

MODIS-NDVI-based mapping of the length of the growing season in northern Fennoscandia

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Abstract

Northern Fennoscandia is an ecologically heterogeneous region in the arctic/alpine-boreal transition area. Phenology data on birch from 13 stations and 16-day MODIS-NDVI composite satellite data with 250 m resolution for the period 2000 to 2006 were used to map the growing season. A new combined pixel-specific NDVI threshold and decision rule-based mapping method was developed to determine the onset and end of the growing season. A moderately high correlation was found between NDVI data and birch phenology data. The earliest onset of the growing season is found in the narrow strip of lowland between the mountains and the sea along the coast of northern Norway. The onset follows a clear gradient from lowland to mountain corresponding to the decreasing temperature gradient. In autumn, the yellowing of the vegetation shows a more heterogeneous pattern. The length of the growing season is between 100 and 130 days in 55% of the study area.

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1. Introduction

Northern Fennoscandia has climatic gradients running from the oceanic coast to the relatively continental interior, and from lowlands to mountains (Moen, 1999; Tuhkanen, 1980; Tveito et al., 2000, 2001). Regional differences in vegetation and length of the growing season are associated with these climatic gradients. Although predictions state that global climate warming will be most severe in northern

latitudes, the strong regionality in climate indicates that changes in temperature may depend on the specific area under investigation. Hence, large-scale monitoring of both climate and vegetation is important in order to improve predictions made for northern Fennoscandia.

Phenology, in its simplest terms, is a study of cyclic events of nature. An immediate and observable effect of global warming is a shift in the seasonal phenological cycle, which is often the first indication of transition in ecosystems. Hence, long-term phenological series are particularly useful in predicting the impacts of climate change on the environment. In northern Fennoscandia, many vascular plants grow at or near their northern

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distribution limits (Hultén, 1971). Accordingly, even small changes in climate may lead to significant impacts in plant growth rhythms.

Carrying out field phenological observations is, however, tedious and expensive, and full coverage of all regions can never be obtained. Satellite image-aided analysis of phenology of natural vegetation provides a spatially complete coverage that can be used to interpolate traditional ground-based phenological observations. 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 near infrared and red channels, respectively (Lillesand and Kiefer, 1994, pp. 506–507).

In most published studies, ground-based phenological observations have been linked to satellite imagery from the low resolution advanced very high resolution radiometer (AVHRR) instrument on board the National Oceanic and Atmospheric Administration (NOAA) series of meteorological satellites (e.g. Schwartz et al., 2002; White et al., 1997). Recently, Karlsen et al. (2006) mapped the phenological cycle of the whole of Fennoscandia by applying the GIMMS-NDVI dataset based on the AVHRR instrument (Tucker et al., 2005). However, the 8-km pixel size of the GIMMS dataset can only differentiate, to a limited degree, the phenological contrasts in the heterogeneous mountain landscape of northern Fennoscandia. In December 1999, the MODIS sensor onboard the NASA TERRA platform was launched. This sensor has a 250 m spatial resolution in the red and near infrared channels, and provides an opportunity to map phenology at a much finer scale than the AVHRR instrument.

The objective of this study was to map the phenological cycle of all of northern Fennoscandia at a 250 m spatial resolution. First, environmental geo-data and phenological field data were organized in a geographical information system (GIS). MODIS-NDVI time-series for the 7-year period 2000–2006 were then processed and compared to phenological ground data, and a new combined NDVI threshold and decision rule-based mapping method was developed to determine the onset and end of the growing season. Finally, this study produced 250 m spatial resolution phenological maps of the onset, end, and length of the growing season in northern Fennoscandia, and describes the contrasts in growing season characteristics along the climatic and ecological gradients in the region.

2. Materials and methods

2.1. Study area

The study area of northern Fennoscandia, approximately between 68–71°N and 17–32°E, includes regions in the north of Norway, Sweden, Finland and northwestern of Russia. It is an ecologically heterogeneous region of about 150 000 km² in the arctic/alpine-boreal transition area (Fig. 1; Moen, 1999). In spring, the daily mean temperature exceeds 5 °C in late May in the lowlands and in late June in the mountains (Fig. 2a). Then, in autumn, the temperature goes below 5 °C early in September in the mountains and in late September in the lowlands (Fig. 2b). The western oceanic coast is characterized by the typically nutrient-rich Caledonian mountain range (Koistinen et al., 2001). These mountains are often steep with their sides facing the Norwegian Sea. The oceanic lowland may constitute only a narrow strip of land between the mountains and the sea, and is characterized by a relative long growing season. In this lowland, crowberry (*Empetrum nigrum*), heather (*Calluna vulgaris*), and dwarf cornel (*Cornus suecica*) heaths are common at exposed sites (Edvardsen et al., 1988; Fremstad, 1997; Karlsen et al., 2005; Oksanen and Virtanen, 1995). Deciduous birch (*Betula pubescens*) forests dominate in more protected parts (e.g. Hämet-Ahti, 1963), while snowbed vegetation characterizes the alpine areas.

In the continental interior of northern Fennoscandia, rocks of Precambrian age, often covered with a thick moraine layer, form a rounded and gentle landscape with nutrient-poor soils. Coniferous forests and oligotrophic mires dominate the eastern lower portion. In the low alpine central parts, the short growing season and nutrient-poor soil allow dominance by dwarf birch-crowberry (*Betula nana-E. nigrum*) heaths and lichen heaths (e.g. Haapasaari, 1988; Johansen and Karlsen, 2005). In the lowland regions of the study area birch is common and dominates large areas.

2.2. Phenological data

Comparable phenophase data on birch (*Betula pubescens* and its subspecies *Betula pubescens* ssp. *tortuosa*) from 13 observation stations across northern Fennoscandia were used (Table 1 and Fig. 1). Finnish data are from the Finnish phenological network launched in 1995 (Poikolainen et al., 1996). At the Finnish stations, at Svanhovd and at Pasvik, phenological observations on birch are obtained from the same four to five individual trees twice a week from April to



Fig. 1. Study area showing the location of sites with phenological observations used in this study.

October each year. At the other stations, observations are more irregular. In this study we used two phenophases; ‘onset of leafing of birch’ and ‘>50% yellowing of leaves’ of birch, for 12 of the 13 observation sites. At Abisko, only budburst data were collected. Budburst is the point in time when leaves have emerged from their buds but have not yet opened (BBCH07 code according to Meier, 1997). Onset of leafing is the point in time when the first leaves unfold and the first leaf stalk is visible. This phase occurs about 1 week after budburst. The phase

‘>50% yellowing of leaves’ is the point in time when more than half of the leaves on each trees have turned yellow (BBCH92). The phenophases are illustrated in Kubin et al. (2007). Birch is the dominant tree species in most parts of the study area and is well suited as a phenological indicator as its deciduous growth form allows for well-defined phenophases, phenomena which are not observed easily in conifers. The chosen birch phenophases represent well the general greening and colouring of the region’s vegetation.

Table 1
Stations with phenological observations were used in this study

Station	Organization responsible for monitoring
Pallasjärvi, Saariselkä, Kilpisjärvi	Finnish Forest Research Institute (Metla), Finland
Muddusjärvi	Finnish Game and Fisheries Institute, Finland
Kevo	University of Turku, Finland
Värriö	University of Helsinki, Finland
Vestre Jakobselv, Korsfjord, Alta	The school network ‘Phenology of the North Calotte’ (http://sustain.no/projects/northcalotte/), Norway
Tromsø	Bioforsk Nord and Northern Research Institute Tromsø, Norway
Svanhovd	Svanhovd Bioforsk Soil and Environment, Norway
Pasvik	Pasvik ‘Zapovednik’ (nature reserve), Russia
Abisko	Abisko Scientific Research Station, Sweden

The geographical locations of the various sites is shown in Fig. 1.

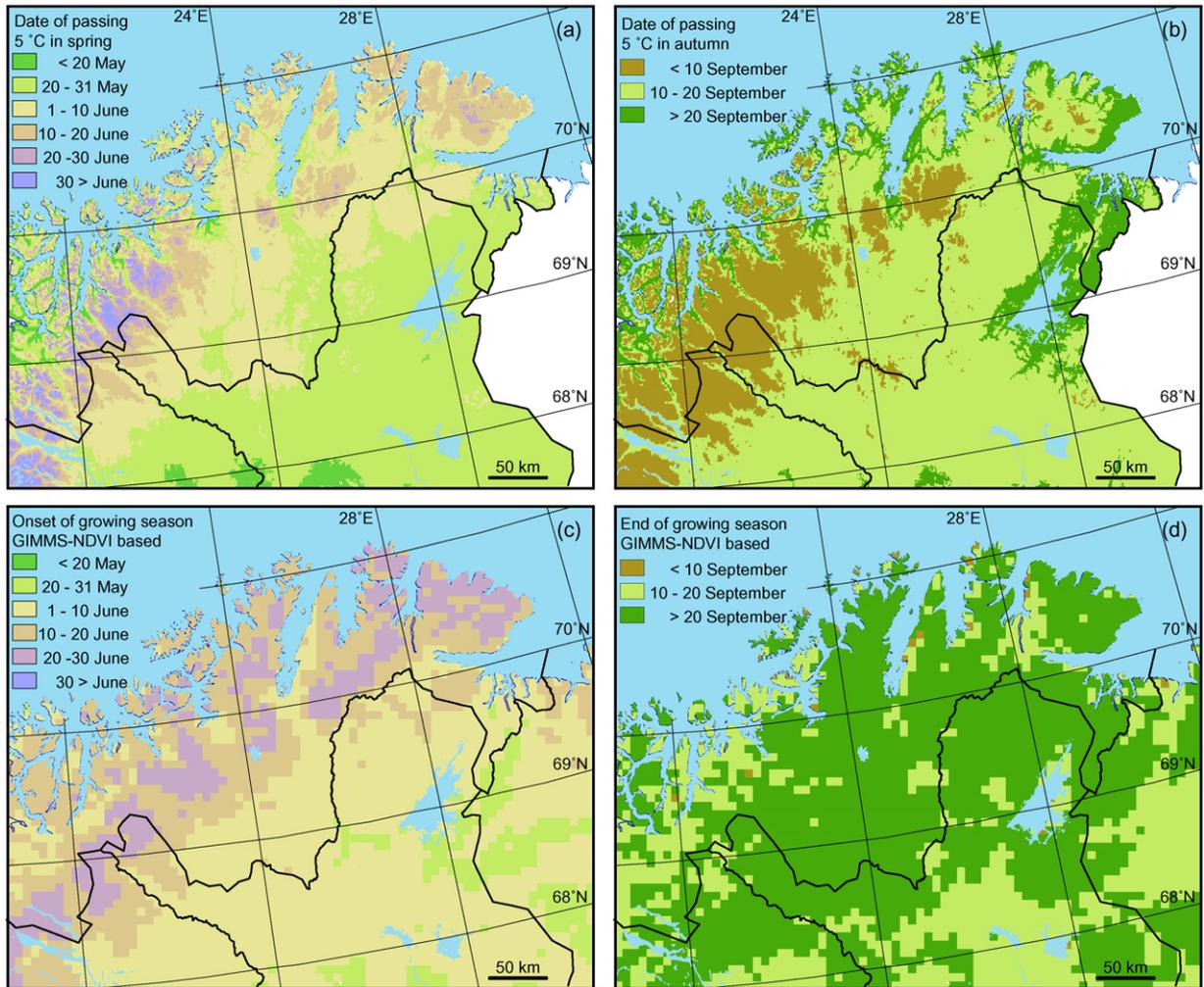


Fig. 2. (a) Date when the daily mean temperature of the 1961–1990 normal period exceeded 5 °C in spring, and (b) went below 5 °C in autumn. The temperature based maps have 1 km resolution and are redrawn and rescaled with permission from Tveito et al. (2001). (c) Time of onset and (d) end of the growing season, based on mean values from the GIMMS-NDVI dataset for the period 1982–2002. The GIMMS-NDVI based maps have 8 km resolution and are extracted, rescaled, and redrawn from Karlsen et al. (2006).

2.3. Processing the MODIS-NDVI dataset

The MODIS 16-day composite NDVI dataset with 250 m spatial resolution for the 2000–2006 period was used in the study (the MOD13Q1 product (Huete et al., 2002)). The data were reprojected from a Sinusoidal projection to a Universal Transverse Mercator (UTM) projection. The reprojected data, originally in $10^\circ \times 10^\circ$ tiles, were stitched into a seamless product covering the entire northern Fennoscandian region.

Some of the 16-day NDVI composites were affected by atmospheric conditions, mainly cloud cover, appearing as a drop in NDVI values at times of the year when a decrease was not expected. These NDVI

values had to be corrected. First, relevant environmental geo-data were organized in ArcGIS 9.2. The most important datasets were Landsat TM/ETM+ based vegetation maps (Johansen et al., 2006; Johansen and Karlsen, 2005), topographical maps, snow-cover maps (Malnes et al., 2007, <http://projects.itek.norut.no/EnviSnow/>; Anttila et al., 2005, <http://www.environment.fi/snowcover>), a digital terrain model from MOD03 data (Guenther et al., 1998), and the surface phenological data (Table 2 and Fig. 1).

In ArcGIS each 16-day NDVI composite in all of the 7 years, from late April to early November, was then evaluated for noise. Each 16-day period was evaluated by comparing the NDVI values with the corresponding

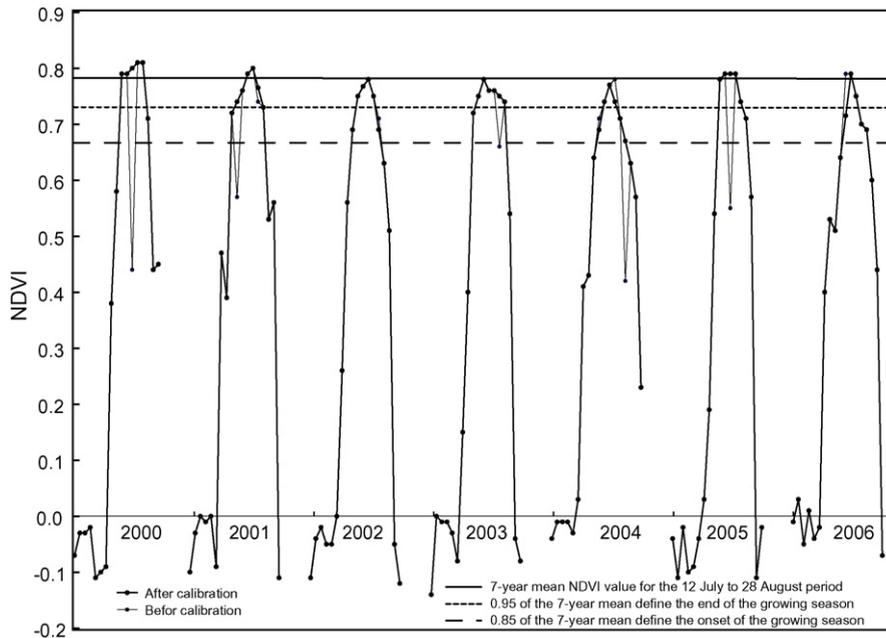


Fig. 3. NDVI values for a random pixel in the study area illustrate the method for the calibration and for measuring the onset and end of the growing season. The original NDVI values are shown with a thin line and the calibrated NDVI values after the evaluation are shown with a thick line. The 7-year mean NDVI value for the 12 July–28 August period is computed (solid line). The onset of the growing season is defined according to the time when the NDVI value each year exceeds 0.85 of this mean value (dashed line), and the end of the growing season when the NDVI value goes below 0.95 of the mean value (dotted line). This procedure was performed for every pixel in the study area.

period from the other years, the 16-day period before and after, and against vegetation maps and a digital terrain model. It was sometimes difficult to distinguish NDVI snow cover values from cloud values. If doubt existed, we compared the NDVI map with snow-cover

maps. In addition, the NDVI curve was plotted for 15 randomly distributed pixels in the study area for each year. This identified periods with dips in the 7-year NDVI curve not related to the start or end of the growing season (Fig. 2). Based on these evaluations, 9 of the 77

Table 2

Onset and end of the growing season as measured from NDVI and as defined from phenology data

Station	Onset of the growing season (onset of leafing of birch)					End of the growing season (>50% yellowing of leaves of birch)				
	# y	Day	<i>r</i>	S.D.	<i>B</i>	# y	Day	<i>r</i>	S.D.	<i>B</i>
Kevo	7	159/152	0.88**	6	7	7	254/264	0.13	10	-10
Muddusjärvi	7	141/144	0.44	10	-3	7	253/274	0.46	12	-21
Saariselkä	7	162/143	0.49	14	19	7	249/270	0.74*	12	-21
Pallasjärvi	7	160/152	0.71	8	8	7	254/269	0.82*	10	-15
Kilpisjärvi	7	167/174	0.76*	10	-7	7	252/254	0.31	6	-2
Värriö	5	134/145	0.28	8	-11	7	253/265	-0.38	12	-12
Pasvik	7	140/143	0.63	10	-3	7	265/260	0.12	6	5
Svanhovd	7	148/147	0.85*	7	1	6	255/259	0.63	5	-4
Vestre Jakobselv	4	150/152	0.33	6	-2	4	262/264	0.45	12	-2
Korsfjord	4	137/150	0.98*	12	-13	4	254/260	-0.34	8	-6
Alta	4	138/136	0.70	7	2	4	251/266	0.97*	11	-15
Tromsø	7	140/154	0.73	14	-14	4	247/253	-0.16	9	-6
Abisko ^a	3	155/157	0.99	7	-2					

'# y' is the number of years with field data, 'Day' is the mean-day number based on field/NDVI data, *r* is the correlation coefficient, * is the significance at the 5% level, ** is the significance at the 1% level, S.D. is the standard deviation between field and NDVI data, '*B*' is the bias, defined as differences in days between date of field observation and NDVI observation.

^a Phenophase 'budburst of birch'.

evaluated composite images were interpreted as having too many unrealistic NDVI values, most likely due to cloud cover. These nine 16-day periods were generally evenly distributed and were replaced with the mean NDVI value from the periods immediately before and after (Fig. 3). However, data for the two continuous 16-day periods from 12 July to 12 August 2002 were missing, and in this case were replaced with the mean values for the periods over the other 6-years. This calibration method removed the noisiest parts of the data and prepared the dataset for the next phase, where decision rules would remove any remaining unreliable pixels in the process of calculating the onset and end of the growing season.

2.4. Mapping the growing season

2.4.1. Determining NDVI-thresholds

The mean NDVI values were calculated for a 3×3 pixel area centred on each of the 13 phenological stations. In most cases, the centre position of the 3×3 pixel area was moved by one or more pixels to avoid land cover heterogeneity, e.g. due to lakes, altitude, or human impact areas, and to include birch forests, as found on the vegetation maps.

To link surface phenology with NDVI data in order to measure the onset and end of the growing season, we computed for every pixel in the study area the 7-year mean NDVI value for the 12 July to 28 August period for the years 2000–2006. The use of only NDVI values between 12 July and 28 August reduces the ‘noise’ from snow-covered ground. The onset of the growing season at each pixel was then defined by the time when the NDVI value each year exceeded 0.85 of the, 12 July to 28 August, 7-year mean NDVI value. The end of the growing season was defined by the time when the NDVI value went below 0.95 of the mean value (Fig. 3). These NDVI thresholds were reached after several iterations, and are relative to the mean threshold levels that give the highest correlation with ‘onset of leafing of birch’ in spring and ‘>50% yellowing of leaves of birch’ in autumn at all 13 phenological data stations.

2.4.2. Inclusion of decision rules

The previous calibration, which replaced the nine noisiest 16-day NDVI composites by the mean value of the composites from the periods immediately before and after, did not remove the noise not found in the visual inspection. Hence, we had to include an additional procedure to remove and replace the remaining unrealistic values (outliers). We did this by including decision rules in the calculation procedure. To

take into account ‘false starts’ and ‘false ends’ of the onset and the end of the growing season, the first/last potential 16-days period was found by studying phenological field data, snow-cover maps, and climatic data in relation to the vegetation maps. For instance, if we found that the onset of the growing season should occur sometime during May in the lowlands of the study area, then we could use a digital terrain model in the decision rule process in the following way:

- If a pixel (based on the NDVI threshold) above 500 m altitude showed onset of the growing season in early April, then the pixel was not labelled as a valid onset of the growing season.
- If a pixel (based on the NDVI threshold) below 200 m altitude did not show onset of the growing season 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 of the growing season onset.

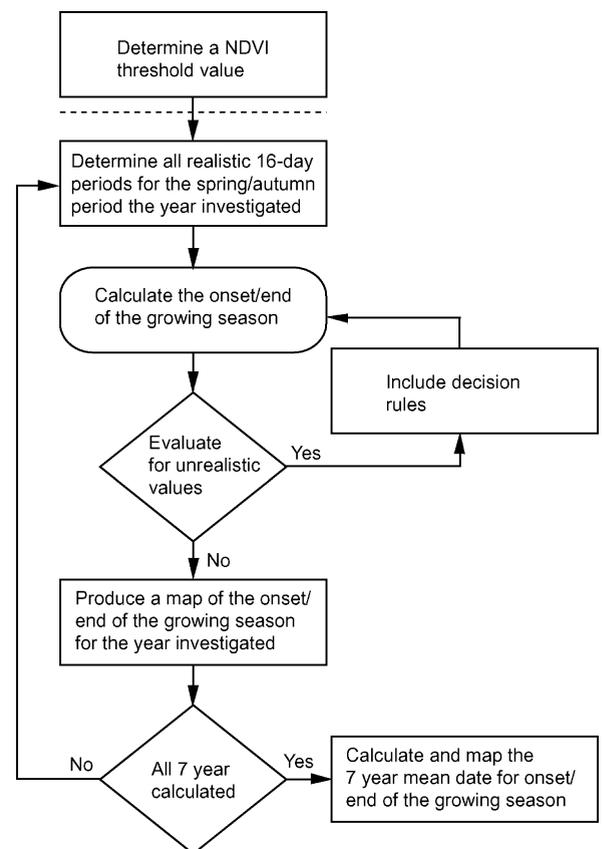


Fig. 4. A flowchart illustrating the process of including decision rules in mapping the onset and end of the growing season (see text for details). This procedure is run for each pixel in the dataset.

The process for including decision rules is shown in Fig. 4 and the stages are summarized as follows:

- (a) Use the NDVI threshold on a pixel-by-pixel basis for the first relevant 16-day period for the onset of the growing season.
- (b) Evaluate in which areas the onset of the growing season occurs, and if some of the pixels are unrealistically labelled or if some of the pixels that are not labelled should be labelled.
- (c) Include decision rules based on geo-data to remove unrealistic pixels or to include realistic pixels.
- (d) Repeat steps (a)–(c) for each relevant 16-day period until each pixel is labelled with a date for the onset of the growing season.
- (e) Repeat steps (a)–(d) for each of the 7 years of MODIS data.
- (f) Repeat steps (a)–(e) for mapping the end of the growing season as well.
- (g) Calculate for each pixel the mean date of onset and end of the growing season for the period 2000–2006, and calculate growing season length by subtracting

the end of the growing season from the onset of the growing season.

Finally, maps that show the 7-year mean (2000–2006) date for onset, end, and the length of the growing season were produced.

3. Results

3.1. Timing of the growing season

Table 2 shows the relationship between NDVI values and phenophases on birch observed in the field. In general, the NDVI-defined onset of growing season data show higher correlation and less bias with birch phenology data, compared with data from the autumn period. During spring, all stations with 7-year time-series data show a moderately strong positive correlation between the NDVI data and ‘onset of leafing of birch’ ($r = 0.44\text{--}0.88$). Four of the stations are significant at the $<5\%$ level, and the standard deviation (S.D.) for all stations between NDVI data and field data is in the range of 6–14 days. The bias between the

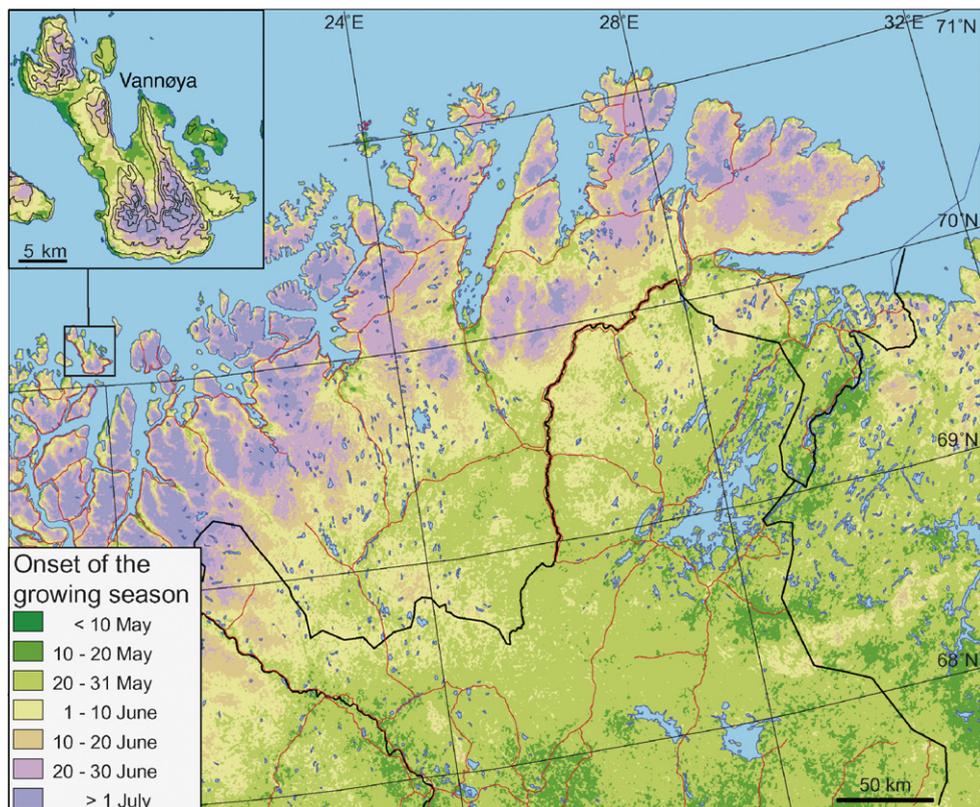


Fig. 5. Time of onset of the growing season, based on mean values from the MODIS-NDVI dataset for the period 2000–2006. Inset: Vannøya (200 m contour interval).

NDVI-defined onset and the observed onset of the growing season is 1 week or less for 7 of the 13 stations, and 8 of the stations show later and 5 earlier NDVI-defined onset than the observed onset of the growing season.

In autumn, the correlation between the NDVI-defined end of the growing season and ‘>50% yellowing of leaves of birch’ is better than 0.45 for 6 of the 12 stations with data, and 3 of the stations are significant at the <5% level. The S.D. is 12 days or less for all stations, and the end of the growing season in the NDVI-based measurement occurs later than the observed date for all stations, except Pasvik.

3.2. The growing season geographical pattern

In 74% of the study area, the onset of the growing season occurs during the 1-month period from 20 May to 20 June (Fig. 5). In northern Finland, the onset usually starts between 20 and 30 May, and in some places even earlier (10–20 May). Northern Norway, with its mountainous topography, shows large local differences. The earliest onset of the growing season

in the study area (<10 May) is found in the narrow strip of lowland along the coast, between the mountains and the sea (Fig. 5). However, this category covers less than 0.5% of the 150 000 km² study area. The onset of the growing season follows a clear gradient from lowlands to mountain areas (Fig. 5). In the mountain plateaus, a few hundred meters from the early greening coast, the onset could be later up to 2 months (‘>1 July’ vs. ‘<10 May’). GIS analysis from the oceanic Vannøya island area (inset in Fig. 5) indicates that the onset of the growing season occurs roughly 6 days later for every 100 m of elevation. The latest onset category, ‘>1 July’, covers 7% of the entire study area and is only found at high altitudes, mainly in Norway.

In autumn, the yellowing of the vegetation occurs during the 10–20 September period in 46% of the study area (Fig. 6), indicating that growing season end processes occur over less than half of the time of the greening processes in spring in much of the study area. In most of northern Finland and northeasternmost Norway, the end of the growing season occurs after 20 September. Unlike in spring, the spatial pattern in autumn is particularly heterogeneous and

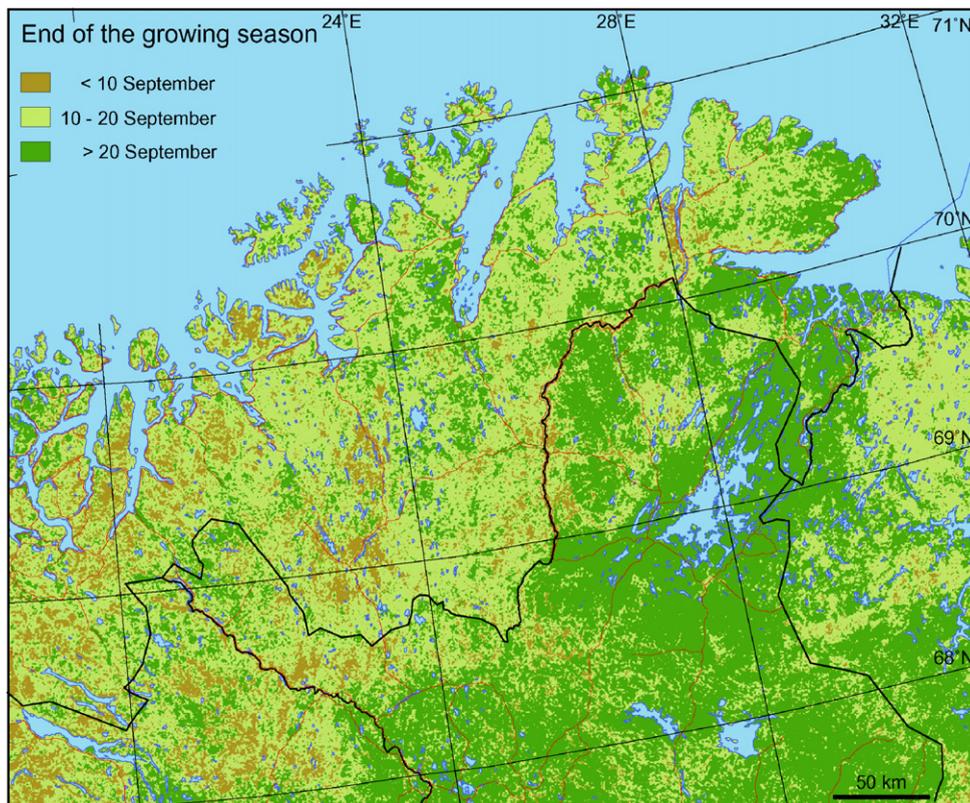


Fig. 6. Time of end of the growing season, based on mean values from the MODIS-NDVI dataset for the period 2000–2006.

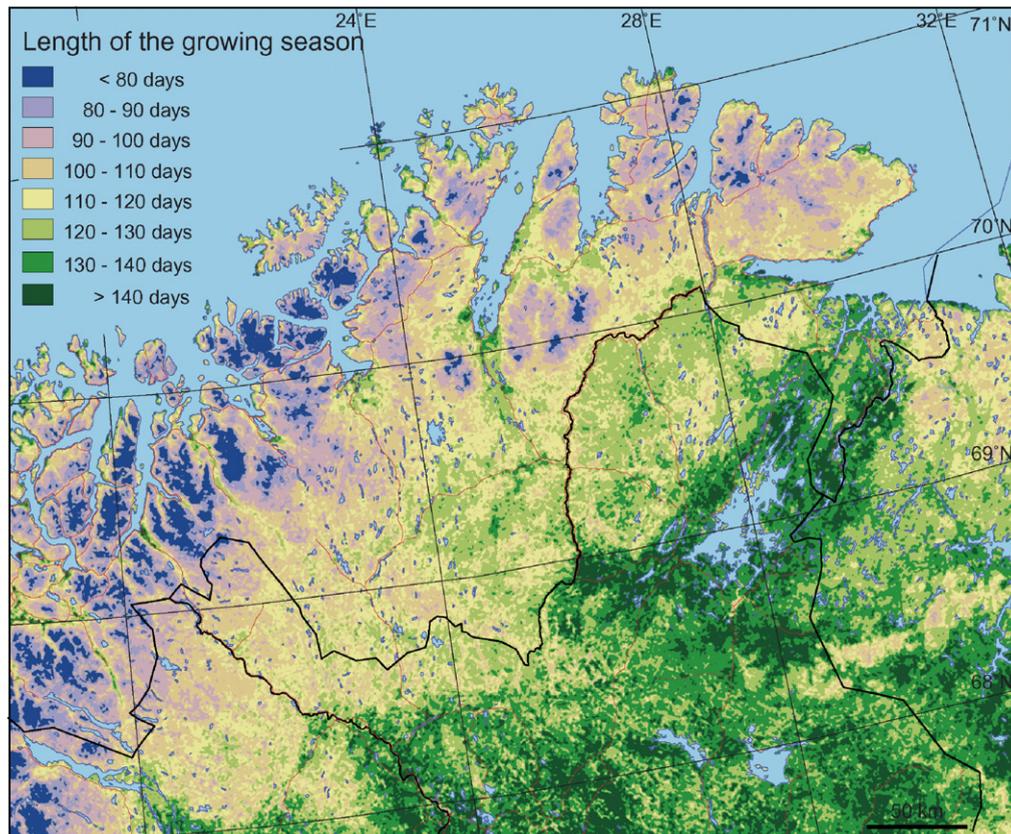


Fig. 7. Length of the growing season, based on mean values from the MODIS-NDVI dataset for the period 2000–2006.

shows only a weak lowland to mountain gradient. Some parts of the narrow strip of lowland between the mountains and sea show a late end of the growing season date but this pattern is much less clear compared with the onset of the growing season pattern.

The length of the growing season is between 100 and 130 days in 55% of the study area (Fig. 7). The 10% of the area that has a growing season longer than 140 days is distributed among spots in northern Finland and the narrow coastal strip of lowland between the mountains and sea in Norway. Coincident with the onset of the growing season pattern, the length of the growing season pattern also generally follows a lowland to mountain gradient, but shows some large local differences due to the heterogeneous end of the growing season pattern. The 26% of the study area that shows a growing season between 80 and 100 days is found mainly above the forest line (Figs. 1 and 7). The remaining 9% of the area, with a growing season of less than 80 days, is found at altitudes above 500 m a.s.l.

4. Discussion and conclusions

4.1. Explaining the geographical pattern of growing season

4.1.1. Onset of the growing season

Several studies show that the onset of plant growth in spring in high latitude regions depends strongly on the spring temperature regime (e.g. Chmielewski and Rötzer, 2001; Karlsen et al., 2007; Karlsson et al., 2003; Shutova et al., 2006; Wielgolaski, 1999). The present NDVI-based map (Fig. 5) follows a clear lowland to mountain pattern, which is related to the altitudinal temperature differences. At the Norwegian coast, the onset of the growing season occurred about 6 days later per 100 m increase of elevation. If we assume that the mean air temperature in spring (May–June) drops by $0.585\text{ }^{\circ}\text{C}/100\text{ m}$ elevation under normal atmospheric pressure (Tveito et al., 2000), then a $1\text{ }^{\circ}\text{C}$ decrease in temperature in the oceanic Vannøya area corresponds roughly to a 10-day delay in the onset of the growing season. In continental parts of the study

area, Karlsson et al. (2003) and Shutova et al. (2006) related spring temperature to budburst of birch and found a 3–8 day difference per 1 °C. Similarly, bud burst data from different tree species in Finnish Lapland indicated nearly a 5 day difference per 1 °C increase in May temperature (Pudas et al., 2008, in press). Karlsen et al. (2007) related spring temperature data with GIMMS-NDVI data and found less than 5 days difference per 1 °C in the continental parts, but 7–9 days for the oceanic parts of Fennoscandia. Since Vannøya is in the markedly to slightly oceanic section (Moen, 1999), the present result is of the same order compared with the results found by Karlsen et al. (2007).

Thematic maps of the Nordic countries showing the onset and end of the growing season for the 1961–1990 normal period were presented by Tveito et al. (2001) (see Fig. 2a and b). These maps were derived entirely climatologically, and used the day when the daily normal temperature exceeded or went below 5 °C to define the onset and end of the growing season, respectively. We analyzed the climatic map for onset (Fig. 2a) in ArcGIS and compared it with the present NDVI-based map (Fig. 5). The NDVI-based map has higher spatial resolution compared with the climatic map (250 m vs. 1 km, respectively) but the maps have many similarities in their geographical patterns. The present NDVI-based map shows a slightly earlier onset in the earliest greening parts of the study area. However, the two maps display almost the same areas with the onset of the growing season during the period from 20 May to 10 June (Figs. 2a and 5). After about 10 June, the climatic maps by Tveito et al. (2001) have larger areas representing the classes ‘20–30 June’ and ‘>1 July’ for the growing season onset compared with the NDVI-based map. This suggests that a 5 °C passing temperature to indicate the onset of the growing season is useful in most of the study areas (northern boreal and low alpine vegetation zones), but the passing temperature value should be increased in the earliest greening parts, and decreased in the mountain areas.

4.1.2. End of the growing season

Compared with the onset of the growing season, the end of the growing season (Fig. 6) pattern follows the altitudinal gradient to a lesser degree, is more heterogeneous, and occurs over a much shorter time span throughout the study area. The main difference between the climatic map (Fig. 2b) and the NDVI-based map (Fig. 6) is that the NDVI-based map is more heterogeneous, although the main pattern of autumn development roughly follows a decrease in mean

temperature. That senescence is linked to mean temperature decrease has been found in experimental studies in northern areas. For example, in the international tundra experiment (ITEX), the temperature of intact ecosystems in the field has been manipulated at 13 circumpolar and alpine sites by using transparent open top chambers over several years. Plants within these 1–3 °C warmer chambers showed a slight trend of later senescence than plants outside the chambers, however, the trend was significant only at one alpine site (Arft et al., 1999). However, a decrease in mean temperature does not explain the heterogeneous pattern that occurs at a finer resolution. One reason for the heterogeneous pattern of autumn phenophases may be cool airflow, which may act locally in valley bottoms (Barry, 1992). Local freezing or a cool period initiates yellowing of leaves in birch (Shutova et al., 2006). Drought may also act locally and initiate drought stress, which leads to the yellowing of plants (Vollenweider and Günthardt-Goerg, 2005). Hence, the late end of growing season in the oceanic narrow strip along the coast could be a result of being less exposed to both drought and cold nights in late summer.

The heterogeneous pattern could also be a result of the fact that different plant species simply change colour at different times due to different response to light. Photoperiodic factors and the spectral composition of light, such as the red:far red ratio are reported to strongly regulate autumn phenophases (e.g. Chmielewski and Rötzer, 2001; Koski, 1990; Menzel, 2002). Birch, the dominant deciduous tree, is characterized by early autumn colouring compared to many other trees/bush species. Willow (*Salix* spp.), rowan (*Sorbus aucuparia*), aspen (*Populus tremula*), and grey alder (*Alnus incana*) are all common in the study area (Hultén, 1971) and can dominate locally. These species normally change colour later than birch (authors' unpubl. obs.). In populated areas, the presence of agricultural fields could explain some of the heterogeneous pattern. The most common cultivated grass, timothy (*Phleum pratense*), remains green until early winter, while other agricultural fields may be plowed in some years as early as late August.

Additionally, climate influences a variety of ecological processes, which can indirectly influence the timing of autumn phenophases. Birch-dominated forests in northern Fennoscandia are influenced by cyclic caterpillar outbreaks. The most common species are the autumnal moth (*Epirrita autumnata*) and various *Operophtera* species (Neuvonen et al., 1999). Local early autumn yellowing of birch could be an attempt to limit outbreak damage (Hagen et al., 2003; Hamilton

and Brown, 2001). On the contrary, population outbreaks of these caterpillar species can result in very late yellowing. Outbreak and defoliation occurred during the period 2002–2006 throughout the study area, which led to leafless trees during late June and early July (Hagen et al., 2007; authors' unpubl. obs.). In some cases, new budburst and leafing occurred in late July. Birch trees stayed green until late September, weeks later than during a normal year (authors' unpubl. obs.). Finally, disease caused by rust attacks from *Melampsorium betulinum* on birch may explain some mapped local early end of the growing season in our study. During 2000–2006, rust attacks were observed at several locations (authors' unpubl. obs.). The rust covers birch leaves and colours them brownish-yellow before the normal autumn yellowing occurs. This could have been interpreted as the end of growing season in the NDVI-based method.

4.2. Method for mapping the growing season

4.2.1. Calibration

To calibrate the MODIS-NDVI 16-day dataset, we first tried to correct the NDVI values by using the MODIS quality assurance (QA) data, which include cloud condition information. However, we evaluated and determined the QA information to be unreliable at a regional scale in northern Fennoscandia. Even pixels with QA information of good, high, or perfect quality did not always detect clouds, particularly in alpine areas.

There exist several techniques for modelling time-series of NDVI data (Jönsson and Eklundh, 2002; Los et al., 1994; Running and Nemani, 1988; Stöckli and Vidale, 2004; Zhang et al., 2003). High latitude areas such as northern Fennoscandia are characterized by short growing seasons and abrupt increases and decreases in NDVI values in spring and autumn (Fig. 3). Beck et al. (2006) used a new double logistic-function-based method and showed it to be more suitable for modelling the yearly NDVI time-series of alpine and boreal zones than previous approaches based on Fourier series or asymmetric Gaussian functions. This new method for modelling missing MODIS-NDVI data in northern areas with short growing seems promising but does not work in areas with particularly short growing seasons, if too many data-points are missing. Beck et al. (2007) used a 5 km averaging window to overcome this problem, but still some alpine parts were not mapped.

To maintain the 250 m spatial resolution, we chose a rather more manual method for modelling the missing

data-points. For calibration of the MODIS-NDVI 16-day composites, we replaced any 16-day periods containing unrealistic NDVI values with the mean values from the periods immediately before and after. During spring we had to manually evaluate about five MODIS-NDVI 16-day periods each year, and in autumn three to four periods each year for the period 2000–2006. This approach is likely much less time-consuming than developing a new calibration method. The main effort required is in gathering appropriate ancillary data in ArcGIS for evaluation of the 16-day periods. We believe that this method is reliable when sufficient ancillary data are available, the interpreter has ecological knowledge of the region, and the area to be evaluated is not too large. When mapping larger areas, however, the disadvantage is that 16-day composites with only a minor flaw (e.g. a small cloud patch) but otherwise good data will not be used, whereas they could be used if only small area was considered.

4.2.2. Threshold

To define the onset and end of the growing season, we applied a threshold method, which has similarities with the method used by Karlsen et al. (2006). However, Karlsen et al. (2006) used the GIMMS-NDVI dataset with a calibration method in which the NDVI values rarely go below 0.1 in Fennoscandia, even during winter with snow cover. Consequently they could then use the threshold from a yearly mean NDVI value in their calculations. In this study, we used a threshold from a mean period not influenced by snow cover (12 July to 28 August). Other methods, to define the onset and end of the growing season, such as using the steepest increase in NDVI value (White et al., 1997) or the seasonal midpoints in the NDVI curve (Schwartz et al., 2002), have been shown not to work in our study area (Karlsen et al., 2006) due to the ecological conditions of a short growing season and snow cover most of the year. In this study, we do not have any phenological field observations in the most extreme areas, the oceanic lowlands and alpine regions. It might be that the threshold method applied shows too early or late onset/end in these parts. In future studies it is therefore important to collect phenological field data along ecological and climatic gradients to test the threshold method along such gradients.

4.2.3. Decision rules

Since the calibration method of replacing the noisiest 16-day NDVI composites by the mean value of the composites before and after did not remove all of the noise in the data, we had to include a procedure to

remove and replace the remaining outliers. We did this by including decision rules in the calculation procedure, a well-known method in vegetation mapping (e.g. Li and Chen, 2005). In most remote sensing-based vegetation-mapping projects today, improvement of the product by applying decision rules from geo-data is common, and there are no principal differences in applying such rules to phenological mapping. In both cases, end products rely on the interpreter's judgment, ecological knowledge, and the quality of the environmental geo-data used. In Burkina Faso, Groten and Ocatre (2002) successfully included decision rules in NDVI-based mapping of the growing season, however, with quite a different approach due to differences in satellite datasets, ecological conditions, and available geo-data.

By applying decision rules, we improved the classification accuracy of mapping the onset and end of the growing season. In spring, most unrealistic pixels were found in mixed pixel areas between water and land, and on high mountains. The high mountain pixels were forced into one class, '>1 July'. There were few other cases where we found unrealistic pixels covering larger land surfaces. In autumn, however, there were many outliers forced into the '<10 September' or '>20 September' classes, not only in land–water mixed pixels and high mountain areas, but also generally throughout the study area. This indicates that closer study of vegetation development of plant cover in autumn is needed to explain the measured NDVI-values.

4.2.4. Evaluation

During spring, correlations between phenological data on birch and NDVI values interpreted as the onset of the growing season are in most cases high, and significant for 4 of 13 stations. The geographical pattern of the onset of the growing season also seems reasonable.

There is a general agreement in the overall pattern between the GIMMS-NDVI based map for the period 1982–2002 (Karlsen et al., 2006; Fig. 2c) and the present MODIS-NDVI-based map (Fig. 5). The MODIS-NDVI-based map shows slightly earlier onset generally, but this is most likely a result of the period 2000–2006 with MODIS-NDVI data being warmer than the period 1982–2002 with GIMMS-NDVI data. As the MODIS-NDVI-based map has 32×32 times better resolution (250 m vs. 8 km), it reveals details not found in the GIMMS-NDVI based map. This is particularly true for the mountain and fiord areas of 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, while the MODIS-NDVI-based map has six classes in these areas (see Vannøya inset in Fig. 5). Mean onset of flowering date for birch for the 1961–1990 period in northern Finland was mapped by Heikinheimo and Lappalainen (1997) and indicate overlap with the present result.

Concerning mapping the end of the growing season, correlations are low for 6 of the 12 stations (Table 2), and there are few relevant studies to compare with. When compared with the GIMMS-NDVI based map (Karlsen et al., 2006; Fig. 2d), the present end of the growing season map (Fig. 6) shows a slightly earlier end of the growing season due to the chosen threshold levels, and the present map has a more heterogeneous pattern due to the higher pixel resolution.

4.3. Future application of the method and growing season maps

The present phenological maps show the mean timing of phenological events for the 2000–2006 period. These maps could be used as reference maps in modelling future normal years, general trends, and multiyear cycles in phenophases due to climatic change. However, this requires taking into account the fact that the 2000–2006 period was warmer than the 1961–1990 normal period. The meteorological station in Kautokeino (St. 93700), located in the central part of the study area, had a mean May temperature of 4.2 °C for the 2000–2006 period compared with 2.8 °C for the 1961–1990 period, and in August the figures were, 11.5 °C and 10.2 °C, respectively.

Sustainable forestry and agriculture are of significant importance in the study region, and changes in growing season length will affect these primary sectors. The northern Fennoscandia region is also the central area for the indigenous Saami people's reindeer herds. The Saami people with their reindeer herds utilize the phenological cycle when they move their herds according to the changing seasons. Reindeer herds in Troms and Finnmark counties in northern Norway migrate large distances at the onset and end of the growing season. In winter, reindeer graze the lichen heaths in the interior and in spring they move to the coast and take advantage of the early greenup there, grazing on herbs and grasses (Johansen and Karlsen, 2005). Shifts in the phenological cycle would affect this finely tuned reindeer grazing system. The phenology maps developed in this study will be used in analyzing the reindeer grazing system in future studies. In addition, these maps will be applied in modelling the

future onset of the growing season under different climate change scenarios and the consequence for the reindeer grazing system.

This new approach in phenological mapping, by combining remote sensing, ancillary geo-data and decision rules, is flexible, and can be applied under many ecological conditions. However, the quality of the end products highly depends on the environmental geo-data available and the ecological knowledge of the interpreters producing the maps. Therefore, applying this method on a continental scale would be time-consuming and less practical. In addition, large areas might have too many 16-day periods removed due to noise. For large regional or continental scales, we would recommend more automatic methods of data calibration, as the present method would likely be most suitable in terms of time and accuracy to areas not larger than northern Fennoscandia.

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