

A satellite-based map of onset of birch (*Betula*) flowering in Norway

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Abstract Birch (*Betula pubescens* L.) is by far the most common deciduous tree in Norway and birch forests define the forest line both northwards and upwards. Because of its mountainous topography, long fjords, and long length from north to south, Norway is climatically and ecologically very diverse. Therefore, developing pollen forecasts in Norway is a challenging task. In this study we use MODIS-NDVI (normalized difference vegetation index) satellite data with 250 m spatial resolution and 16-days time resolution for the period 2000–2007, and birch pollen counts from ten Burkard traps distributed throughout Norway, to characterize the onset of birch flowering in Norway. Four of the seven trap stations with long-term series show significant values at the 5% level or better between the MODIS-NDVI defined onset and the date when the annual accumulated birch pollen sum reaches 2.5% of the annual total. A map of Norway that shows the eight-year mean (2000–2007) onset of birch flowering was produced. It reveals large differences in the timing of the onset of birch flowering along the north–south and altitude

gradients. The map provides useful general information that can be utilized by the Norwegian pollen forecast service. This study shows that remote sensing is a useful tool for not only characterizing the onset of the birch pollen season but also revealing regional differences not easily detected by pollen stations alone.

Keywords *Betula* pollen · Birch pollen · MODIS-NDVI · Norway · Onset of birch flowering · Onset of birch pollen season · Phenology · Satellite data

1 Introduction

Betula spp. is the major pollen-allergen-producing tree in Norway. Birch (*Betula pubescens* L.) is very common throughout Norway and birch forests delineate the forest line both northwards and upwards (Moen 1999; Johansen and Karlsen 2007). In addition, silver birch (*Betula pendula* Roth.) is common in the lowlands of southern Norway, and dwarf birch (*Betula nana* L.) is among the most common shrubs in the low-alpine belt. Birch pollen is by far the most important allergenic airborne pollen in Norway, and approximately 14% of the population is sensitised to its allergens (Haugen 1998).

In terms of vegetation zones, Norway comprises the nemoral zone, characterized by broad-leaved forest in the south to the treeless arctic zone in the north, along a

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distance of about 1,500 km (Moen 1999; Karlsen et al. 2006). In addition, because of the mountainous topography of Norway, an altitudinal replication of this north–south gradient can be found in many locations over much shorter, vertical distances. For instance, in western Norway, with its steep mountains, it is common to find within a few kilometres both the boreonemoral zone characterized by mixed broadleaf and coniferous forests at low altitude, and the partly year-round, snow-covered high-alpine belt (Moen 1999). The onset of flowering of the birch depends strongly on the spring temperature regime (Emberlin et al. 2002; Rasmussen 2002; Van Vliet et al. 2002; Porsbjerg et al. 2003), and the timing of the local pollen dispersal is a result of the local climate, which follows the macro climatic gradients running from north to south and from mountains to lowlands in Norway. Thus, making pollen forecasts for Norway is a challenging task, and, hence, there is a need to better understand the spatial pattern of pollen dispersal of birch.

Male flowering and leaf-bud burst of birch are well correlated. Linkosalo (1999, 2000) found in southern Finland that the difference in time from male flowering to the first date of bud burst is only 1.1 days with male flowering occurring first. This indicates that the phenophase observed as leaf-bud burst could be used to determine the timing of local birch pollen release.

Satellite image-aided analysis of phenology of natural vegetation provides spatially complete coverage that can be used to interpolate traditional ground-based phenological observations. This indicates that the measurements of leaf-bud burst of birch from remote sensing could be used to determine the timing of local birch pollen release. Phenological changes during the growing season can be studied by examining changes in the remote sensing-based normalized difference vegetation index (NDVI) value. The NDVI is defined as: $NDVI = (Ch2 - Ch1) / (Ch2 + Ch1)$, where Ch1 and Ch2 represent reflectance measured in the near infrared and red channels, respectively (Lillesand and Kiefer 1994). NDVI has evolved as the primary tool for monitoring changes in vegetation activity (e.g. Myneni et al. 1997; Walker et al. 2003; Stöckli and Vidale 2004). Karlsen et al. (2006) mapped the onset of the growing season of the whole of Fennoscandia by applying the GIMMS-NDVI satellite dataset based on the AVHRR instrument (Tucker et al.

2005), where the onset was well correlated with the phenophase “onset of leafing of birch”. In a preliminary study, Høgda et al. (2003) also used the GIMMS-NDVI dataset, correlated it with birch pollen measurements from five stations, and found correlation values (r) in the range from 0.55 to 0.85. However, the 8-km pixel size of the GIMMS dataset can only differentiate to a limited extent the phenological contrasts in the heterogeneous mountain landscape of most of Norway. In December 1999, the MODIS sensor onboard the NASA TERRA platform was launched. This sensor has 250 m spatial resolution in the red and near infrared channels, and provides an opportunity to map phenology on a much finer scale than the AVHRR instrument. Beck et al. (2007) used MODIS-NDVI data and mapped the growing season of the whole of Fennoscandia, but only at 5-km resolution and excluding some areas of altitude, because of the calibration procedure used.

Recently, Karlsen et al. (2008) mapped the growing season of northernmost Fennoscandia with MODIS-NDVI data at 250 m resolution. For stations with seven-year time-series data, they found moderately strong positive correlation ($r = 0.44$ – 0.88) between the NDVI data and “onset of leafing of birch”. The main objective of this paper is to apply the method used by Karlsen et al. (2008) to map the onset of flowering of birch for all of Norway. First, we examine how well NDVI data with 250 m resolution from the MODIS sensor correspond to five different methods of defining the onset of the birch pollen season at ten pollen stations distributed throughout Norway. We then map the average and the spatial and temporal variability of the onset of birch flowering of all of Norway for the 2000–2007 period.

2 Material and methods

2.1 Study area

The study area of mainland Norway, $57^{\circ}57' - 71^{\circ}11' N$ and $4^{\circ}29' - 31^{\circ}10' E$ ($323,802 \text{ km}^2$), is climatically and ecologically heterogeneous. The mean July temperature has a range from $9.2^{\circ}C$ in the lowlands at Vardø in the north to $17.1^{\circ}C$ at Fornebu close to Oslo in the south (Aune 1993; Tveito et al. 2000). The range in annual precipitation extends from above 2,500 mm on the west coast to

less than 300 mm in the most continental areas in both the northern and southern parts of Norway (Førland 1993; Tveito et al. 2001). Most of the country has mountainous topography (the Caledonian mountain range) with at least 200 mountain peaks above 2,000 m (Fig. 1b; Helgesen and Helgesen 2006).

Recently, the vegetation of all of Norway was mapped for the first time (Fig. 1a; Johansen and Karlsen 2007), using Landsat TM/ETM+ satellite data with 30 m resolution. A first analysis of the map indicates that approximately 20% of Norway consists of deciduous forest. Most of this deciduous forest is dominated by birch, except some parts in the lowland in the south in the nemoral and boreonemoral zones, where temperate deciduous forest (mainly *Quercus* spp., *Fraxinus excelsior* L., *Ulmus glabra* Huds., or *Tilia cordata* Mill.) can dominate locally (Fremstad 1997). About 21% of Norway is coniferous forest or mixed birch and coniferous forest. In addition, about 25–30% of Norway is low-alpine heath, where dwarf birch is very common. The birch forest line extends to more than 1,150 m in the south (Moen 1999) whereas in the northernmost regions birch is only found in the lowlands in wind-protected valleys (Moen 1999; Karlsen et al. 2005).

2.2 Airborne birch pollen data

The pollen traps (Burkard type) in Norway are run by the Norwegian Federation of Asthma and Allergy (NAAF) in cooperation with the Norwegian University of Science and Technology, Trondheim (Ramfjord and Brobakk 2007). The pollen traps are distributed throughout Norway and are placed partly according to climatic and ecological gradients and partly on the basis of population patterns. Most of the traps are located on open roofs in urban areas (Ramfjord and Brobakk 2007). This study uses counts of airborne birch pollen grain from ten sites in Norway for the 2000–2007 period (Figs. 2, 3).

The onset of the birch pollen season in this study is defined by five different methods: (a) the date (after April 1st) of the first recorded birch pollen, (b–d) the dates when the accumulated pollen sum reaches 1%, 2.5%, and 5% of the annual total, respectively, and (e) the first day of the earliest five-day period with airborne birch pollen ($5 \times d$). The date of the first recorded pollen was included to enable easier identification of possible long-distance-transported (LDT) pollen, and $5 \times d$ was included because it is in common use in Sweden (Dahl 1997).

Fig. 1 **a** Land cover units of Norway, extracted from Johansen and Karlsen (2007). **b** A terrain model of Norway and neighbouring parts of Sweden and Finland

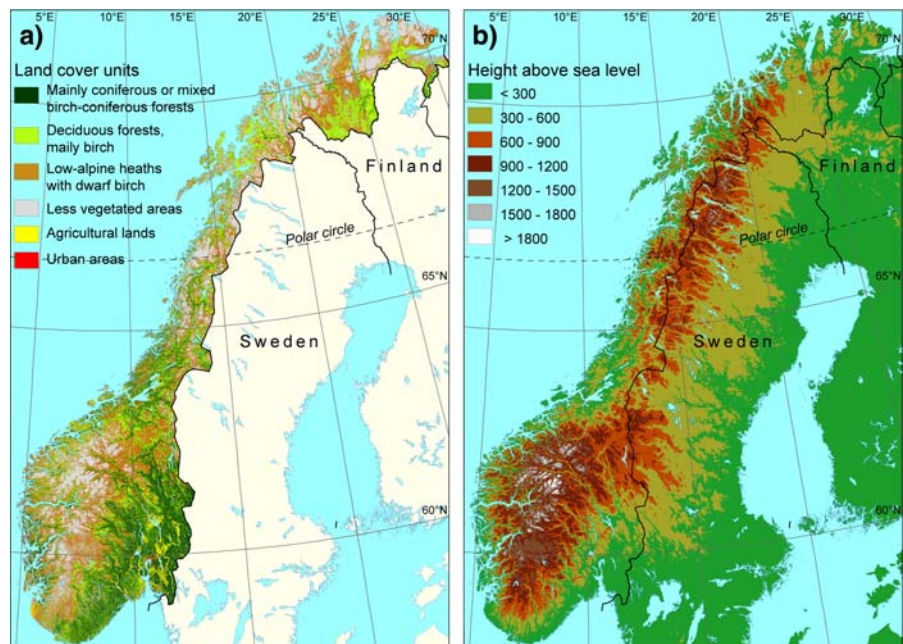
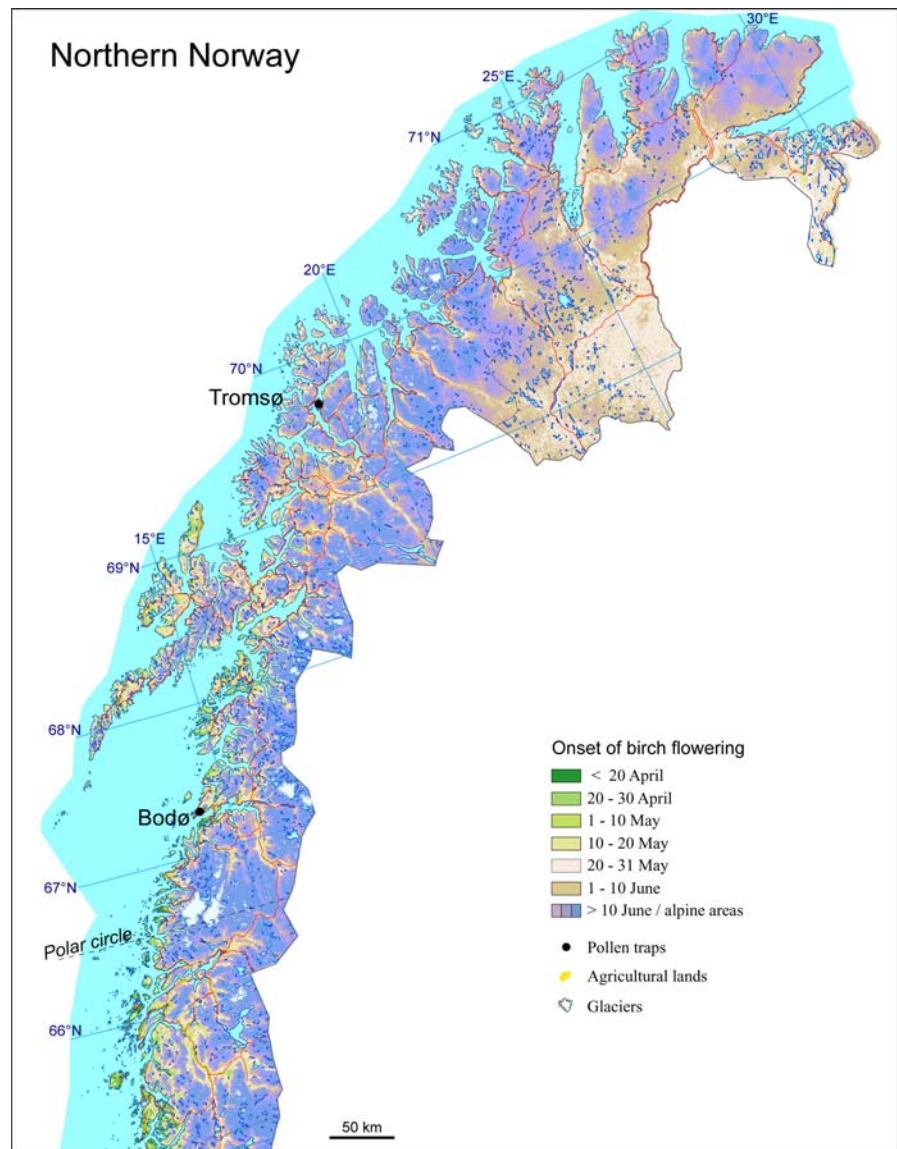


Fig. 2 Onset of birch flowering in northern Norway, based on mean values from the MODIS-NDVI dataset for the period 2000–2007

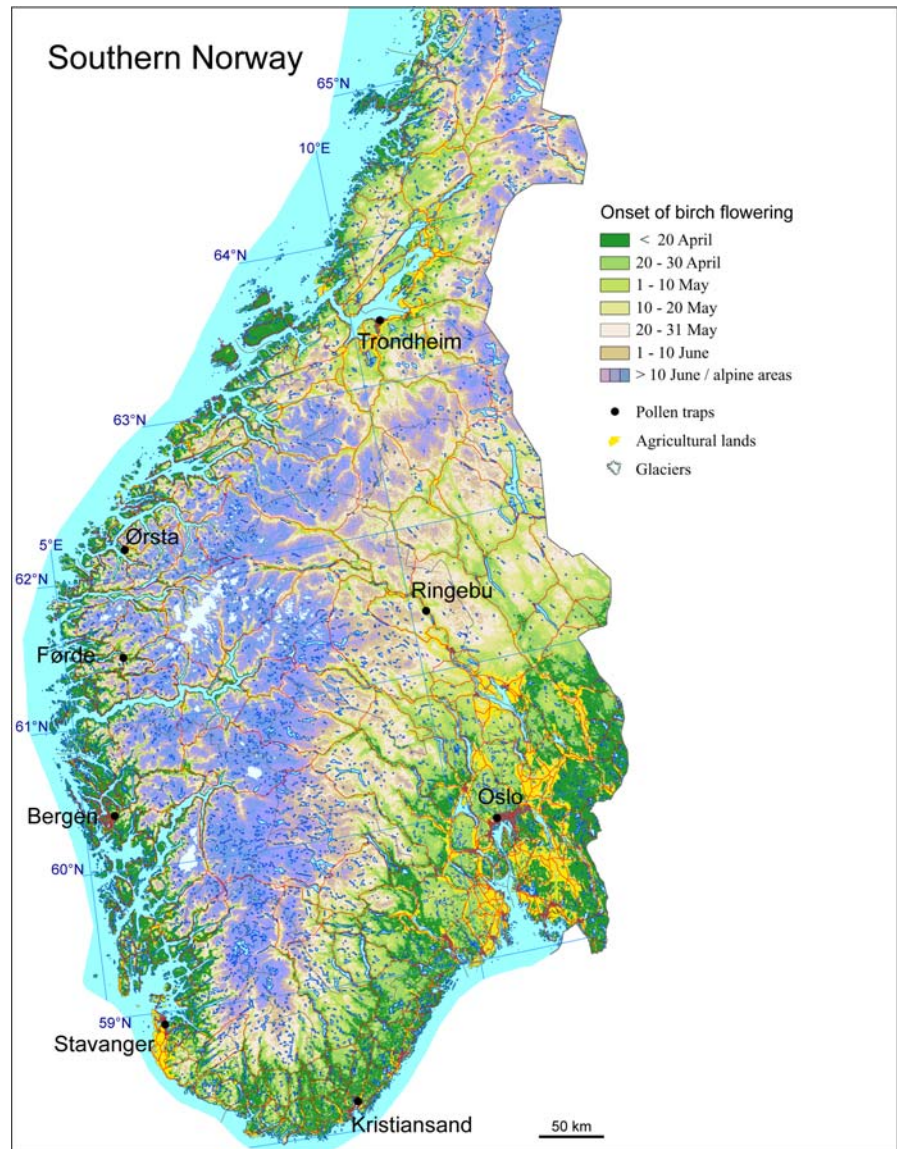


2.3 Satellite data in mapping onset of birch flowering

The MODIS 16-day composite NDVI satellite dataset with 250 m spatial resolution for the 2000–2007 period was used in the study (MOD13Q1 product (Huete et al. 2002) version V004 for the 2000–2006 period, and version V005 for 2007). The data were reprojected from a sinusoidal projection to universal transverse mercator (UTM). The reprojected data, originally in 10° by 10° tiles, were stitched into a seamless product covering all of Norway.

To calibrate the data and to estimate the onset of birch flowering we applied the methods described and discussed by Karlsen et al. (2008). In the following text we give a brief summary of the methods. It should be noted that the method used by Karlsen et al. (2008) for calibrating data works best for smaller regions. To overcome this issue we divided Norway into three parts, completed a visual inspection for noise in the data for each part, and then corrected the data following Karlsen et al. (2008). In the calibration process, relevant environmental geo-data organized in ArcGIS 9.2 were used. The most important

Fig. 3 Onset of birch flowering in southern Norway, based on mean values from the MODIS-NDVI dataset for the period 2000–2007



datasets were a digital terrain model (Fig. 1b) and topographical maps from the Norwegian Mapping Authority, a Landsat TM/ETM+-based vegetation map of Norway (Fig. 1a), and the surface birch pollen data.

Mean NDVI values were calculated for a 3×3 pixel ($750 \text{ m} \times 750 \text{ m}$) area centred on each of the ten pollen trap sites. However, several of the pollen traps are located in urban areas, where NDVI values from gardens, roads, and buildings surrounding the traps give unreliable results. For these traps the centre

position of the 3×3 pixel area was moved to the closest area with natural vegetation containing birch trees, as found on the new vegetation map of Norway (Fig. 1a).

To link surface pollen data with NDVI data in order to measure onset of birch flowering, we first computed for every pixel in the study area the eight-year (2000–2007) mean NDVI value from July 12th until August 28th. The use of NDVI values between only July 12th and August 28th reduces the “noise” from snow-covered ground. The onset of birch

flowering at each pixel was then determined from the time when the NDVI value each year exceeded 0.85 of the July 12th until August 28th eight-year mean NDVI value. This NDVI threshold was reached after several iterations, and is relative to the mean threshold level that gives the highest correlation with the birch pollen data from the pollen traps. In the procedure to map onset of birch flowering, decision rules were included in the calculation procedure based on the geo-data. For instance, a decision rule could be: if a pixel (based on the NDVI threshold) below 200 m altitude did not show onset of birch flowering during the period from mid-May to mid-June, but all of the surrounding pixels below 200 m altitude did, the pixel was assigned the most reasonable 16-day period for growth onset. The method does not work for urban areas and agricultural fields and so these were masked out.

Finally, a map with 250-m spatial resolution that shows the eight-year mean (2000–2007) onset of birch flowering was produced. To examine the spatial and temporal variability of onset we also determined for each of the eight years the deviation from the mean onset for the 2000–2007 period. To improve the cartographic presentation of the deviation maps, a 50×50 median filter was applied.

3 Results

3.1 Timing of the onset of birch flowering

Table 1 shows the relationship between the NDVI-defined onset of birch flowering and the onset of the birch pollen season as measured from pollen traps. In most cases, the correlations between the NDVI-based results and the five different definitions of onset date are moderately high. The highest correlation and significance values are found between the NDVI-based results and the dates for when the accumulated pollen sum reaches 2.5% of the annual total. The average r -value is 0.74, and all stations except Tromsø have r -values above 0.6. Four of the seven stations with seven or eight-year time-series data are significant at the 5% level or better. The correlation between NDVI data and the 1% and 5% level and $5 \times d$ are slightly lower, and the average r -value is 0.70. The largest variation ($r = 0.25$ – 0.74) is found between the NDVI data and the date of first recorded birch pollen, and in this case only one station (Bergen) shows a significant value.

The NDVI-based values fell closest to the date of the 1% level, where the NDVI results have an average day number of 118 (April 28) and the 1%

Table 1 Onset of the birch pollen season as measured from NDVI data and as defined from pollen traps

Station	# Y	NDVI	1st rec.			1%			2.5%			5%			5 × d		
			Day	<i>r</i>	RMS	Day	<i>r</i>	RMS	Day	<i>r</i>	RMS	Day	<i>r</i>	RMS	Day	<i>r</i>	RMS
Tromsø	8	147	0.46	20.8	131	0.47	18.2	136	0.49	18.0	137	0.48	17.4	139	0.77	11.6	145
Bodø	8	129	0.25	12.0	131	0.76*	9.1	135	0.69	11.4	137	0.68	12.0	137	0.67	12.1	137
Trondheim	8	116	0.38	13.3	118	0.41	8.2	118	0.61	8.2	121	0.44	10.2	122	0.63	7.1	119
Ørsta	8	109	0.38	9.7	110	0.63	8.3	115	0.78*	8.7	117	0.76*	9.4	118	0.54	7.8	113
Førde	3	111			114			121			122			122			122
Ringebu	4	119			107			116			122			123			115
Bergen	8	114	0.74*	6.5	111	0.79*	5.1	114	0.81*	4.9	115	0.70	6.4	117	0.63	7.8	116
Stavanger	2	118			105			116			116			119			114
Kristiansand	7	104	0.62	8.9	109	0.96**	12.6	116	0.86**	14.8	118	0.90**	16.5	120	0.83*	12.7	116
Oslo	8	110	0.68	7.9	105	0.91**	5.6	115	0.92**	5.8	115	0.94**	6.0	116	0.82*	4.1	111
Mean		118	0.50	11.3	114	0.70	9.6	120	0.74	10.2	122	0.70	11.1	123	0.70	9.0	121

“# Y” is the number of years with birch pollen counts; “Day”, mean day number; r , correlation coefficient between NDVI data and birch pollen count data for stations with seven or eight years of data; *, significance at the 5% level; **, significance at the 1% level; RMS, root mean square between NDVI data and birch pollen trap data; “1st rec.”, first recorded birch pollen; “1%”, “2.5%”, and “5%”, the date when the accumulated pollen sum reaches these levels of the annual total, respectively; “ $5 \times d$ ”, the first date of the earliest five-day period with airborne birch pollen

level result a day number of 120. The root mean square (RMS) is also the lowest between NDVI and the 1% level, with a mean RMS value of 9.6 days. However, the differences in mean dates among the five different methods of defining the onset on the basis of pollen counts are small. The average date of first pollen recording was four days earlier than the NDVI-based date of onset of birch flowering, and the other methods of defining the onset based on pollen counts were from two to six days later than the NDVI-based date. Eight of the ten stations show an earlier NDVI-based date than the 2.5% level, where Kristiansand had the largest deviation with an NDVI-based date 14 days earlier. Closest in time between pollen counts and NDVI data was Bergen with exactly the same date for the NDVI-based onset of birch flowering and the 1% level, and only a day lag at the 2.5% level compared with the NDVI-based results. Bergen also has the lowest RMS value with 4.9 days between the 2.5% level and NDVI.

3.2 The geographical pattern of onset of birch flowering

The geographical pattern of the NDVI-based map of the onset of birch flowering (Figs. 2, 3) shows a clear pattern of later onset from south to north and from lowlands to mountains. As found by GIS analysis, in 19.9% of Norway onset of birch flowering occurs before the beginning of May. In central and northern Norway this timing category is found only in a narrow coastal strip between the lowland and mountains, whereas in the south it is the most common category at lower altitudes. In 28.3% of Norway the NDVI-defined onset occurs during the month of May. This starting period is the most common at lower altitudes in northern Norway, whereas in southern parts onset of birch flowering usually starts during May between 300 and 700 m altitude, and in some places even at higher altitudes. In 43.8% of Norway the NDVI-based map indicates that onset of flowering of birch occurs after June 1st. This is the case even at sea-level in the northernmost part of Norway, whereas in the south it is common above 700 m altitude. Norway's mountainous topography leads to large local differences and onset of birch flowering follows a clear gradient from lowland to mountains (Figs. 1b, 2, 3). This is particularly the case in western Norway, where the narrow strip of lowland

along the coast, between the mountains and the sea, often shows a mean onset of flowering of birch before April 20th, whereas in the mountain plateaus, a few hundred metres from the early flowering in the coastal strip, the onset could be more than two months later. The remaining 8% of Norway consists of lakes, glaciers, and agricultural and urban areas where the onset was not mapped.

3.3 Annual and spatial variability

Figure 4 shows that the timing of birch flowering displays large regional variation from year-to-year. The year 2000 was generally the most extreme in terms of late NDVI-defined onset of birch flowering: this year 48% of Norway showed a more than one week later onset of birch flowering than the 2000–2007 average. All of northern and most of central Norway were classified as late that year (Fig. 4). The onset in 2005 was late in 45% of Norway, but not in the northwestern and southeastern parts. The years 2002 and 2004 both had early NDVI-defined onset of birch flowering in 47% of Norway, in 2002 in most of northern Norway, and in 2004 in most of southern Norway. Both 2003 and 2007 showed average timing for most of Norway, except in the lowland in southern Norway which had early onset those years.

4 Discussion

4.1 Use of the NDVI-based map of onset of birch flowering

At present, the pollen forecast in Norway (<http://www.pollenvvarslingen.no/>) is split into 12 regions, which mostly follow county borders and partly climatic/ecological borders. The pollen forecast for each region is based on data from the pollen traps and subjective evaluation of weather forecasts and pollen counts from previous years. A Norwegian version of the NDVI-based map of the mean onset of birch flowering presented here can be downloaded from: <http://www.naaf.no/>. Users of the map can then estimate an approximate time for the local birch flowering, and, together with the pollen forecast for the region, estimate the differences within the region.

Another use of the NDVI-based map is adjustment of current divisions of pollen regions in Norway for

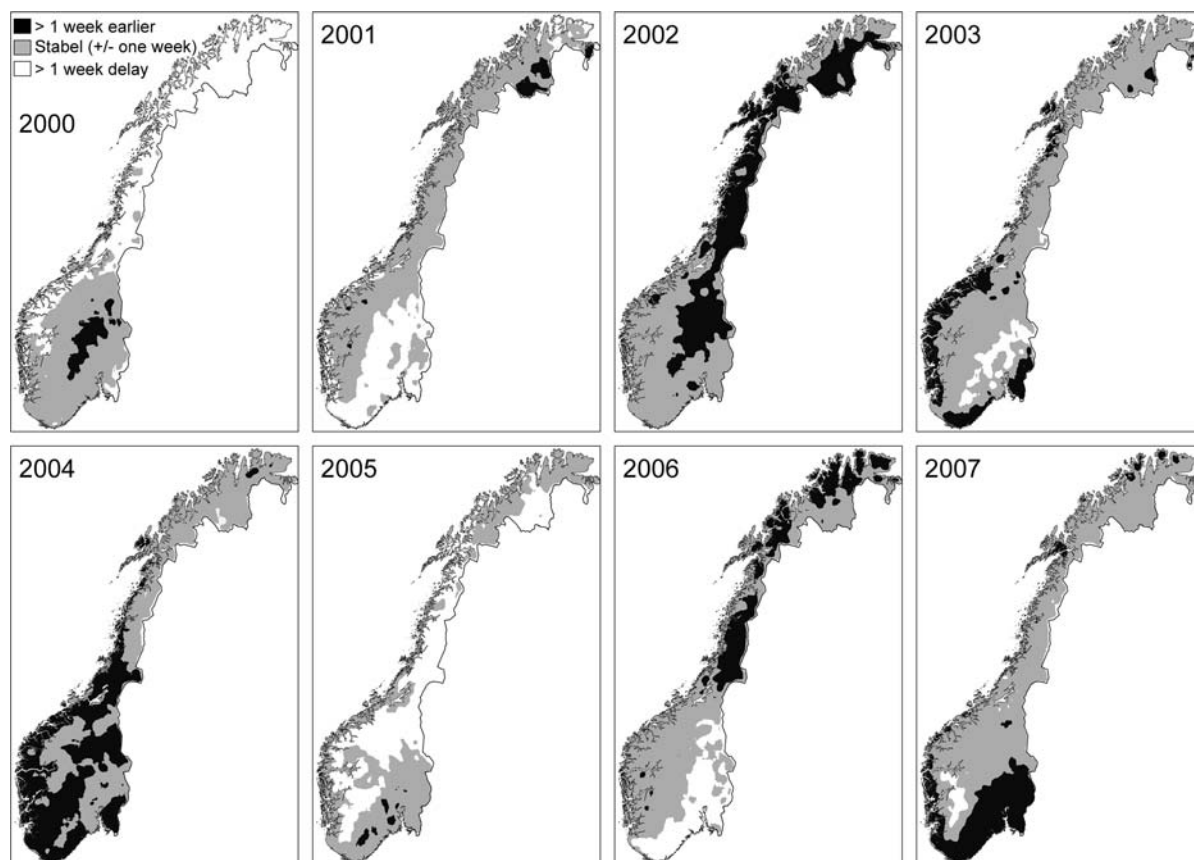


Fig. 4 Regional deviation in onset of birch flowering from the 2000–2007 average

pollen forecasts. This is particularly relevant for western Norway with its large local differences in onset of flowering. The map is also useful as a reference map if new pollen traps must be established; for example, it clearly shows that the present pollen stations along the west coast of Norway are not well representative of the inner fjord zones. The research also showed that averaging results over many years is necessary to develop a reference map of the mean timing of onset of birch flowering, given the large variation in the timing of the flowering from year-to-year (Fig. 4).

When using the NDVI-based map in pollen forecasting it is important to be aware that the map only shows onset of local birch flowering and provides no information about LDT of birch pollen. Long-distance transport of birch pollen may complicate utilisation of the NDVI-based map. In Germany, for example, the onset of birch pollen season as recorded from pollen traps occurred, on average,

5.7 days earlier than birch flowering observed at phenological stations nearby (Estrella et al. 2006). This time span is too large to assume pollen dispersal exclusively from local birch trees. Also in Norway's neighbouring countries, Sweden, Finland, and Denmark, long-distance transport of birch pollen is well known (Oikonen et al. 2005; Ranta et al. 2006; Mahura et al. 2007; Skjøth et al. 2008), in particular during periods with south-southeast winds (Hjelmroos 1991). However, because of the mountainous topography of Norway, it is reasonable to believe that Norway is less affected by LDT pollen compared with the flatter neighboring countries. Table 1 also gives an indication of LDT birch pollen. On average the first recorded pollen occurs seven days before the $5 \times d$ date, indicating that LDT of birch pollen may occur. A closer look at the pollen data counts for the 2000–2007 period shows that only in 2005 and 2007 did some stations have much earlier first recordings than $5 \times d$. In 2005, all stations in southern Norway,

except Førde and Ringeby, had pollen recordings during 3–5 April, which was from 11 to 23 days before pollen became common. In 2007, five of the ten stations had first recordings more than seven days earlier than the second recordings, with the station Tromsø as much as 46 days before. In the other six of the eight years studied there was no clear evidence of LDT of birch pollen leading to an earlier onset date, as seen in data from pollen traps. Based on the moderately high correlations found between the NDVI-based date for onset and the 2.5% level (Table 1), Norway's mountainous topography, and the studies of data from pollen traps, it is reasonable to believe that in most years and in most areas of Norway the onset of the birch pollen season is not significantly affected by LDT pollen.

The NDVI-based map of onset of birch flowering does not give any direct information about the amount of birch pollen. Birches in northern and high-altitude areas produce less pollen, on average, than those in warmer areas. For instance, Oslo in the south has an annual average for the 1984–2007 period of 8,045 birch pollen/cm³ compared with Tromsø in the north with 632 birch pollen/cm³ (Ramfjord and Brobak 2007), even though birch is much more common in Tromsø than in Oslo (Fig. 1a; Johansen and Karlsen 2007). However, it is reasonable to believe that in most cases, areas with early onset of birch flowering also have higher birch pollen production than areas with late onset, because earlier onset is associated with warmer climate and higher pollen production.

4.2 Is the map of the onset of birch flowering reliable?

The geographical pattern of the NDVI-based map showing the onset of birch flowering (Figs. 2, 3) seems reasonable, because it follows a south–north and altitude pattern which corresponds to the general temperature decrease along the same gradients (Tveito et al. 2000). Correlations between the dates when the accumulated birch pollen sum reaches 2.5% of the annual total and the NDVI values interpreted as onset of birch flowering are usually high, and are significant for four of the seven stations with long time series data. It should be noted, however, that all stations in southern Norway are located at lower altitudes and, therefore, not very representative of the

climatic and ecological diversity of southern Norway. However, this study can be seen as an expansion of the study by Karlsen et al. (2008) in which they mapped northernmost Norway (Troms and Finnmark counties) with the same method and satellite data but with a year's fewer data (2000–2006). Because 2007 was an average year in the north (Fig. 4), the results of the two studies are almost identical for the northernmost counties. Karlsen et al. (2008) used phenology data on birch from 13 stations and found, for stations with seven-year time-series data, moderately strong positive correlations ($r = 0.44–0.88$) between the NDVI data and the “onset of leafing of birch”, when the NDVI-defined onset was tuned to occur on average 1.5 days before the observed onset of leafing of birch. The phenophase “onset of leafing of birch” occurs a few days after “bud burst”, and bud burst is well correlated with male flowering (Linkosalo 1999, 2000). Because northernmost Norway has many similarities with altitudinal areas of southern Norway, it is reasonable to believe that the presented NDVI-based onset map also is valid for altitudinal areas of southern Norway. Karlsen et al. (2008) also discussed the reliability of the NDVI-defined onset of the growing-season map compared with the map with other phenological and climatic maps, and usually found good agreement. This indicates that we can usually expect the method to reflect the actual onset of birch flowering.

In addition, the presented NDVI-based map is in agreement with comparable studies. Karlsen et al. (2006, 2007) used the 8-km resolution GIMMS-NDVI dataset for 1982–2002 and mapped the mean onset and the yearly deviation in onset of growing season correlated with the “onset of leafing of birch” for the whole of Fennoscandia. The current MODIS-NDVI-based maps (Figs. 2–4) show general agreement in the pattern of onset but a slightly earlier mean onset compared with the GIMMS-NDVI-based map. However, this is most likely to be a result of the 2000–2007 period with MODIS-NDVI data being warmer than the 1982–2002 period with GIMMS-NDVI data. As the MODIS-NDVI-based map has 32×32 times better resolution than the GIMMS-NDVI-based maps (250 m vs. 8 km), it reveals details not found in the GIMMS-NDVI-based map. This is particularly true for the mountain and fjord areas of western Norway, where the GIMMS-NDVI-based onset of the growing season map has only one

or two classes representing the average pixel response from sea, lowland, and mountains, whereas the MODIS-NDVI-based map has seven classes in these areas. The MODIS-NDVI data therefore seem more suitable than GIMMS-NDVI data in a mountainous landscape, such as most of Norway.

4.3 Future use of satellite data in pollen forecasts

Northern regions, for example Norway, are particularly well suited to remote sensing-based monitoring of the onset of birch flowering because of the abrupt onset of the growing season, which can be easily detected by NDVI data, and the rather small human influence on vegetation. The method applied does not work in agricultural areas, where onset relies on the sowing time, or in urban areas, where the land has been radically transformed. However, this is not of great importance for Norway, because these areas cover only 3.2% and 1.4% of Norway, respectively (Figs. 2, 3; Statistics Norway 2007). In more southern areas, for example the southern part of the nemoral zone and in the Mediterranean region of Europe, with a less clear onset of the growing season and where drought periods during the growing season affect the shape of the NDVI curve, it would be more difficult to apply the method. In addition, birch becomes more rare or even absent in these parts. In areas where LDT of pollen is frequent, for example in most of Finland, the satellite data should serve only as a supplement to atmospheric and biological models in pollen forecasting. However, we believe our method could, in particular, be useful in other more topographically complex areas than Norway, for example the Alps, where atmospheric and biological models are less reliable.

The NDVI-based map showing the onset of birch flowering is intended to be used as one criterion in the development of a new and improved division of Norwegian pollen regions. As far as we are aware, this is the first time remote sensing has been used as input to improve the divisions for pollen forecasting. The next step in applying remote sensing to pollen forecasts is real-time monitoring to extrapolate the point measurements from pollen traps to a spatially wide area. In an operational framework, because of clouds and limited spatial and temporal coverage of available satellite systems, it is not possible to obtain daily data coverage over large areas such as all of Norway. Only a fraction can normally be covered each

day. However, the available satellite data, together with meteorological data, can be assimilated into phenological models, in order to obtain full coverage and estimate deviation in birch flowering compared with a determined normal year. This will help in forecasting pollen emissions over large and ecologically and climatically heterogeneous areas such as Norway. White and Nemani (2006) have described a system for real-time monitoring and short-term forecasting of surface phenology which can be related to pollen production, the next step in our project.

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