Predicting the Risk of Frost Occurrence after Budburst of Norway Spruce in Sweden

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Temperature sums required for budburst in various Norway spruce provenances were determined, and weather statistics were then used to predict the risk of potentially damaging frosts at 11 locations in Sweden. Frost risk was quantified as the probability of a frost occurring within 100 day-degrees (two weeks) after budburst. The examples provided show that a spruce seedling from central Sweden has to sustain almost twice as many frost occasions as a seedling from Belorussia, when planted in southern and central Sweden. The method presented here can be used for mapping early summer frost risk in Sweden and for supporting provenance transfer guidelines.

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1 Introduction

In all tree breeding programmes, the degree of adaptation is one of the most important traits to consider. If growth starts too early in spring or ceases too late in autumn, the tree is subject to increased frost risk, reflecting poor *survival adaptation*, whereas a late growth start and early cessation of growth implies reduced growth, reflecting poor *capacity adaptation* (Heide 1985). By matching the annual rhythm of the tree to photoperiod and climatic conditions on the site, frost risk can be reduced without sacrificing yield.

Numerous reports have been published concerning the regulation of the annual growth rhythm of trees. The timing of budburst has been shown to depend mainly on the temperature sum and chilling, and to some extent on photoperiod and soil temperature (e.g. Campbell and Sugano 1975, Sorensen and Campbell 1978, Thomson and Moncrieff 1982, Cannell and Smith 1983). Growth cessation is induced primarily by short days (Dormling et al. 1968), and hardening in the autumn is affected by temperature (Cannell and Sheppard 1982). If a model could be developed that relates budburst and growth cessation to temperature and photoperiod, then climate recordings can be used to predict frost risks.

In this paper a method is proposed for estimating the frost risk in spring as the proportion of years during which a frost occurs after budburst. Budburst was predicted using a pure temperature-sum model.

The study is a pilot survey, aimed at presenting the method and providing examples of frost risk when transferring provenances. Temperature sums required for budburst in various Norway spruce provenances were estimated from three independent nursery studies. Thereafter, the risk that these provenances would sustain frost was calculated for 11 locations in Sweden based on local meteorological data.

2 Material and Methods

2.1 Temperature Sum Required for Budburst

Three independent nursery studies were used to estimate the temperature sum required for budburst in various Norway spruce (*Picea abies* (L.) Karst) provenances (Fig. 1). The temperature sum at budbreak, i.e. when the needle tips emerge through the bud scales, was calculated as:

$$TS(t) = \sum_{t=t_0} (T(t) - T_b) \qquad T(t) > T_b \qquad \text{Model 1}$$

where
$TS(t)$ = temperature sum on day t (day-degrees)
$T(t)$ = average temperature (°C) on day t
T_b = base temperature (°C)
t = time
t_0 = starting day from which the temperature is accumulated

A fixed base temperature of +5 °C was used in the computations. Starting day was the day in spring when three consecutive days with mean temperature above +5 °C occurred.

The first study was published by Prescher (1982) and included 600 provenances. The study

Fig. 1. Meteorological stations providing data for the study and nurseries where the phenology studies were made.

was divided into two rounds, with sowing years 1974 and 1976. Measurements of phenology were made on seedlings 3–5 years old in five nurseries. In Prescher's report mean values of temperature sums for budburst were presented for provenance regions in graphs. The number of regions as well as the number and type of seed sources in each region varied between rounds and nurseries. In Prescher (1982) the temperature sum was calculated with +6 °C as base temperature. The data in this paper were recalculated using a threshold of +5 °C instead of +6 °C. The transformations were carried out by solving regression equations using temperature data from five evenly spread meteorological stations obtained for the period encompassed by Prescher's study (1978–1980). Deviations from regression functions were larger between years than between stations. One regression function was calculated for each year in the temperature sum-range 50–200:

1978: $TS_5 = 13.707 + 1.089 \cdot TS_6 \, (R^2 = 0.995)$
1979: $TS_5 = 13.297 + 1.112 \cdot TS_6 \, (R^2 = 0.996)$
1980: $TS_5 = 21.575 + 1.141 \cdot TS_6 \, (R^2 = 0.996)$

where
TS_5 = temperature sum with base temperature +5 °C
TS_6 = temperature sum with base temperature +6 °C

Two nursery studies made on 3-year-old seedlings were also analysed. One study in Uppsala (59°48'N, 17°38'E, 15 m. asl) in 1987 included 23 Belorussian and Baltic provenances and two Swedish provenances. Temperature sums were calculated based on data from the meteorological station at Ultuna, situated 300 m from the nursery.

The other study was made in Brunsberg (59°37'N, 12°59'E, 75 m. asl) in 1993. The study included nine Swedish (56.5°N–62.5°N) and three Belorussian provenances. The temperature sum was calculated from data registered by a temperature logger in the nursery (Campbell, CR10).

2.2 Temperature Data and Frost Risk Predictions

Daily minimum and mean temperatures between 1970 and 1993 from 11 meteorological stations in Sweden were used (Fig. 1) (SMHI, 1970–1981; SMHI, 1981–1983; SMHI, 1985–1993).

For each year and station the daily temperature sum was estimated as in model 1 above, with a base temperature of +5 °C. The starting day varied from January 1st at the southernmost station (55°43') to May 1st at the northernmost one (68°27').

The lateral shoots of young Norway spruce are as most susceptible to frost injury from budburst until the first developmental stages of the shoot elongation have been completed (Hannerz 1994). This period lasts for about 2 weeks, corresponding to approximately 100 day-degrees. Frost risk was expressed as the probability (proportion of years) of a potentially damaging frost occurring within 100 day-degrees from budburst:

$$P_f = P(T < T_f \mid TS_c) \qquad \text{Model 2}$$

where
P_f = probability of frost occurrence
T_f = threshold temperature for frost
TS_c = critical value of temperature sum for budburst

The threshold temperature for frost used in the computations was +2 °C in the screens at the meteorological stations. For comparision, computations were also made for the thresholds 0 °C and –2 °C.

3 Results

3.1 Temperature Sum Required for Budburst in Norway Spruce Provenances

Recalculated temperature sums required for budburst in the study by Prescher (1982) are presented in Table 1. The provenances are grouped by region, and each of the figures are mean values from three of the nurseries in Prescher's study. Since the regions differ in their numbers and types of seedsources, it was not possible to subject the data to statistical analysis. Rather

Table 1. Temperature sum (threshold +5 °C) required for budburst for different Norway spruce provenance groups. Recalculated values from Prescher (1982).

Provenance group	Sowing year 1974		Sowing year 1976		Mean
	Seedling age 4	5	3	4	
Finland	92	87	111	116	96
Sweden appr. 60°	132	123	122	114	123
Baltic states	172	160	150	168	163
Poland	175	165	150	168	166
Czechoslovakia	158	157	137	151	152
Belorussia	-	-	165	203	184
Rumania	179	178	145	172	170
Jugoslavia	193	196	-	-	195

Table 2. Temperature sum (threshold +5 °C) required for budburst for different Norway spruce provenances. Data from Uppsala in 1987 and Brunsberg in 1993. Three-year-old seedlings.

Provenance group	Uppsala 1987	Brunsberg 1993
Sweden approx 59°N	110	132[1]
Sweden approx 62°N	-	126[1]
Belorussia, Grodno	172[2]	165[3]
Belorussia, Vitebsk	158[2]	154[3]
Belorussia, Minsk	168[2]	145[3]
Baltic states	156[2]	-

[1] Estimated from regression line with natural stand seed from 56°30' to 62°40'N.
[2] 4–8 seed sources per group
[3] 1 seed source per group

than regarding the mean values as absolute, they should be considered as approximations of the temperature sum thresholds for the different provenances.

Corresponding temperature sums from the studies in Uppsala in 1987 and in Brunsberg in 1993 are presented in Table 2.

For the comparisons of frost risk it is assumed that a four-year old central Swedish spruce seedling requires 120 day-degrees and that a corresponding Belorussian spruce seedling requires 180 day-degrees.

3.2 Temperature Sum and Frost Risk

Naturally, the date on which a given temperature sum is reached will vary with latitude. For example, the date on which 100 day-degrees is reached occurs, on average, 41 days earlier in Lund than in Karesuando. In Table 3 it is shown that the difference in the date of budburst between a four-year-old, central Swedish seedling and a Belorussian seedling of the same age are around 8 days at all the included meteorological stations.

Examples of how the frost risk decreases as the temperature sum required for budburst increases are given from five of the meteorological stations in Fig. 2. The threshold temperatures for

Table 3. Mean dates on which temperature sums of 120 and 180 day-degrees are reached at the different meteorological stations. The former value corresponds to the budburst of a 4-year-old, central Swedish spruce and the latter value to a Belorussian spruce.

Station	Date reaching 120 day-deg.	Date reaching 180 day-deg.	Difference in days
Lund	9/5	18/5	9
Växjö	15/5	23/5	8
Säve	15/5	23/5	8
Stockholm	16/5	24/5	8
Ultuna	18/5	26/5	8
Karlstad	20/5	28/5	8
Falun	22/5	30/5	8
Härnösand	1/6	9/6	8
Haparanda	10/6	18/6	8
Stensele	10/6	19/6	9
Karesuando	19/6	27/6	8

Table 4. Probability (%) of a frost occurring after reaching 120 or 180 day-degrees at meteorological stations representing a range of latitudes. The former value corresponds to the budburst of a 4-year-old, central Swedish spruce and the latter to a Belorussian spruce.

Station	Frost threshold <0°, Temperature sum 120	<0°, 180	<+2°, 120	<+2°, 180
Lund	0	0	14	0
Växjö	18	9	46	27
Säve	6	0	18	12
Stockholm	8	0	17	8
Ultuna	20	13	40	40
Karlstad	0	8	25	12
Falun	17	12	42	29
Härnösand	4	0	17	8
Haparanda	0	0	9	4
Stensele	21	0	37	5
Karesuando	0	0	10	5

frost are +2 °C, 0 °C and –2 °C at standard height (1.5 m). In Table 4 the frost risks for a central Swedish spruce seedling and a corresponding Belorussian spruce seedling are presented for

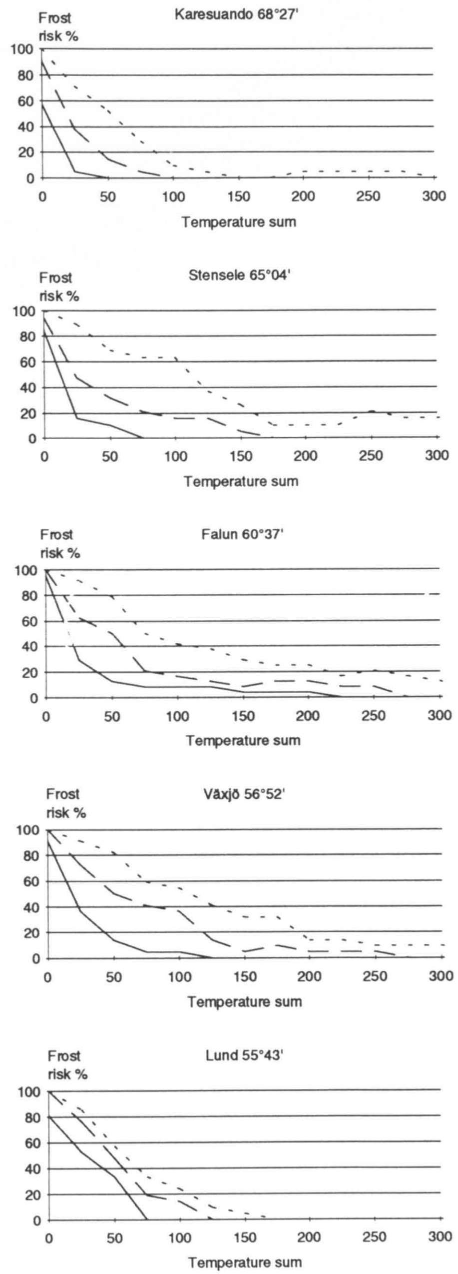

Fig. 2. Change in frost risk with increasing temperature sum in spring at five meteorological stations. ——— <–2 °C, — — — <0 °C, - - - - - <+2 °C.

locations representing a variety of latitudes. It is evident that for an injury threshold of +2 °C at standard height, frost risk decreases sharply if budburst is delayed from 120 to 180 day-degrees.

4 Discussion

4.1 Temperature Sum and Budburst

Many biological processes in spring start in response to increasing temperature (Sarvas 1972), and the timing of budburst is strongly dependent on the temperature sum, as shown in *Picea abies* (Lindgren and Eriksson 1976), *Picea sitchensis* (Cannell and Smith 1983) and *Pseudotsuga menziesii* (Thomson and Moncrieff 1982). However, chilling is needed to break dormancy in many conifers in the temperate zone (*Pseudotsuga menziesii*: Campbell and Sugano 1975, *Picea sitchensis*: Cannell and Smith 1983, *Picea abies*: Worrall and Mergen 1967, Nienstaedt 1967, *Picea glauca*: Nienstaedt 1967), and any lack of chilling has to be compensated for by an increased temperature sum to reach budburst. Cannell and Smith (1983) and Hänninen (1990) have presented models for predicting budburst and dormancy release that take into account both the chilling requirement and temperature sum.

In this paper budburst is predicted from a pure temperature-sum model. This model is based on the assumption that the chilling requirement is almost fullfilled and that deviations in chilling only have small effect on the timing of budburst in Norway spruce grown outdoors in Sweden. Many of the previous studies of the relation between chilling and temperature sum were made under controlled conditions in growth chambers or in greenhouses. As is summarized in Cannell and Smith (1983, their Figure 4), the number of chill-days in many of these experiments was lower than the actual number occurring outdoors in

Sweden during winter. At the meteorological station at Ultuna (59°49'N, 17°39'E) the average number of chill-days <5 °C from Oct–May was 173 days over a 15-year period. Cannell and Smith (1983) showed that below 180 chill-days the chill-days affected the timing of budburst in *Picea sitchensis*. However, as they pointed out, *Picea sitchensis* is a maritime species with high chilling requirements. Nienstaedt (1967) found that *Picea abies* had lower chilling requirements compared with *Picea glauca*, *P. engelmanni* and *P. pungens*. Incorporating chilling into the temperature-sum model presented in this paper, might increase the model's accuracy. Further work is needed to evaluate this possibility.

There are also other complications when assessing the relationship between budburst and temperature. Sarvas (1972) stressed that the air temperature may differ considerably from the temperature inside the bud. This difference is especially pronounced in springtime when air temperatures may be low at the same time as the buds are heated by intensive solar radiation. Furthermore, in many studies temperature data have been collected from meteorological stations far from the study sites. Budburst is also affected by the hardening conditions in the autumn, and insufficient hardening may lead to a delay in budburst (Dormling 1982). The growth rhythm of a seedling also changes with age, as does the temperature sum required for budburst (Ununger et al. 1988). In view of all these constraints it would seem advisable to make studies of budburst under standardized conditions; i.e. autumn and winter frost damage should be avoided, and the seedlings or cuttings used should be of a defined age.

4.2 Frost Risk Figures

Cannell (1985) expressed frost risk in spring as the probability that a frost would occur within seven days after budburst. The timing of budburst was predicted with the model presented in Cannell and Smith (1983). Methods of predicting frost risk for Douglas-fir seedlings were developed by Timmis et.al. (1994). Perttu (1981) published a frost risk map for Sweden, based on frost frequencies over all or parts of the growing season. Perttu assumed that budburst took place during a fixed period, and he did not consider differences in temperature-sum.

The prediction of frost risk in a forest plantation based on temperature data from a nearby meteorological station involves many problems. The air temperature in the meteorological screen, at 1.5 m height, may differ considerably from the temperature that the seedlings are exposed to. The threshold temperature below which seedlings are injured depends on many factors, such as seasonal variation in frost resistance, duration of the low temperatures, cooling rate, exposure to sun, etc. Frost resistance is generally lowest at budburst (e.g. Dormling 1982, Cannell and Sheppard 1982, Christersson and von Fircks 1988, Hannerz 1994). Christersson and von Fircks (1988) showed that new shoots on Norway spruce seedlings were injured when the temperature around the needles sank below –2 °C. In constructing his frost risk map of Sweden, Perttu (1981) assumed a horizontal correction of 2 °C and a vertical correction of 3 °C, when using the minimum temperature in the screen to calculate the lowest temperature on a nearby clearcut area. He used +2 °C in the screen as the threshold for potentially damaging frosts on a clearcut.

From March to June during 1979–1993 at Ultuna meteorological station, minimum temperatures on the ground averaged 2.6° lower than those in the screen (Hannerz, unpublished data). The difference between the two levels was most pronounced in late spring-early summer. In the end of May minimum temperatures on the ground averaged –2 °C when the minimum temperature at 1.5 m height was +2 °C. At the end of March the difference between the two levels was about 1.5 °C. Based on these results, it would seem appropriate to use the +2 °C-curve to predict frost risk.

In this study only 11 meteorological stations were represented, and the frost risk at a certain locality seemed to depend more on local conditions than on regional ones.With a broader network of meteorological stations it would be possible to produce frost risk maps of Sweden that consider the timing of budburst as well.

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