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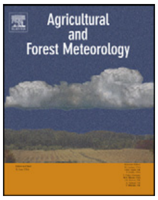

A double-threshold temperature sum model for predicting the flowering duration and relative intensity of *Betula pendula* and *B. pubescens*

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ABSTRACT

The accurate prediction of the flowering period and the amount of released pollen of wind-pollinated trees is important for predicting the aerobiological pollen amounts and for estimating the intensity of background pollination of orchard seed production. Current phenological models, such as the commonly used temperature sum (thermal time) model, are efficient for predicting the timing of point events, e.g. the onset of flowering or leaf unfolding. However, the flowering period of boreal trees, including *Betula pendula* and *B. pubescens*, may last up to 5 weeks with widely varying flowering intensity. Therefore, the ability to predict the duration of the whole flowering period and the intensity of pollination is very important.

In this paper, we present a new phenological model that predicts the whole flowering period and daily (normalized) variation of flowering intensity. The model is based on similar principles as the temperature sum model. The model was calibrated against pollen data recorded with pollen traps placed in several locations in Southern and Central Finland. Our new model predicted accurately the variation in the intensity throughout the flowering period. Moreover, it was able to predict the start and end of the pollination season with accuracy comparable to that achieved with an ordinary temperature sum model for point events. Due to limited amount of test data, the data-dependency of the model had to be tested with a bootstrapping approach. With this method, the model fit and parameter values showed to be independent of the parameter fitting data. The model can be used to predict the whole flowering period of wind-pollinated boreal trees for many different purposes, such as aerobiological forecasts of allergenic pollen, or generation of input data for models of long-range pollen transport.

1. Introduction

Silver birch (*Betula pendula* Roth.) and downy birch (*Betula pubescens* L.) are common forest trees with distribution covering most of Eurasia, excluding the northernmost and southernmost areas (Atkinson, 1992; Hämet-Ahti et al., 1998). They are monoecious, wind-pollinated trees. Successful flowering and production of viable seeds requires large concentrations of airborne pollen. Thus, an exponential positive relationship exists between the amount of pollen production and the pollination efficiency and seed viability (Sarvas, 1952). Moreover, there is a strong evolutionary pressure towards simultaneous flowering and a positive correlation between the annual amounts of male and female birch catkins (Masaka and Maguchi, 2001). The female flowers usually become receptive one day before the male flowers of the same tree start pollinating (Sarvas, 1952, 1955); therefore, cut-crossing (i.e. fertilization with pollen from a different individual) is strongly preferred (Hagman, 1971).

In Northern Europe, the main pollination seasons of *B. pendula* and *B. pubescens* begin in late April to late May and in the subarctic area during the first half of June (Jäger and D'Amato, 2001). The length of the birch pollen season in Finland, our study area, may vary from two to five weeks (Luomajoki, 1999). The beginning of the flowering period depends mostly on the prevailing meteorological conditions, especially on the cumulative air temperature. Flower buds are developed during the previous summer and fall for the winter into a state of inhibited growth, i.e. dormancy (Sarvas, 1974). The buds need to be released from dormancy before bud development can proceed in the spring. However, factorial

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modeling studies indicate that additional cues, related to changes in the light environment of the plants, are required to initiate the bud development in the spring (Linkosalo and Lechowicz, 2006). After the initiation, the bud development is driven by ambient air temperature (Sarvas, 1972; Linkosalo and Lechowicz, 2006).

The release of mature pollen is largely a passive process dependent on gravity, anther splitting when dry, and agitation of the source plant by air currents (Solomon, 2002). Consequently, once the flowering has started, other factors in addition to the temperature affect the actual pollen release, too. For example, rainy weather can postpone the beginning or inhibit the already started pollen release, even if the required temperature sum has been accumulated. Windiness, on the other hand, has been shown to positively correlate with airborne pollen concentrations (Peternel et al., 2005).

Many phenological events, such as leaf bud burst, can be considered point events, in other words, they take place in a discrete moment of time. This does not apply to flowering of wind-pollinated trees whose flowering period may last up to 5 weeks on a stand level (Luomajoki, 1999). There is some variation in the ripening of catkins within a single tree, as is in the onset of flowering between individuals of the same population. This variation adds to the overall length of the flowering period.

Many applications of pollen release models require data covering the whole extent of the flowering period, as well as daily variation in the flowering intensity. For example, determining the pollen release of surrounding stands is important for estimating the significance of background pollination for seed orchard plantations (Parantainen and Pulkkinen, 2003). Aeroallergic pollen forecasts are another obvious application. In addition, the long-range transport models, developed to predict the occurrence of the pollen airborne transport episodes, require the whole temporal distribution and intensity of flowering events as input data for the predictions (Skjøth et al., 2008; Sofiev et al., 2006).

Most spring phenological models can only predict a specific point event in time. Incidentally, comparisons of several models of spring phenology suggest that simple temperature sum (thermal time) type models, with a fixed starting date for temperature sum accumulation, predict the observed onset of flowering with the highest accuracy (Linkosalo et al., 2006, 2008). However, such models cannot be used to predict the whole flowering period of wind-pollinated trees. In this study, we developed a new model, which is based on the same principles as the temperature sum model but can be used to describe the whole period of flowering from its onset to the end, and especially daily variations of the flowering intensity. The aim of this paper is to describe this new phenological model and to test it with historical flowering data.

2. Materials and methods

The pollen data used in this study was collected by the Finnish Forest Research Institute during 1963–1973 from several locations in Finland. Luomajoki (1999) describes the data in detail. There are 45 records for flowering of *B. pendula* and 84 for *B. pubescens;* each record corresponds to a specific location and year. The data was collected with 1–3 self-recording pollen samplers (Sarvas, 1968) per site, and the daily observations were the average values of the data from all the samplers at that site. The locations of the study sites are presented in Table 1 and Fig. 1.

Luomajoki (1999) had omitted altogether 13 observations from the original data, due to obvious long-range transport episodes detected based on measurements of substantial pollen concentrations before the local start of flowering. For technical reasons related to the model implementation, we also omitted the cases where the flowering extended past 1 July. Finally, we omitted the northernmost site in the sub-arctic area (Utsjoki) as it represents different climate conditions and vegetation zone as the rest of the data.

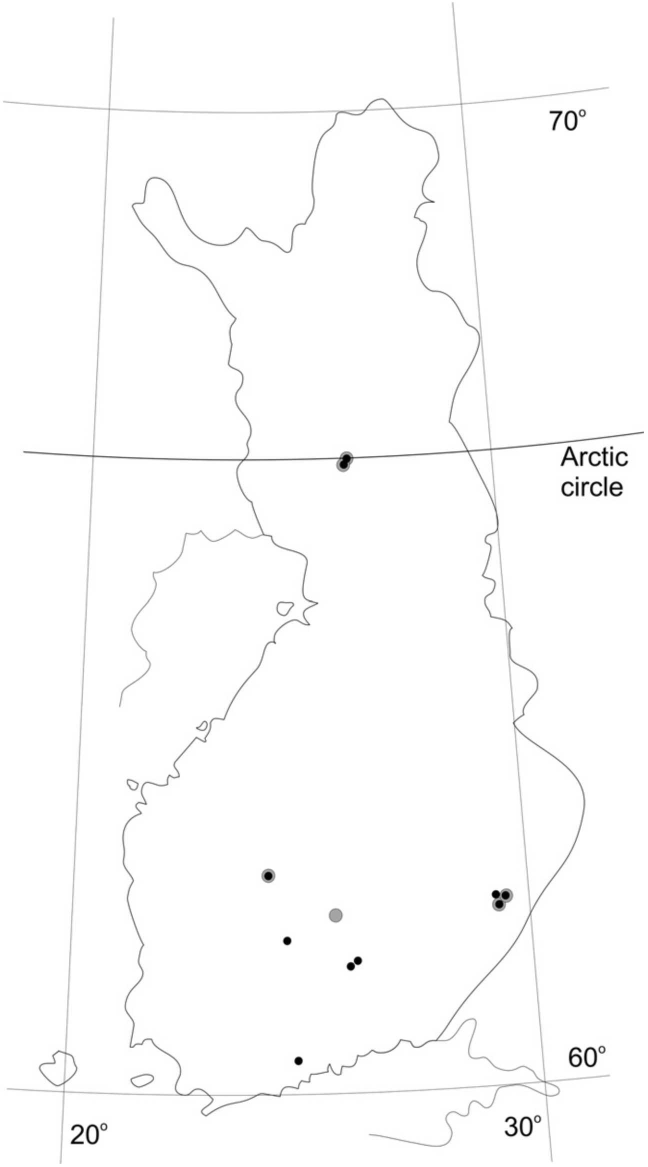

Fig. 1. The phenological observation sites on the map of Finland. Grey circles refer to *Betula pendula* observation sites and the black ones for *B. pubescens*.

The original data, consisting of the daily numbers of caught pollen grains, showed a great annual variation of overall pollen grain numbers. We normalized the absolute numbers of pollen grain counts in order to focus on the temporal development of the flowering and pollen release, disregarding the year-to-year variation in the flowering intensity and total amount of pollen released. For each day, the ratio of the cumulative pollen count until that day was divided by the total pollen count recorded at the site during that particular year; this procedure yields a daily figure starting from zero, before the flowering has started, and ending at unity, once the flowering has finished. We chose this approach, as the current models for flowering intensity, especially those derived from data of airborne pollen, seem to be rather data-dependent (Ranta et al., 2005; Jato et al., 2007).

The corresponding temperature data were extracted from those operational weather stations of the Finnish Meteorological Institute (FMI) most adjacent to the pollen recording sites. Three