

Copenhagen – a significant source of birch (*Betula*) pollen?

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Received: 5 September 2007 / Revised: 29 November 2007 / Accepted: 30 November 2007 / Published online: 20 December 2007
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Abstract Current aerobiological research applies the hypothesis that the main source of atmospheric birch (*Betula*) pollen is forest trees. Our results indicate that the measured levels in Copenhagen are not only due to birch trees in Danish forests but that the urban areas also seem to be a significant source of birch pollen. A number of episodes in 2003 with enhanced pollen levels in Copenhagen seem to be associated with parks and gardens inside and just outside the city. Our results also indicate one long-range transport episode from remote sources in Poland and Germany. Finally, our results show that the pollen levels vary considerably over the day and geographically between Copenhagen and the city of Roskilde, 40 km away. We suggest, that these differences in time and space in the pollen levels are mapped using an integrated monitoring strategy.

Keywords Back-trajectory analysis · Modelling · Denmark · Local and regional sources

Introduction

Measured atmospheric pollen concentrations may be related to both local and remote sources (Stach et al. 2007). In

Denmark, remote sources for birch pollen include Germany, Poland (Skjøth et al. 2007) and most likely also Sweden. Research on atmospheric transport of birch pollen is based on the assumption that the most important sources of atmospheric birch pollen in Europe are the forests in Russia, Belarus, and Baltic and Nordic countries (Ranta et al. 2006; Sofiev et al. 2006). However, long-range transport of birch pollen is an episodic phenomenon (Hjelmroos 1991, 1992; Ranta et al. 2006; Skjøth et al. 2007). It is therefore likely that most of the observed birch pollen in Denmark is related to Danish birch trees. In Denmark, the most frequent forest trees are Norway spruce (*Picea abies*), beech *Fagus sylvatica*) and oak (*Quercus robur*) (Larsen and Johannsen 2002), in comparison with birch, which is not accounted for separately. The Danish forest inventory includes 12 categories, where birch, due to limited frequency, is included in a residual group for other deciduous trees. Danish forests cover about 11% of the land area of the country (Larsen and Johannsen 2002) compared to 7% of the urban area (Nielsen et al. 2000). Urban areas may contain trees in considerable numbers (Konijnendijk et al. 2005). The amount of urban trees in Denmark is unknown, but an inventory from Munich in southern Germany has shown that the area covered by trees may be 20–30% for areas with housing estates, parks and cemeteries (Pauleit and Duhme 2000). Since the surface area covered by trees and the production of pollen correlate strongly (Galan 2007; Molina et al. 1996), the urban areas are most likely a significant source of tree pollen. A pilot study has shown that the eight most common road and park trees in Northern Europe include the two birch taxa *Betula pubescens* and *B. pendula* (Konijnendijk et al. 2005; Pauleit et al. 2002). Due to the small fraction of birch in Danish forests, it is likely that a large fraction of the observed birch pollen in Denmark is associated with trees in the urban

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areas, sources outside Danish forests and remote sources such as Germany, Poland and Sweden.

We have therefore formulated following hypothesis: “a significant part of the observed birch pollen in Copenhagen is related to trees outside the Danish forests”.

This hypothesis is tested by analysis of pollen counts from two pollen traps. In the analysis of the measurements, we use trajectory analysis, calculated distributions of birch trees in Danish and foreign forests as well as maps of potential pollen sources in and outside Denmark.

Materials and methods

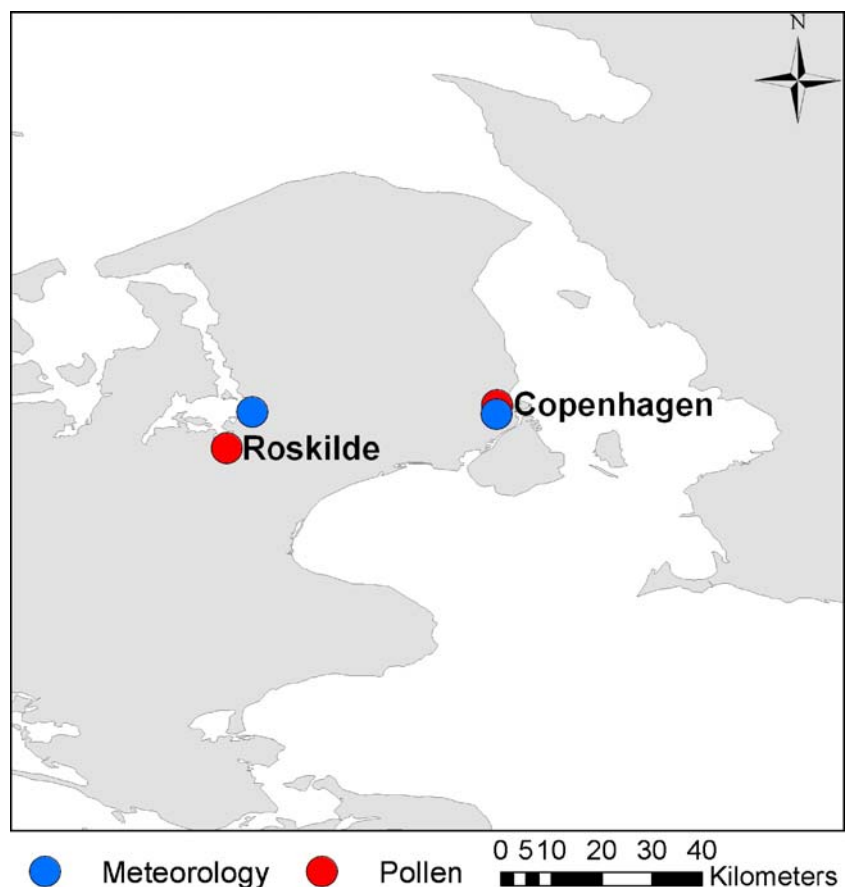
Sites and observation methods

The observations in this study were obtained from two sites on Zealand: Roskilde and Copenhagen (Fig. 1). The surroundings of the pollen trap in Copenhagen are of urban character, and the coastline is about 1 km east of the site. Continuous monitoring of pollen content in the air has been carried out using a Burkhard volumetric spore trap of the Hirst design (Hirst 1952) in Copenhagen since 1977 and in Roskilde for the year 2003. We investigated the entire 2003 birch pollen season by both diurnal samples and 2-h samples

from pollen traps in Copenhagen and Roskilde. In Copenhagen, sampling is performed from the roof of the Danish Meteorological Institute (55°43'N, 12°34'E) 15 m above sea level. Roskilde is situated about 40 km west of Copenhagen, south of the Roskilde Fjord. The surroundings of Roskilde are agricultural but also include large deciduous forests, especially west and south-west of the city. The pollen trap in Roskilde in 2003 was placed on top of the county building (55°38'N, 12°05'E) 15 m above ground level. Daily and diurnal variations in birch pollen counts are expressed as grains/m³. Collection of pollen and preparation of slides was performed according to the procedures described in Sommer and Rasmussen (2006). Pollen was counted at 640× magnification on 12 transverse strips for every 2 h, according to Käpyla and Penttinen (1981). Pollen from birch was identified to generic genus.

The time period selected for detailed investigation was determined by threshold analysis. The thresholds used in this study were the thresholds for birch pollen forecasts in Denmark, which are indicated by three classes: few, moderate and high, corresponding to below 30, from 30 to 100 and above 100 birch pollen grains/m³, respectively. These thresholds are based on clinical thresholds defined by Petersen and Munch (1981) and Weeke (1981) and subsequently used in threshold studies as in Skjæth et al. (2007).

Fig. 1 Location of pollen traps (red) and meteorological stations (blue) in Copenhagen and Roskilde, respectively



Meteorological observations have been obtained from two sites close to the pollen traps (Fig. 1): Lille Valby (55° 41'N, 12°07'E) and on the roof of the H.C. Ørsted Institute Building (55°42'N, 12°34'E), Copenhagen University. Both masts are operated by National Environmental Research Institute (NERI) and provide meteorological data on a half-hourly basis for use in the integrated monitoring of air quality in Denmark (Hertel et al. 2007).

Source location maps

In order to evaluate potential sources for the pollen levels observed in Roskilde and Copenhagen, maps of potential source areas such as forest and urban areas have been compiled on local and regional scales. Forest and nature areas in the immediate vicinity of Copenhagen have been investigated in detail using printed local forest maps (see <http://www.skovognatur.dk/Emne/Skov/Statsskovene/Skovkort/> for the online version).

The regional scale map of potential birch pollen sources are based on Danish (National Environmental Research Institute 2004), Swedish (Lantmäteriet 2004), German (Umweltbundesamt- DLR 2005) and Polish (GIOS 2004) land use information. This land use information is produced within the CORINE cooperation “The CORINE Land Cover Classification” (European Commission 2005). The resulting classification of the land surface is provided as irregular polygons with a minimum width of 100 m for each country in the European Union. The entire classification contains 44 classes, including deciduous forest, mixed forest, coniferous forest, and low built-up area. It is assumed that areas classified as agricultural areas and coniferous forest will not produce birch pollen, whereas areas classified as forest and scrub, deciduous forest, mixed forest and built-up areas are considered as potential birch pollen sources.

The national forest inventories from Germany (Bundesministerium für Ernährung 2004), Poland (Budna et al. 2005), and Sweden (<http://www.nfi.slu.se>) were used for calculating the resulting birch tree densities in the forest areas surrounding Denmark. For the Danish area, it is only possible to calculate the maximum birch tree density for the class “other deciduous trees”. In reality, this figure is an upper limit that is only valid if these areas are totally covered by birch trees and do not contain other trees like alder (*Alnus*) or willow (*Salix*).

Back trajectory calculations

Trajectory calculations are based on meteorological calculations from the operational THOR weather and air pollution forecast system (Brandt et al. 2001a,b,c) using the Eta weather forecast model (Janjic 1990, 1994;

Nickovic et al. 1998) and a flexible trajectory model (Skjøth et al. 2002). In the trajectory analysis, backward trajectories are used as an indicator of potential source areas according to Stach et al. (2007) and Skjøth et al. (2007).

Results

Pollen counts

The birch pollen season 2003 started on 22 April and ended on 8 May (Fig. 2) using the 2.5% accumulation method (Goldberg et al. 1988). The concentrations peaked between 22 April and 5 May when the daily mean value exceeded 100 pollen/m³. The highest concentrations were measured on 26 April, when diurnal mean values reach 710 and 1,300 pollen/m³ in Copenhagen and Roskilde, respectively. The 2-h concentration varied with short-term peaks during the period 22–24 April (Fig. 3). Concentrations were low during most of 25 April, and the peak was during the night of 26 April with 4,050 pollen/m³ in Roskilde. During the period 27–29 April the concentration during the night was in general very low. Day concentrations were about a factor of two higher in Copenhagen (1,000–2,000 pollen/m³) than in Roskilde (500–750 pollen/m³). The day concentration reached a level about 500 pollen/m³ and was generally low at night during the period 30 April to 5 May. On 1 May, the pollen concentration was approximately a factor of two higher in Copenhagen (500 pollen/m³) than in Roskilde (200 pollen/m³).

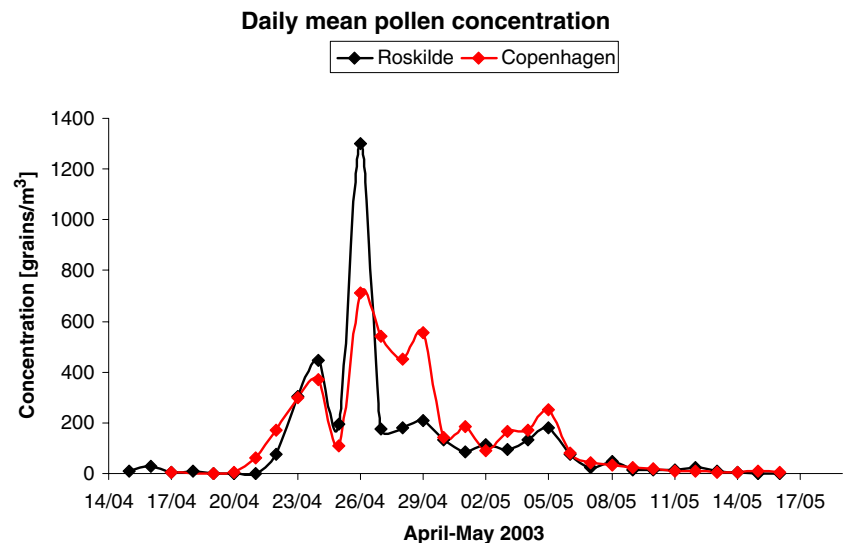
Temperatures

Temperatures were high on 22 and 23 April when the day temperatures peaked at 18°C (Fig. 3). On 24–26 April, temperatures were generally low with a minimum below 4°C during the night of 25/26 April. This is below the critical temperature (marked in blue on Fig. 3) for phenological development of birch trees around the start of the season (Rasmussen 2002; Spieksma et al. 1995). On 27 April the temperature increased and during the period 27 April to 5 May the day temperature was between 12°C and 18°C and during the night down to 8°C.

Back trajectory analysis

The main season has been analysed using backward trajectories. Here, we show trajectories for the day with the lowest concentrations (25 April), the highest concentrations (26 April) and those days where the concentrations in Copenhagen are about twice the concentration in Roskilde (daytimes 27–29 April and 1 May). The backward trajectories indicate transport from the southern

Fig. 2 Birch pollen concentration (daily values) for the 2003 season measured in Roskilde (black) and Copenhagen (red). Missing values for Roskilde on 19, 20 and 21 April was due to trap failure



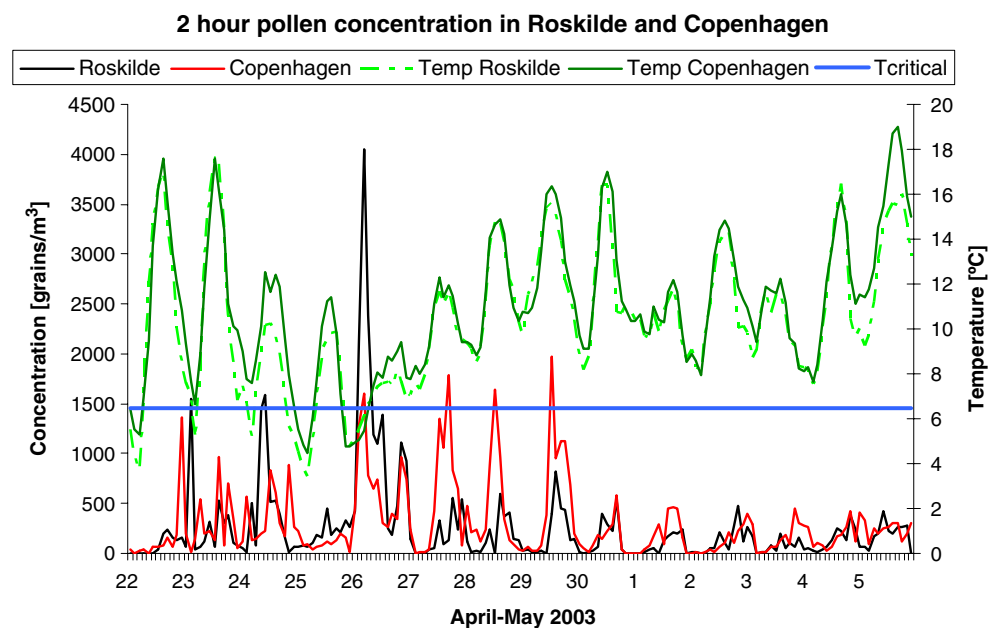
Scania in Sweden on 25 April (Fig. 4a), and transport from Poland on 26 April (Fig. 4b). For 27–29 April and for 1 May, the trajectories primarily indicate transport of air masses from west over the Roskilde area towards Copenhagen (Fig. 5).

Potential Danish sources

The local scale map shows that no deciduous forests are found in the area between Roskilde and Copenhagen (Fig. 6). Limited areas categorized as “mixed forest” and “forest and scrub” are seen. Forest areas are found north of Copenhagen and west of Roskilde. The local forest maps show no large birch forest localities in or around Copenhagen except for the two natural areas named Pinseskoven

and Fasanskoven. These forest areas are located south of Copenhagen on the island of Amager. Today, they are the largest birch forest area in Denmark. The area between Roskilde and Copenhagen has an additional potential birch pollen source in the built-up areas. The maximum density of forest birch tree for Denmark is shown in Fig. 7, and the fraction of birch trees in Danish forest is shown in Table 1. Figure 7 shows the maximum area of forest birch trees in the Danish municipalities. For most of the municipalities, the maximum birch forest cover is less than 100 m² birch/ha or less than 1% of the total area. Highest figures are found for Bornholm and Zealand while the lowest figures are found in the western part of Denmark. The municipalities between Roskilde and Copenhagen have generally figures between 0 and 100 m² birch/ha, with the exception

Fig. 3 Bi-hourly birch pollen concentration in 2003 in Roskilde (black) and Copenhagen (red). Bi-hourly temperatures in Copenhagen (solid dark green) and Roskilde (dashed light green) and critical temperature (blue) for phenological development of birch trees



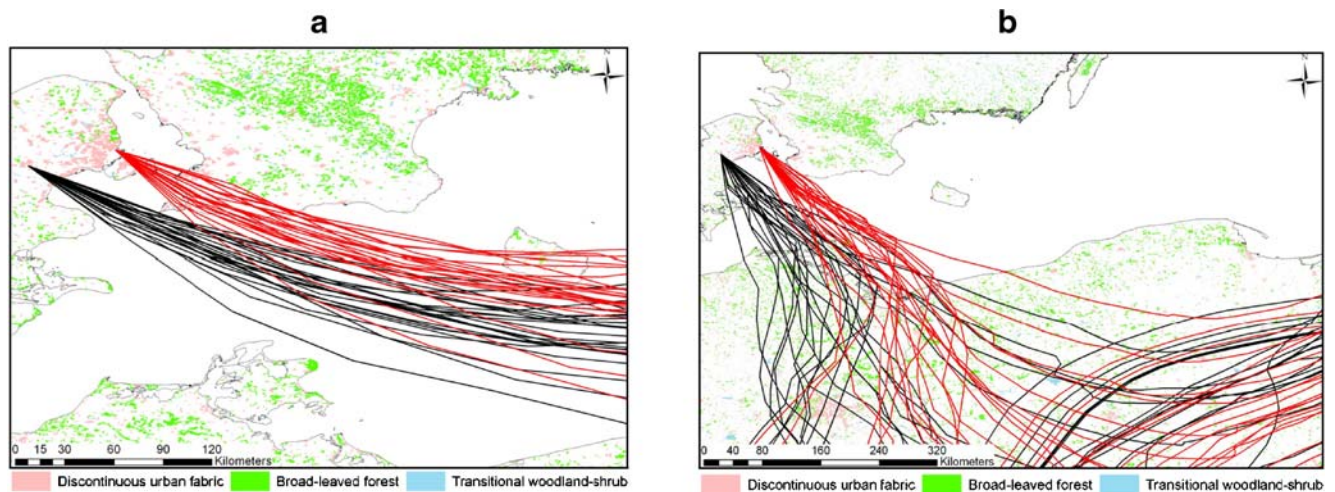


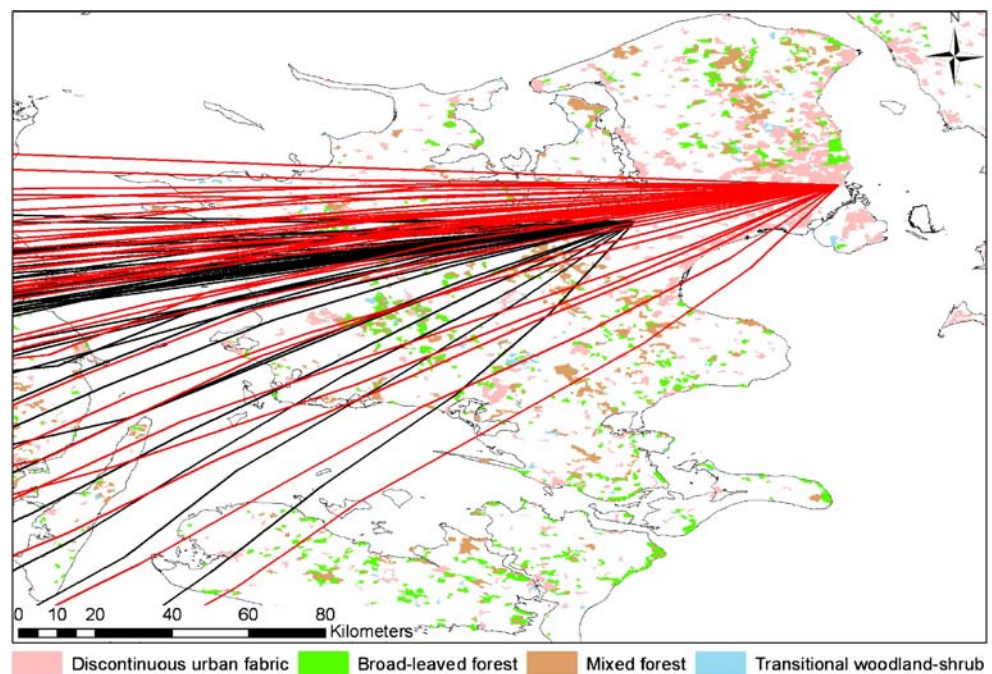
Fig. 4 Possible source areas and back trajectories for 25 (a) and 26 (b) April. *Black* trajectories have receptor points in Roskilde and *red* in Copenhagen; 24 trajectories are shown for each location for every hour (0000–2300 hours UTC)

of the municipality containing mixed forest and forest and shrub, where the density is between 100 and 150 m² birch/ha.

Potential sources outside Denmark

On the regional scale (Fig. 6), broadleaved forests are located in Sweden, Germany and Poland. The southern part of Scania is agricultural land and contains fewer broadleaved forest areas compared to other Swedish regions (Table 1). The broadleaved forests in this area also contain fewer birch trees compared to other Swedish regions, as the most common broadleaved tree is beech. The deciduous forests on Zealand and Funen contain a relatively small amount of birch compared to many of the regions in Sweden and Poland.

Fig. 5 Possible source areas and back trajectories to the pollen traps in Roskilde (*black*) and Copenhagen (*red*). Back trajectories are shown with arrival times at 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, and 1800 hours UTC, respectively for 27, 28 and 29 April and 1 May



Discussion and conclusion

Our investigations support the hypothesis that a significant part of the measured birch pollen in Copenhagen is related to sources outside the Danish forests. Furthermore, it is very likely that a significant part of the measured birch pollen concentrations in Copenhagen can be attributed to sources within the city.

Increased atmospheric pollen concentrations from Roskilde to Copenhagen

On local scale, 4 days (27 April 27 to 1 May) in the main season had air mass transport coming from west and

Fig. 6 Possible birch pollen source areas in selected areas of Denmark, Sweden, Poland and Germany

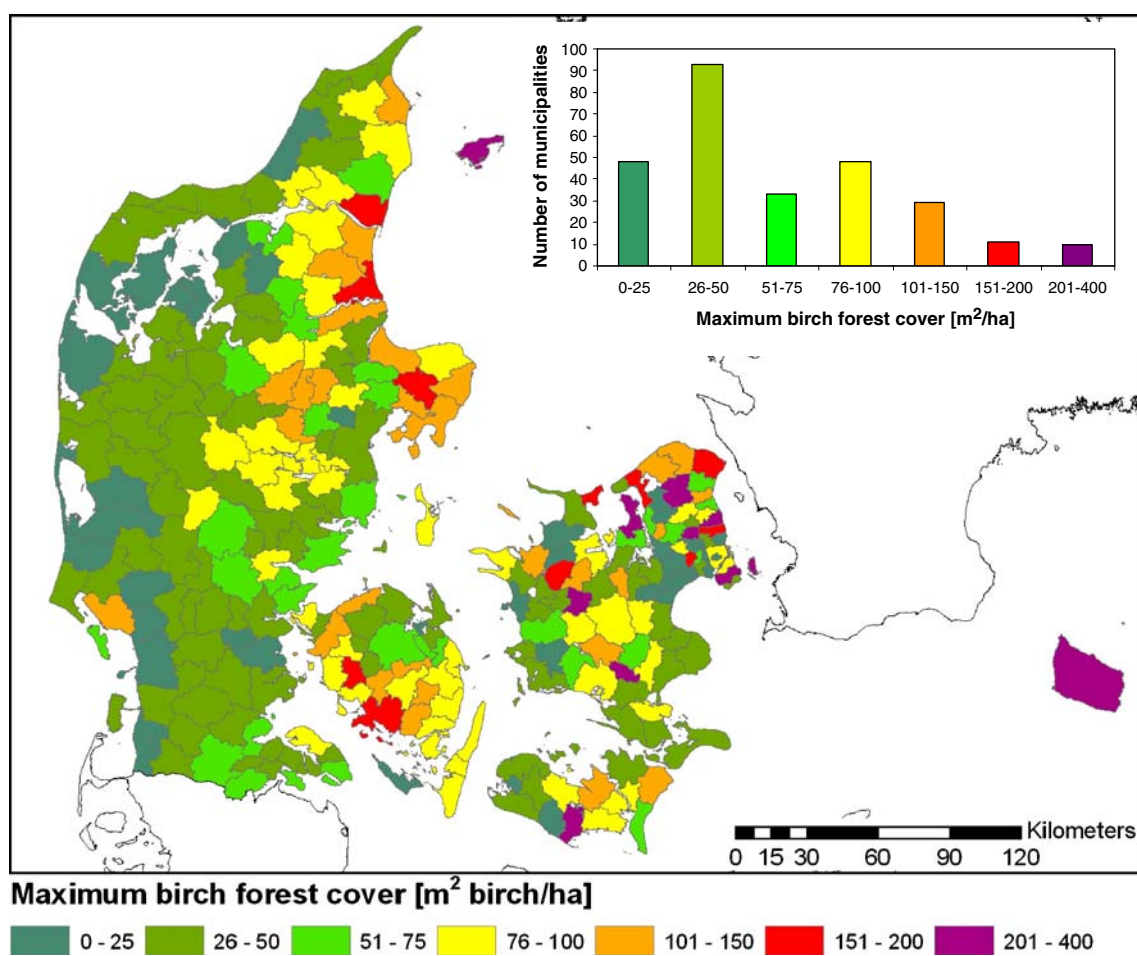
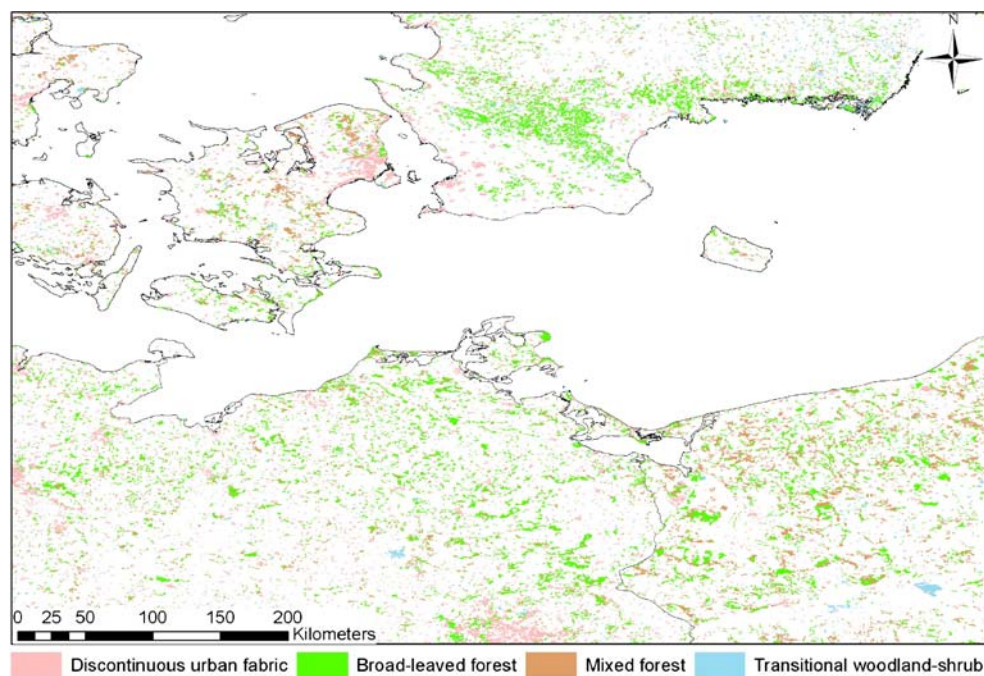


Fig. 7 Maximum forest birch cover in Denmark on municipality level for the year 2000

Table 1 Percentage birch trees in broad leaved forest in Swedish (Se), Danish (Dk), German (Ge) and Polish (Pl) regions near Copenhagen and Seeland. Calculations based on National forest Inventories

Region	Species	Percentage among broadleaved trees [%]
Kronoberg (Se)	Birch (<i>Betula</i>)	66
Scania (Se)	Birch (<i>Betula</i>)	22
Halland (Se)	Birch (<i>Betula</i>)	46
Blekinge (Se)	Birch (<i>Betula</i>)	34
Zealand (Dk)	Other broadleaved trees including birch (<i>Betula</i>)	11
Funen (Dk)	Other broadleaved trees including birch (<i>Betula</i>)	6
Zachodniopomorskie (Pl)	Birch (<i>Betula</i>) and false acacia (<i>Robinia pseudoacacia</i>)	37
Pomorskie (Pl)	Birch (<i>Betula</i>) and false acacia (<i>Robinia pseudoacacia</i>)	31
Lubuskie (Pl)	Birch (<i>Betula</i>) and false acacia (<i>Robinia pseudoacacia</i>)	48
Mecklenburg-Vorpommern (Ge)	Birch (<i>Betula</i>)	15
Schlesvig-Holstein (Ge)	Birch (<i>Betula</i>)	14
Brandenburg+Berlin (Ge)	Birch (<i>Betula</i>)	30

passing the Roskilde area on its way to Copenhagen. The backward trajectories (Fig. 5) indicate that areas west of Roskilde are the main sources of pollen both in Roskilde and in Copenhagen during this period. During this 4-day period, the concentrations in Copenhagen are about twice the concentrations in Roskilde (Fig. 3), despite the fact that the source maps (Fig. 6) do not indicate any important broadleaved forests with birch trees between Roskilde and Copenhagen. On 3 of the 4 days (27–29 April), the pollen number in Copenhagen was at its maximum for the 2003 season. The sources for the enhanced pollen number must therefore be placed in the area between Roskilde and the trap in Copenhagen. This supports the hypothesis that a significant part of the observed birch pollen in Copenhagen is related to trees outside the Danish forests.

Sources within and near Copenhagen

Pollen sources close to the trap in Copenhagen will in general have a stronger impact on the observed pollen number than remote sources. The detailed study of the printed forest maps shows that the forests in and surrounding Copenhagen, with the exception of the two forests 12 km south of the pollen trap, contain few birch trees compared to other types of deciduous trees. The location of

the two birch forests in the vicinity of Copenhagen means that they may be of great importance for the birch pollen concentration in limited areas of Greater Copenhagen, depending on the wind direction. The general low number of birch trees in the Danish forest will increase the importance of urban trees with respect to the overall measured pollen level.

Sources on the regional scale and atmospheric transport

On the regional scale, the trajectory analysis for 25 April indicates transport from southern Scania, and on 26 April from the countries south of Denmark (Fig. 4). In the area surrounding Copenhagen/Roskilde, relatively low temperatures were observed, which are near the critical temperature for growth of birch trees in spring (Fig. 3). The critical temperature for growth of birch trees is determined to be around 6.5°C (Rasmussen 2002; Spieksma et al. 1995). The low temperatures with little sun will generally lead to low pollen numbers as a result of a low release of pollen (Bernard 2001) in the area between Roskilde and Copenhagen. In the main season between 23 and 30 April, the lowest concentrations were measured on 25 April. The trajectory analysis indicates atmospheric transport from southern Scania, which is primarily agricultural land (Fig. 6) and therefore contains few forests and with a lower birch tree fraction compared to other Swedish, German and Polish regions (Table 1). The high pollen concentrations during the night of 26 April (Fig. 3), as well as the trajectory analysis, indicate that the episode with the highest pollen levels in 2003 were the result of long-range transport from the countries south of Denmark. Except for the southern part of Scania, the regions surrounding Denmark, in general contain more broadleaved forest and a higher birch fraction in the forests (Table 1). This result therefore supports the conclusions by Skj  th et al. (2007) that long-range transport of birch pollen from Poland/Germany to Denmark takes place before the start of the local birch pollen season almost every year. However, in the 2003 season, this transport from the south overlapped the local birch pollen season. The source of the highest birch pollen concentrations in both Roskilde and Copenhagen was thus outside the Danish forest areas, and therefore this analysis also supports the hypothesis raised in this paper.

Large cities as pollen sources?

Our results indicate that forest inventories alone are not sufficient to generate a complete mapping of birch pollen sources. Sources outside the forests, such as nature areas and city areas, must be included. In the United Kingdom, the highest annual birch pollen count is from London, in

comparison with other cities (Corden et al. 2000). Corden et al. (2000), speculate on whether the magnitude of the residential areas in the cities may be a factor of importance for the pollen level. Corden et al. (2000) did not have access to measurements outside the city and they did not use trajectories in the analyses of their observations. The present investigation and the investigations of Corden et al. (2000) indicate that urban areas may be a significant source of birch pollen, especially if the amount of forest area on a regional scale and/or density of birch trees in the forests is low.

Diurnal variations in the pollen load

Our investigation shows large variations over the day in the pollen level. Concentrations at night may be below 50 pollen/m³ and day time concentrations exceed 1,000 pollen/m³. The year 2003 had relatively low pollen levels (Sommer and Rasmussen 2006). The measured level of 1,000 pollen/m³ has been exceeded other years, since the variations in pollen level may be large between years (Sommer and Rasmussen 2006). However, the diurnal variation in the pollen number does not follow a fixed pattern. Pollen released in Poland 12 h earlier will arrive during the night—like the episode observed on 26 April. Such factors may be handled by use of atmospheric transport models. Current transport models may be easily adapted to handle pollen (Helbig et al. 2004; Pasken and Pietrowicz 2005; Schueler and Schlünzen 2006; Sofiev et al. 2006) including prognoses for the pollen concentration several days ahead. A constraint on obtaining realistic results with the transport models is that the pollen release must be correctly described both locally and regionally. Our results indicate that in Denmark this pollen release should include forest inventories as well as sources outside the forests—including nature areas with considerable tree growth and urban areas including parks and gardens.

Uncertainty in the analyses of source areas and air mass transport

The source maps are based on the Landsat ETM+ satellite images. This is considered the best satellite based mapping of potential source areas of birch pollen on a national scale. ETM+ has a resolution of 30 m and the resulting Corine classification of the surface is 100-m resolution (European Commission 2005). The classification therefore has the limitation that smaller groups of trees will not be included. Furthermore, the ETM+ will only distinguish between deciduous forest and coniferous forest, and not between single tree species like birch and beech. Additional methods

must therefore be included to quantify birch pollen sources in urban areas. This is necessary in order to quantify local differences in pollen concentrations. The national forest inventory has other limitations. It only considers areas larger than 0.5 ha and not small groups of trees and single trees. Furthermore, the Danish forest statistics may only be used to provide the maximum birch tree density. The actual birch tree density is most likely to be smaller, which further supports the hypothesis of a significant influence from sources outside the Danish forest areas.

Backward trajectories have been used in the analyses. A single trajectory has a considerable uncertainty with a typical error of about 20% of the transport distance (Stohl 1998). Groups of trajectories are therefore often applied, see, e.g., Borge et al. (2007), which has also been used in this analysis. Furthermore, the transport distance between Roskilde and Copenhagen is only about 40 km, and the error due to transport distance is therefore of minor importance. For the analysis of 25 and 26 April, the transport distance to Poland and Sweden makes the importance of the error on the trajectories larger. Since the most important conclusions relate to the measurements at Roskilde and Copenhagen we do not consider this uncertainty on the trajectories as being of high importance.

Combined measurements and model results: Integrated monitoring

Our results indicate that the governing processes for the pollen level may be analysed in a similar way to chemical air pollution. In Denmark, NERI performs Integrated Monitoring (IM) of chemical air pollution in order to explain and understand the pollution levels (Hertel et al. 2007). In IM, data for the regional, urban background and local street levels are used to distinguish between contributions from local and remote sources. Atmospheric transport models are used to understand the governing processes and provide data for sites that are not covered with the measurements. This will provide the opportunity to map regional and local variations in pollen levels both in nowcasting and forecasting. The mapping will have great use for patients suffering from allergic rhinitis, and provide better possibilities for relating illnesses to exposure of high pollen levels.

Future work

The presented analyses indicate that there are significant variations in the pollen concentrations in time and space over the Danish area. Analyses from Germany show only limited correlation between development of the pollen

season and local phenological development (Estrella et al. 2006). It is therefore likely that similar variations for other pollen types, such as grasses (*Poacea*), mugwort (*Artemisia*), alder (*Alnus*) and hasel (*Corylus*), will be observed. The analyses are, however, insufficient for a full understanding and description of the variations in the pollen level on regional and local scales. The analyses should therefore be supplemented with more series of measurements in the urban areas, carried out in dedicated campaigns that will support the further development of the Danish pollen monitoring programme supplemented by calculations with atmospheric transport models and very detailed land use data.

Acknowledgements This study was partly funded by the Copenhagen Global Change Initiative (COGCI) Research School (www.cogci.dk), and the National Board of Health Project: “Country-wide pollen forecasts”.

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