlier onset of dehardening and bud burst will thus prolong the period when frost damage may occur in southern Sweden. The difference in seasonal temperature progression was observed as a larger standard deviation for the start of dehardening processes in south than in north of Sweden. This was also indicated by the start of dehardening calculated as 5 consecutive days with a mean temperature above 5 °C (Index 1) occurring 1 month earlier than the start calculated as 4 days above 5 °C each day (Index 2) in south, but only a week later in the north. Also in northern Sweden, the onset of dehardening and bud burst was calculated to occur earlier than today. However, the change was not as large and the risk for temperature backlashes did not increase as much as in southern Sweden as the timing will be closer to the spring equinox. At that time, the seasonal temperature progression is faster. In addition, the annual temperature amplitude is larger in the northern part, which strengthens the seasonal temperature increase.

In the southeastern Sweden, the spring backlash index indicated an increase in the severity in scenario A2, but a reduction in the severity of the temperature backlash in scenario B2 (Fig. 3). This illustrates the fine balance between a lowered risk for frost damage owing to an elevated temperature and the attendant increased risk for frost damage due to an earlier start of dehardening. Additionally, the latitudinal pattern was modified by altitude and closeness to the sea. This was observed as a more pronounced decrease in the risk of frost damage after bud burst in the western part of mid-Sweden. This area is dominated by mountains and also affected locally by maritimity (Raab and Vedin, 1995).

The reduced frequency of autumn backlashes was caused by warmer temperatures in combination with a fixed date for the onset of hardening, simulating the effect of reduced light conditions. The frequency of potentially harmful backlashes during autumn was very high in the mountainous area in northern Sweden, however, large parts of this region is above the current timber line during present day climate. Also, the cold hardiness model may not be able to accurately predict the hardiness level during autumn in this area, as the bud set, a prerequisite for winter hardening (Bigras et al., 2001) has been found to be considerably more difficult to model than the bud break (Murray et al., 1994).

The geographical pattern of changes was more pronounced in scenario A2 than in scenario B2 as the overall temperature change was larger because of the larger greenhouse gas forcing. Thus, it is an advantage to look at more than one scenario with different impact strength in order to see the magnitude of change more clearly. The pattern also appeared more clearly with indices that had a relatively higher frequency of potential harmful temperature backlashes. For instance, although more frequent, a temperature backlash after the start of dehardening will probably cause a less severe damage than a temperature backlash after bud burst. According to the result by Index 4, not all of the potential backlashes after the start of dehardening (Index 1) are likely to cause damage as the trees are able to regain hardiness. The difference in frequency of backlashes between Index 1 and Index 4 were approximately three to four events per year. Concern has also been raised about temperature backlashes occurring after the fulfillment of the chilling requirement needed by the trees to start dehardening processes (Hänninen, 1990; Leinonen, 1996). However, the chilling requirement of Norway spruce is most commonly met before the 1st of January in Sweden, already during present day climate (Hannerz, 1999). By that date, the ontogenetic development of Norway spruce is hindered by shortening day length (Partanen et al., 1998). This protection against frost damage will be overseen if the effect of climate change is evaluated solely by the chilling requirement (Häkkinen et al., 1998; Partanen et al., 1998; Linkosalo, 2000; Linkosalo et al., 2000).

The indices calculated from observed and simulated temperature data for the five validation sites indicated a larger mismatch between observed and simulated climate in northern Sweden than in southern Sweden (Table 4). This pattern was due to the larger variation in the south, caused by the less pronounced seasonal temperature progression, which masked the differences between modelled and observed data. In the north where the variation was lower, the difference became statistically significant. Compared to observed temperature data, the general tendency was that the frequency and severity of temperature backlashes calculated from HadRM3H data were underestimated. This was a consequence of the tendency towards an overestimation of the hardiness level and later dehardening and later bud burst (Table 4). Moberg and Jones (2004) showed that the difference between model and observations in the number of frost days is variable in Sweden. The main explanation for these differences is the fact that the HadRM3H produces grid cell data representing area averages that by necessity masks local temperature extremes that may occur in observed point data. Locally, the interaction between topography and tree height will be one of the most important factors influencing the degree of frost damage. The large-scale pattern, the direction of changes and the differences between the common period and the scenarios are, however, unlikely to be erroneous.

5. Conclusion

This study shows that the latitudinal variation in seasonal temperature progression can be an important factor for modifying the interaction between the timing of phenology and the risk for frost damage in Norway spruce. During the period 1961–1990, there was a tendency towards a larger risk for frost damage during spring in the southern part compared to the northern part of Sweden. The reverse pattern was found during autumn. A reinforcement in the north–south gradient of spring backlashes, and a reduced frequency of autumn backlashes in general, was indicated in both SRES scenarios A2 and B2. The resulting frost damage will, however, depend not only on the temperature, but also on the phenological state of the trees. The variation among provenances in the temperature sum needed before bud burst is therefore likely to be a critical parameter.

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