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Growing-season trends in Fennoscandia 1982–2006, determined from satellite and phenology data

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ABSTRACT: The study area of Fennoscandia is a heterogeneous climatic region. To map the linear trends in onset, end, and length of the growing season in Fennoscandia, the bimonthly Global Inventory Modeling and Mapping Studies (GIMMS) normalized difference vegetation index (NDVI) satellite data set was used. The data set has an 8×8 km^2 spatial resolution and covers the period from 1982 to 2006. The mapping was done by applying pixel-specific threshold values to the NDVI data. These threshold values were determined from surface phenology data on birch *Betula pubescens* from 28 stations across the study area. During spring, most stations showed a moderately strong positive correlation between field and NDVI data. However, mapping of the end of the growing season showed less correlation with field phenology data and presented some uncertainty. On average, there was a linear trend for all of Fennoscandia of a 0.27 d yr^{-1} earlier onset of the growing season, a 0.37 d yr^{-1} later end of the growing season, and a 0.64 d yr^{-1} longer growing season. Within Fennoscandia, the trends showed similarities with vegetation zones and sections, which reflect the climatic gradients from north to south and from west to east in the study area. The southern and oceanic regions showed a trend of about a 1 d yr^{-1} longer growing season, in contrast to the alpine and northern continental regions which showed either no trend or a slightly shorter growing season.

KEY WORDS: Fennoscandia · GIMMS · Growing season · NDVI · Phenology · Linear trends · Vegetation regions

1. INTRODUCTION

In most of the northern hemisphere, advancements of phenological events in spring, and to a lesser degree in autumn, have been recorded in recent decades (e.g. Menzel & Fabian 1999, Parmesan & Yohe 2003, Schaber & Badeck 2005, Menzel et al. 2006, Parmesan 2007). However, in some regions, for example in Eastern Europe and the Balkans, there are indications of a delayed trend in spring phenophases (Menzel & Fabian 1999, Menzel 2000, Ahas et al. 2002). In Switzerland, even more regional differences have been found, with a stronger trend of earlier onset of spring in the northern lowland parts compared with a weak trend at high altitude and in southern regions (Studer et al. 2005, 2007). Fennoscandia (defined here as Norway, Sweden, Finland, and the Kola Peninsula and Karelia of northwestern Russia) is characterized by strong climate gradients running from north to south, from west to east, and from the lowlands to the mountains. In the northern continental parts of Fennoscandia, a slight shortening of growing-season length has been reported for the 1930–1998 period (Kozlov & Berlina 2002). However, Pudas et al. (2008a,b) report that this shortening trend seems to have ended, with an earlier onset of spring and no changes in the timing of autumn

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phenophases for northern Finland for the 1997–2006 period. In central, southern, and western oceanic parts of Fennoscandia, there are indications of a different pattern, with only weak trends in change of onset and end of the growing season on a century time scale, but with significant earlier onset of spring phenophases during the last 2 decades (Emberlin et al. 2002, Nordli et al. 2008, Pudas et al. 2008b). However, neither the spatial nor the temporal pattern of the changes in the growing season within Fennoscandia is obvious.

The main problem with applying phenological field data to study changes in timing of the growing season within Fennoscandia is that phenological field data are sparse, compared with the climatic and ecological differences in the region. Finland has a rather well-developed network of phenological stations (Pudas et al. 2008b), whereas Norway has only a few stations. In Sweden, there are very few long-term series of continuous phenological data. The existing long-term phenological series may be useful for local studies of climatic and environmental effects through time, but carrying out field phenological observations is tedious and expensive, and full coverage of all regions can never be obtained. As a result, to document the effects of the current climatic trends on the growing season, there is a need for objective methods applicable on a regional level.

Satellite image-aided analysis of phenology of natural vegetation provides spatially complete coverage that can be used in addition to 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 = (NIR – RED)/(NIR + RED), where RED and NIR are the spectral reflectance measurements acquired in the red and near-infrared regions, respectively (Lillesand & Kiefer 1994). The NDVI is correlated with the fraction of photosynthetically active radiation absorbed by plants, and thus to photosynthetic activity. 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 onboard the NOAA series of meteorological satellites (e.g. White et al. 1997, Schwartz et al. 2002). Karlsen et al. (2006, 2007a) mapped the mean onset and end of the growing season and the variability in the onset of the whole of Fennoscandia by applying the Global Inventory Modeling and Mapping Studies (GIMMS) NDVI data set based on AVHRR data (Tucker et al. 2005). Høgda et al. (2007) used an early version of the GIMMS-NDVI data set, and mapped the trends in the growing season for the 1982–1999 period; however, their study included data from only 4 stations with birch phenology data and 5 stations with birch pollen data.

The aim of the present study was to use the GIMMS-NDVI data set for the 1982–2006 period to map the linear trends in onset, end, and length of the growing season, and to analyze the spatial pattern according to vegetation zones, sections, and regions.

2. DATA AND METHODS

2.1. Vegetation zones, sections, and regions

The study area of Fennoscandia includes Norway, Finland, most of Sweden, and northwestern Russia (Fig. 1). The region is climatically and ecologically heterogeneous (Tuhkanen 1980, Moen 1999, Tveito et al. 2001). The regional variation in vegetation in Fennoscandia can be expressed in terms of vegetation zones and sections (Moen 1999). Vegetation zones (Fig. 1a) and altitudinal belts are considered to mostly reflect summer temperatures, whereas vegetation sections indicate oceanic gradients (Fig. 1b). In the study area, the northern, middle and southern boreal zones (NB, MB and SB, respectively) are characterized by coniferous forests. The boreonemoral zone (BN) forms a transition between the nemoral zone (N)—which is characterized by broad-leaved deciduous forest—and the typical coniferous forests. The alpine belts are the area above the climatic forest line, and the southern Arctic zone is the area north of the climatic forest line. The highly oceanic (O3), markedly oceanic (O2), and slightly oceanic (O1) sections are all characterized by a long growing season, high annual precipitation, and western species, as defined by Moen (1999). The intermediate section (OC) forms a transition between the oceanic and continental sections and occupies roughly three-quarters of the study area. The slightly continental section (C1) is characterized by a short growing season and low annual precipitation. The maps of vegetation zones and sections by Moen (1999) are used in the analyses. However, some of the zones and section cover only small areas and were thus included in the nearest zone/section in the analyses: the southern Arctic zone was included in the alpine belts, the N zone in the BN zone, and the O3 section in the O2 section. In the present study, vegetation regions are defined as the combination of overlapping vegetation zones and sections.

2.2. Phenology data

Comparable phenophase data on birch (*Betula pubescens* and its subspecies *Betula pubescens* ssp. *tortuosa*) from 28 observation stations in Finland and Norway

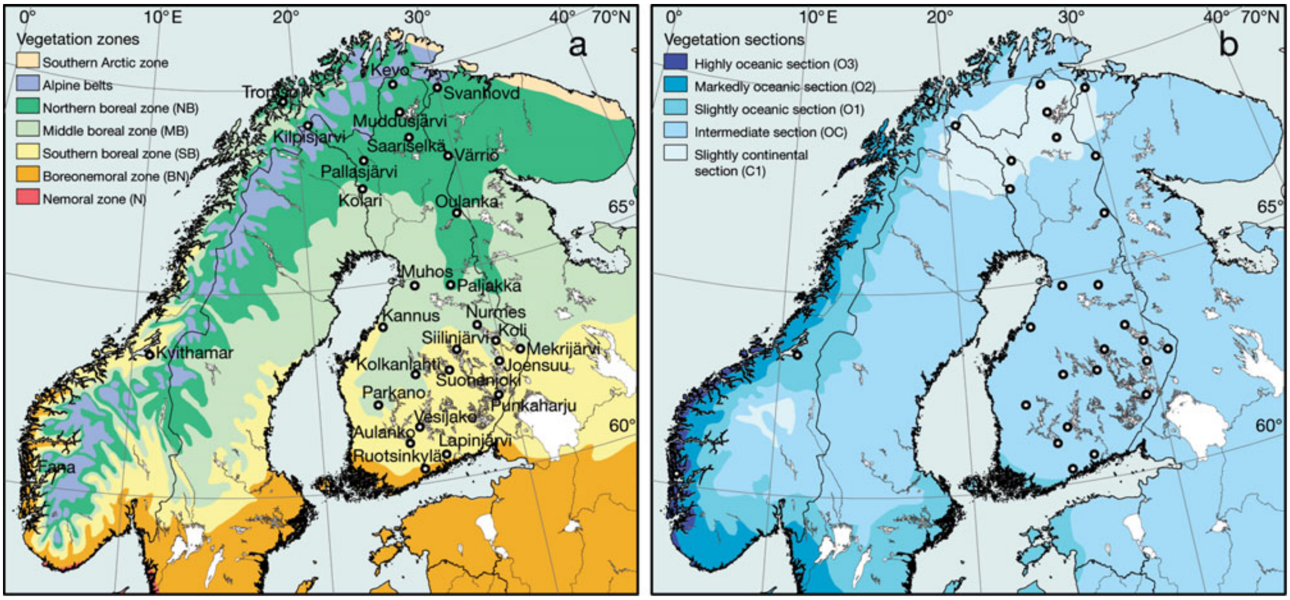

Fig. 1. Vegetation (a) zones and (b) sections in the study area according to Moen (1999), redrawn with permission, showing the positions of phenological stations used in the present study

Table 1. Relationship between NDVI values and observed phenophases of birch. Onset and end of the growing season (onset of leafing and >50 % yellowing of leaves, respectively) were measured from normalized difference vegetation index (NDVI) and phenological field data. The stations are sorted from north to south. Vegetation regions (zones and sections)—NB: northern boreal, MB: middle boreal, SB: southern boreal, BN: boreonemoral; O1, O2, O3: slightly, markedly, and highly oceanic, respectively; OC: intermediate; C1: slightly continental. Yr: number of years with field data; RMS: root mean square between field and NDVI data; B: bias, defined as differences in days between date of field observation and NDVI observation. (–) no data; $^{*}p < 0.05$; $^{**}p < 0.01$

Station region	Vegetation region	Onset of the growing season				End of the growing season			
		Yr	r	RMS	B	Yr	r	RMS	B
Tromsø	MB-O1	25	0.30	20.7	–16	–			
Svanhovd	NB-OC	14	0.36	11.6	–6	12	0.17	10.5	0
Kevo[a]	NB-C1	25	0.61**	10.1	5	10	0.47	6.3	–3
Kilpisjärvi	NB-C1	15	0.37	8.7	1	17	–0.28	9.7	–6
Muddusjärvi	NB-C1	10	–0.05	16.2	10	10	0.35	4.8	0
Saariselkä	NB-C1	10	0.45	12.6	10	10	–0.02	9.6	–7
Pallasjärvi	NB-C1	10	0.36	13.6	7	10	0.69*	6.3	–5
Kolari	MB-OC	10	0.60	10.4	8	10	0.15	17.2	–14
Värriö	NB-OC	8	0.60	10.7	7	10	0.20	5.6	–4
Oulanka	NB-OC	10	0.50	7.6	0	10	0.32	6.9	–7
Muhos	MB-OC	10	0.29	15.1	11	10	–0.18	17.9	–17
Kvithamar	NB-O1	23	0.45*	17.2	–14	19	–0.20	22.7	14
Paljakka	MB-OC	10	0.66*	8.1	4	10	0.04	16.1	–14
Kannus	MB-OC	10	0.72*	19.1	18	10	–0.11	16.8	–13
Nurmes	MB-OC	10	0.57	9.7	6	10	–0.03	16.5	–14
Koli	SB-OC	10	0.30	9.0	1	10	0.41	6.7	0
Siilinjärvi	SB-OC	10	0.60	8.1	–4	5	0.45	9.9	–4
Mekrijärvi	SB-OC	10	0.31	14.6	11	7	0.07	14.2	–10
Kolkanlahti	MB-OC	10	0.45	8.3	4	6	–0.03	8.1	–2
Suonenjoki	SB-OC	9	0.45	12.1	9	9	0.56	11.9	–8
Joensuu	SB-OC	10	0.51	10.7	8	10	0.24	12.0	–9
Parkano	MB-OC	10	0.56	23.0	22	8	0.19	13.8	–5
Punkaharju	SB-OC	10	0.51	7.6	0	10	0.20	12.9	11
Vesijako	SB-OC	10	0.89**	15.8	16	9	0.41	7.7	0
Aulanko	SB-OC	10	0.60	7.5	5	10	0.51	6.4	2
Lapinjärvi	SB-OC	10	0.56	8.1	6	10	0.04	7.2	–4
Fana	BN-O2	20	0.54*	16.2	–10	11	0.31	23.6	13
Ruotsinkylä	BN-OC	10	0.69*	8.7	6	10	0.01	11.8	7

[a] Phenophase budburst

(Fig. 1a; see Table 1 for vegetation region of each station) were used. Finnish data are from the Finnish phenological network launched in 1995 (Poikolainen et al. 1996, Pudas et al. 2008b). The data for Norway are from Tromsø at 69′ 65° N, Svanhovd at 69′ 45° N, Kvithamar at 63′ 47° N, and Fana at 60′ 27° N. The stations are unevenly distributed. None of the 28 stations were located in the Arctic/Alpine zone and 19 of the stations were located in the intermediate (OC) section. At the Finnish stations and at Svanhovd in Norway, phenological observations on birch were obtained from the same 4 to 5 individual trees twice a week from April to October each year. At the other stations, observations were more irregular. In the present study we used 2 phenophases—onset of leafing of birch and >50 % yellowing of leaves of birch—except for Kevo where we used the phenophase budburst due to the long time series of this phase. Budburst is when leaves have emerged from their buds but have not yet opened (BBCH07 code according to Meier 1997); onset of leafing is when the first leaves unfold and the first leaf stalk is visible, about 1 wk after budburst; and >50 % yellowing of leaves is recorded when more than half of the leaves on each tree 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, since its deciduous growth form allows for well-defined phenophases, phenomena not observed easily in conifers. The chosen birch phenophases represent well the general greening and colouring of the region's vegetation.

None of the stations have complete time-series for both the spring and autumn phenophases. The phenophase onset of leafing (including budburst) was observed in 338 seasons of data and >50 % yellowing of leaves comprises 272 observations.

2.3. Mapping the growing season

2.3.1. GIMMS-NDVI data set

An NDVI data set was acquired from the NASA GIMMS project for the 1982–2006 period from the University of Maryland Global Land Cover Facility (www.landcover.org/). The GIMMS data set is produced by data from the AVHRR instrument onboard the afternoon-viewing NOAA satellite series (NOAA 7, 9, 11, 14, 16, and 17). The data set has an 8×8 km^2 resolution and is composed of the maximum NDVI values for bimonthly periods between July 1981 and December 2006. There are 2 half-month composites per month, from Day 1 to 15 and from Day 16 to the month's end. The processing of the applied version of the data set includes reduced NDVI variations arising from calibration, view geometry, volcanic aerosols, and other effects not related to actual vegetation change. This includes NOAA-9 descending node data from September 1994 to January 1995, volcanic stratospheric aerosol correction for 1982–1984 and 1991–1994, and improved NDVI using empirical mode decomposition/reconstruction (EMD) to minimize effects of orbital drift. Details of the data set are described by Tucker et al. (2004, 2005) and Pinzón et al. (2005). Different versions of the GIMMS-NDVI data set have been used in numerous studies investigating vegetation activity and phenological changes (e.g. Myneni et al. 1997, Karlsen et al. 2006, 2007a, Raynolds et al. 2008, Verbyla 2008).

2.3.2. Estimating the growing season from NDVI

To estimate the onset and end of the growing season, we applied a pixel-specific threshold method. We modified a method first used by Høgda et al. (2001) and later described and discussed by Karlsen et al. (2006). This modified method has also recently been used on MODIS-NDVI data (Karlsen et al. 2008), but with different thresholds due to differences in the spectral bands on the MODIS and NOAA-AVHRR sensors, as well as the smoothing methods used on the GIMMS-NDVI data set. Here we give a short summary of the method and thresholds we used; for an illustration of the method, see Karlsen et al. (2008). First, the NDVI values were calculated for a 3×3 pixel area centered on each of the 28 phenological stations. In some cases, the centre position of the 3×3 pixel area was adjusted by 1 pixel to avoid inclusions of pixels not representative for the area around a station, e.g. water, high altitude, and human impact areas. Topographical maps, terrain models, and vegetation maps from the Baltic Sea drainage area (Malmberg 2001) and Norway (Johansen & Karlsen 2007) were used in the adjustment process to find representative areas. To link surface phenology with NDVI data to measure the onset and end of the growing season, we computed, for every pixel, a 25 yr mean NDVI value of the period 15 June to 1 September for the period 1982–2006. The use of this specific period reduces the noise from snow-covered ground. The date for the onset of the growing season for each pixel for each year was defined as the first day in the half-month period when the NDVI value passed (upwards) 0.70 of the 25 yr mean NDVI value for the 15 June to 1 September period. The date for the end of the growing season for each pixel for each year was defined as the first day in the half-month period when the NDVI value passed (downwards) 0.72 of the 25 yr mean NDVI value for the 15 June to 1 September period. These thresholds were chosen because they showed the highest correlation with the birch phenophases of onset of leafing and yellowing of leaves.

From the yearly onset and end of growing season values, for each pixel within the study area, the linear trends over the period were computed and the mean linear trends for vegetation zones, sections, and regions determined. As agricultural activities can be expected to have an influence on the results, for example by misinterpreting the harvesting time as the end of the growing season, agricultural lands and major lakes were omitted from the analyses. Due to uncertainties in the vegetation zones and section maps, the Baltic countries were omitted from the linear trend analyses. Finally, to improve the cartographic presentation, a 3 × 3 spatial median filter was applied to the final NDVI-based products.

3. RESULTS

3.1. Timing of the growing season

Table 1 shows the relationship between NDVI values and observed phenophases of birch. In general, the NDVI-defined onset of growing season showed a higher correlation with birch phenology data during spring as compared with data from the autumn period. During spring, most of the stations showed a moderately strong positive correlation: 20 of the 28 stations showed correlation values (r) above 0.45, and 7 of these were significant ($p < 0.05$). The root mean square (RMS) values between field data and NDVI data were <11 d for 15 of the stations. However, RMS values for both the Tromsø and Parkano stations were >20 d. The bias was <1 wk for 15 of the stations, and the NDVI-defined onset occurred earlier than the phenophase onset of leafing of birch at 23 of the stations.

The NDVI-defined end of the growing season was correlated with the phenophase >50% yellowing of leaves. Seven of the 28 stations showed r-values >0.40, but only one station was significant (Pallasjärvi, $p < 0.05$), and 6 of the stations showed negative correlation values. However, for half of the stations the RMS values between NDVI data and field data were better than 10 d. Additionally, the bias between field and NDVI data was ≤1 wk for 16 of the stations, and the NDVI-defined onset occurred earlier than the phenophase >50% yellowing of leaves of birch at slightly more than half of the stations (18 of 28).

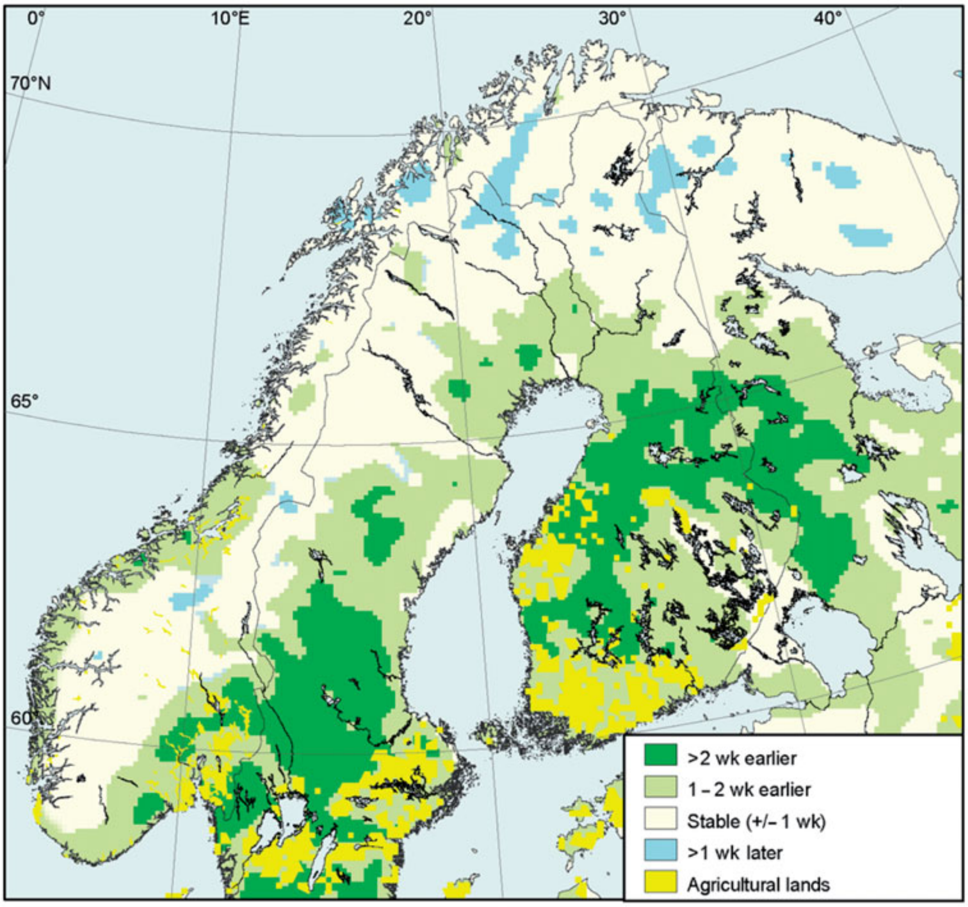

Fig. 2. Changes in onset of the growing season based on GIMMS-NDVI data for the 1982–2006 period

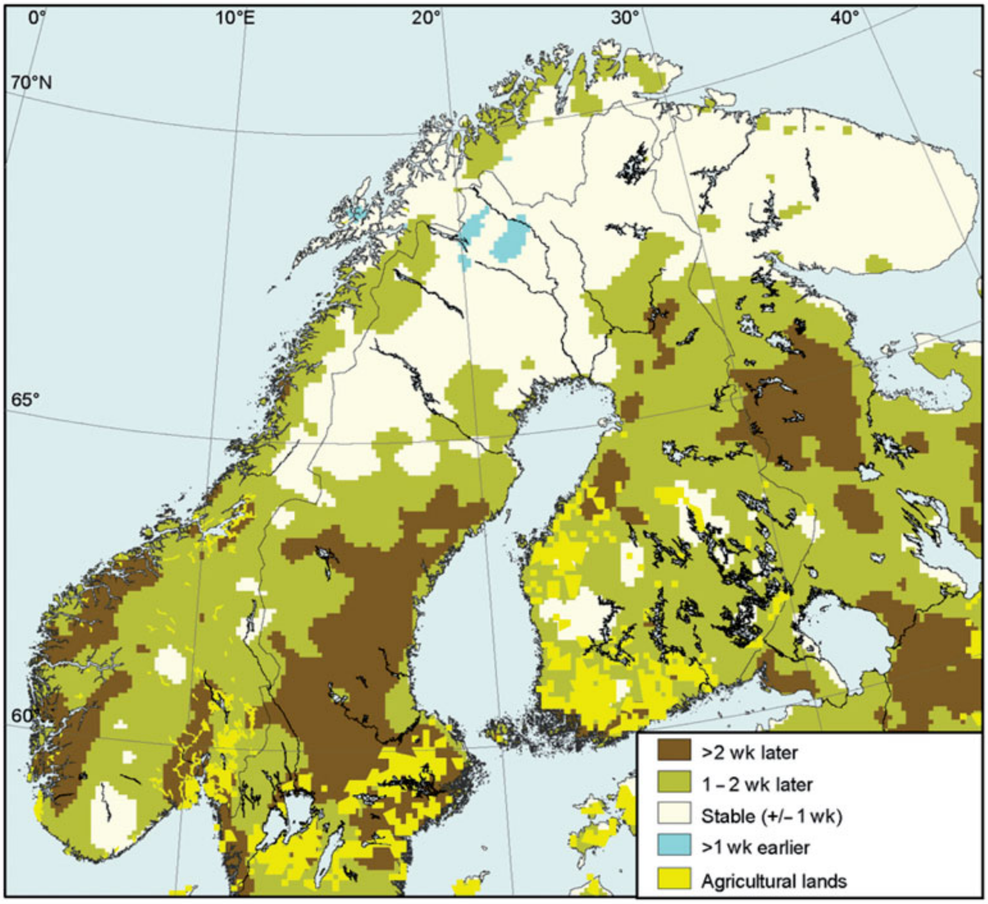

Fig. 3. Changes in end of the growing season based on GIMMS-NDVI data for the 1982–2006 period

3.2. Pattern of change in the growing season

Figs. 2–4 show the trends in onset, end, and length of the growing season, respectively, as analyzed from the NDVI data, and Table 2 shows the trends within the different vegetation zones, sections, and regions. The average linear trend in onset of the growing season for all of Fennoscandia indicates a 6.75 d (–0.27 d yr^{-1}) earlier onset for the 1982–2006 period (Fig. 2, Table 2). However, there were large differences in trends within Fennoscandia, and the pattern shows similarities within the vegetation zones, sections, and regions. The southern zones and the oceanic sections had the strongest trend of earlier onset, and the northern zones showed no trends or a weak trend of delayed onset. A trend in the range –0.33 to –0.59 d yr^{-1} was found in the southern oceanic regions (the SB, BN, and N zones within the O3, O2, and O1 sections). In both the Arctic/Alpine and NB zones within the C1 section there was a delay trend of 0.22 d yr^{-1}, however, these trends were not significant.

On average, there was a significant ($p < 0.01$) linear trend of a later end of the growing season by 0.37 d yr^{-1} for the whole study area (Table 2). Fig. 3 indicates that in parts of western Norway, central Sweden, and central Finland, the end of the growing season is >2 wk later compared with its timing in the early 1980s. The most oceanic sections (O3/O2) showed the strongest delay trend at 0.52 d yr^{-1} ($p < 0.01$), with a decreasing trend for more continental parts. The strongest trend of an earlier end to the growing season, although not significant, was found in the NB-C1 region (–0.12 d yr^{-1}), while in the Arctic/Alpine-C1 region there was no trend at all.

The trends in length of the growing season are the results of the differences between the trends in onset and end of the growing season, and on average a 16 d (0.64 d yr^{-1}, $p < 0.01$) longer growing season was found over the 25 yr period studied (Table 2). When regional differences were analysed, a >3 wk lengthening of the growing season was found in parts of southern and central Sweden and Finland (Fig. 4), and along a narrow coastal strip in western Norway (not easily seen in Fig. 4 due to the scale). The southern zones (SB, BN, and N) within the oceanic sections (O1, O2, and O3) all showed a significant ($p < 0.01$) trend of a >1 d yr^{-1}

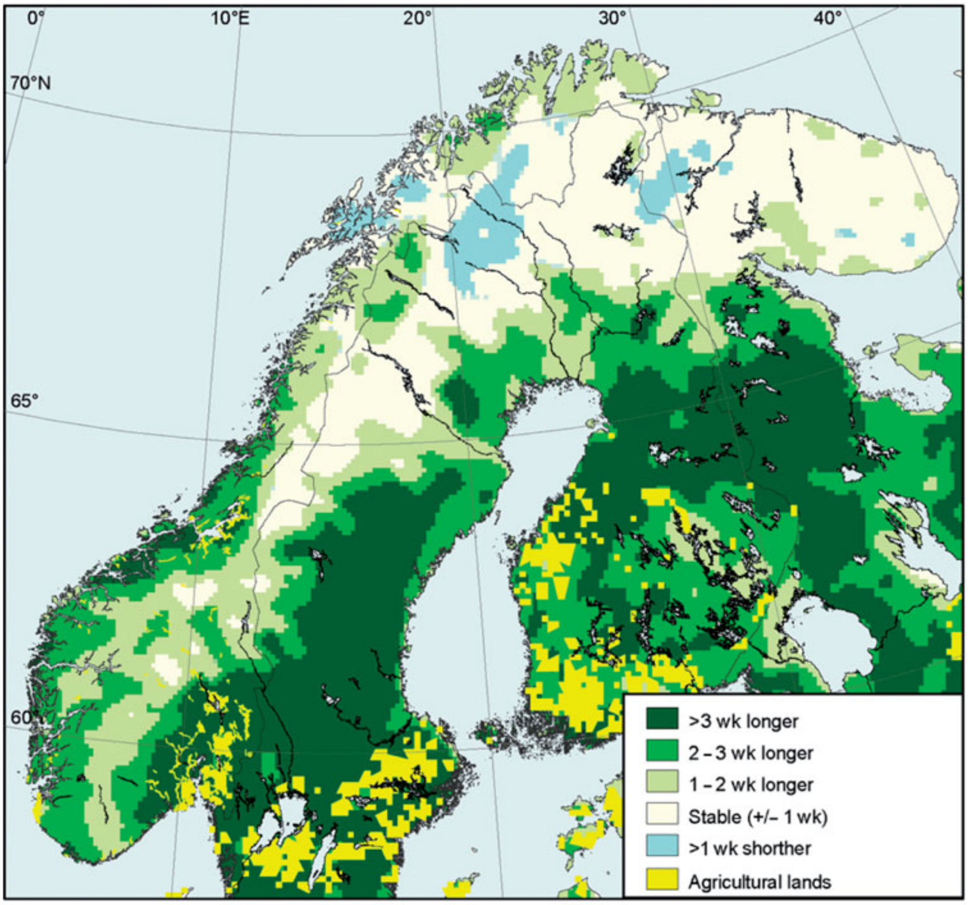

Fig. 4. Changes in length of the growing season based on GIMMS-NDVI data for the 1982–2006 period

longer growing season (Table 2). Arctic/Alpine-C1 and NB-C1 were the only regions with a shorter growing season trend, at –0.22 and –0.34 d yr^{-1} shorter, respectively.

4. DISCUSSION

4.1. Spatial and temporal variation

On average for all of Fennoscandia, the present study indicates a 0.27 d yr^{-}1 earlier onset of the growing season for the 1982–2006 period (Table 2). At such a continental scale, the results fit well with the rest of the northern hemisphere, as Parmesan (2007) calculated an overall northern hemisphere spring advance due to climate change of 0.28 d yr^{-1}. Our results also fit well with the general European trend, for which Menzel et al. (2006) reported an average advance of 0.25 d yr^{-1} in spring/summer from 1971 to 2000 in a study covering 21 European countries, with temperature increase believed to be the main reason for the advancement of spring/summer. Additionally, the spatial pattern of the changes in onset of the growing season within Fennoscandia for the 1982–2006 period (Fig. 2, Table 2) shows similarities with the rest of Europe. Ahas et al. (2002) found that in western lowland Europe and in the Baltic Sea region, the advance of the spring phases during the 1951–1998 period could be as high as an average of –0.3 to –0.4 d yr^{-1}, of the same order of magnitude as found in many of the southern and oceanic regions of Fennoscandia in the present study (Fig. 2, Table 2). Several other recent studies in western Europe have shown an advanced spring with increasing temperature (e.g. Luterbacher et al. 2007), and that the advancement corresponded well with changes in the North Atlantic Oscillation (NAO) index (Post & Stenseth 1999, Chmielewski & Rötzer 2001, Scheifinger et al. 2002, cf. Menzel et al. 2005). The strongest influences on advanced phenophases are generally observed in the earliest phases (e.g. Chmielewski et al. 2004) and in the most recent years (Fitter & Fitter 2002).

The weak trend of a delayed onset of growing season in the northern continental regions of Fennoscandia in the present study has similarities to the

Table 2. Linear trends (d yr^{-1}) in the normalized difference vegetation index (NDVI)-based onset, end and length of the growing season for the 1982–2006 period for various vegetation zones, sections, and regions. Zones: NB: northern boreal; MB: middle boreal; SB: southern boreal; BN: boreonemoral; N: nemoral. Sections: O3, O2, O1: highly, markedly, and slightly oceanic, respectively; OC: intermediate; C1: slightly continental section. (–): no data; $^{*}p < 0.05$; $^{**}p < 0.01$

Section/ zone	Arctic/ alpine	NB	MB	SB	N/BN	All
Onset						
O3/O2	–	−0.04	−0.04	−0.33	−0.46	−0.23
O1	0.08	−0.04	−0.04	−0.52**	−0.59*	−0.20
OC	0.01	−0.03	−0.52**	−0.46**	−0.29	−0.32*
C1	0.22	0.22	–	–	–	0.20
All	0.06	0.02	−0.46**	−0.45**	−0.41*	−0.27
End						
O3/O2	–	0.58**	0.39**	0.69**	0.57**	0.52**
O1	0.45**	0.28**	0.27**	0.51**	0.62**	0.41**
OC	0.27**	0.17	0.47*	0.46**	0.55**	0.38**
C1	0.00	−0.12	–	–	–	−0.08
All	0.30	0.14*	0.46**	0.48**	0.57**	0.37**
Length						
O3/O2	–	0.62**	0.43	1.02**	1.03**	0.76**
O1	0.37	0.32	0.31	1.03**	1.21**	0.62**
OC	0.26	0.20	0.99**	0.92**	0.84**	0.71**
C1	−0.22	−0.34	–	–	–	−0.27
All	0.24**	0.12	0.92**	0.93**	0.98**	0.64**

delay in spring phases in Eastern Europe from 1951 to 1998 (IPCC 2001, Ahas et al. 2002). The aforementioned authors explained the delay as an influence of the Siberian high-pressure system. Emberlin et al. (2002) predicted flowering of birch to occur about 6 d later at Kevo (northernmost Finland) during the next 10 yr due to cooler springs if the weather continues as it was around the millennium shift. Also, Shutova et al. (2006) showed that the timing of birch bud burst was delayed during the 1982–2002 period in northernmost Fennoscandia, including the Kola Peninsula, and in particular in eastern parts of the district. They concluded that snowmelt occurred later in more recent periods due to more precipitation falling as snow. This may even be seen as one reason for the stable (or even delayed) onset of the growing season at higher elevations further south in Fennoscandia (and in particular in southern Norway) for the 1982–2006 period in spite of increased temperatures (Hanssen-Bauer et al. 2003). Both Studer et al. (2005) and Menzel et al. (2001) observed that in Switzerland from 1965 to 2002 and in Germany from 1951 to 1996, respectively, earlier onset of spring was was less pronounced at higher elevations. However, neither discussed the findings further.

Linear trends are sensitive to the choice of starting year. Pudas et al. (2008a) found that the advance of birch budburst in Finland increased during 1997–2006 by –0.7 d yr^{-1} in the SB zone and –1.4 d yr^{-1} in the MB and NB zones. The present study, however, found a stable situation in the NB zone of Finland (Fig. 2). This disagreement could be a result of different starting years. The study by Pudas et al. (2008a) began in 1997, a period with generally late onset dates in the NB zone, while the present study began in 1982, a period with more average onset dates in the same area, as seen on the yearly onset maps by Karlsen et al. (2007a). The first flowering of various plant species in Norway during the period 1928–1977 is currently being analyzed (Wielgolaski 2009, F. E. Wielgolaski et al. unpubl. data), after the phenological curves were smoothed using a Gaussian filtering technique, it is clear that there is a 10 to 15 yr fluctuation in plant earliness throughout this period, masking to some degree an overall trend. The present study has revealed the regional pattern in linear trends over a 25 yr period; however, the regional pattern of the fluctuations in onset of the growing season over the last decades within Fennoscandia is still not clear. Also, across Fennoscandia there are indications that since the late 1990s many years have had an early onset of the growing season (Karlsen et al. 2007a, 2009, Nordli et al. 2008, Pudas et al. 2008a,b), influencing the trends and perhaps the fluctuation pattern.

In the present study (as seen by comparing Figs. 2 & 3, and Table 2), the end of the growing season was generally delayed in the same regions of Fennoscandia that showed an earlier onset. An exception is found in the alpine parts of southern Norway, which primarily show a delayed trend in end of the growing season (Fig. 3), but an unchanged situation in onset of the growing season (Fig. 2). In the SB and MB zones of Finland, a weak significant correlation between the delay of leaf colouring of birch and autumn temperatures was observed (Pudas et al. 2008a). A trend in the delay of the timing of autumn, however, was not found to be significant, either there or in Germany (Menzel 2000, Menzel et al. 2001, 2006), although higher autumn temperatures were found to delay autumn colouring of horse chestnut *Aesculus hippocastanum* (Menzel 2003). In northern continental regions, the end of the growing season may even occur somewhat earlier throughout the study period (Table 2), a result also found by Shutova et al. (2006) for the continental parts of northernmost Fennoscandia. They concluded that a cool period was necessary to trigger the yellowing of birch leaves. However, they also hypothesized that reduced light conditions, e.g. because of more clouds due to climate change resulting in shorter days in autumn in the far north (north of the Arctic Circle), might influence birch yellowing (Håbjørg 1972a,b, Shutova et al. 2006).

As a consequence of earlier spring and later autumn in southern and oceanic parts of Fennoscandia, the length of the growing season is prolonged during the study period. The same result was found in other studies (Menzel 2000, Menzel et al. 2001, 2003, Pudas et al. 2008a,b) in various parts of Europe. In contrast, as a consequence of both later spring and earlier autumn in the northern continental regions of Fennoscandia, the growing season length there was found to decrease during the study period 1982–2006. This, however, is not true in alpine parts of southern Norway, where later autumns follow the sometimes later onset of the vegetation period, possibly due to the predicted strongly increasing winter precipitation (Hanssen-Bauer et al. 2001, 2009) through the first half of the 2000s (up to 5–6% per decade compared to about 4% in the north of Fennoscandia). Although winter temperature may also increase (Hanssen-Bauer et al. 2003, 2009), winter precipitation in the southern mountains (as well as in the northern continental regions) will still fall mainly as snow (see the winter temperature scenario up to 2100 for Finnmarksvidda in northern continental Norway in Hanssen-Bauer et al. 2009).

4.2. Reliability of the trend maps

The geographical pattern of the NDVI-based maps, showing the trends in onset, end, and length of the growing season (Figs. 2–4), seems reasonable because it follows a climatic pattern. This is particularly true in spring, where the strongest trend of earlier onset is found in the southern and oceanic regions, and a slightly positive (delay) trend in the alpine and northern continental parts. During spring, the correlation values between phenology data on birch and NDVI values interpreted as the onset of the growing season are moderately high and significant ($p < 0.05$) for 7 of the 28 stations. However, in some years there are large disparities between the field and NDVI data. These outliers influence the correlation values and the trends. For example, at Parkano station in southern Finland in 2005, the field data shows onset of leafing of birch at Day 144 (24 May), while the NDVI data indicate onset at Day 107 (17 April). The overall correlation value increases from 0.56 to 0.81 if this year is removed. Since the surrounding phenological stations also have onset of leafing at about the same time, and in those locations the NDVI data correspond well with the field data, it seems reasonable that the error can be explained by noise in the GIMMS-NDVI data set. Such a local error could be due to long periods with cloud cover, very heterogeneous land-cover, or changes in land-use.

During autumn, the correlation values between phenology data of >50% yellowing of leaves of birch and NDVI data were low, and the climatic pattern is less clear than in spring. However, the bias between field and NDVI data was ≤2 wk for all stations except one (Muhos), indicating that the NDVI-based map corresponded well with the field observations of yellowing of birch. There were also several outliers in autumn, with the disagreement between field and NDVI data strongly influencing the correlation values and the trends. This may be due to an observation error since autumn phenological phases are more difficult to observe on the ground than spring phases. Another explanation for the lack of correlation could be that the autumn colouring shows a very heterogeneous pattern due to the fact that different plant species simply change colour at different times because of variation in responses to light, and thus this would not be detected by birch alone.

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, we have masked out the agricultural areas, and urban areas only cover relative small areas in the study area, for instance only 1.4% of Norway (Statistics Norway 2008). In addition, the method used here is also sensitive to changes in forestry; however, we believe that year-to-year land use changes occur at smaller scales than the NDVI data set of 8×8 km^2 resolution is likely to detect. For instance, large-scale logging of coniferous (pine and spruce) and deciduous forests (birch) is restricted by law in the Nordic countries (Swedish Forest Agency 2007), and hence the forestry in the Nordic countries are managed in a sustainable way with small- to medium-scale clear-cut areas, mainly <0.25 km^2, not affecting the spatial resolution considered here. However, due to an ending of subsidies in 1994, extended reduction in clearing of birch and willows on the clear-cut areas has occurred in Sweden (Swedish Forest Agency 2007) and the annual area of clearing dropped from 278 to 138 km^2 in 1995, with a subsequent increase to 179 km^2 in 2002 (Swedish Forest Agency 2008). This may affect the proportion of deciduous forests in the northern part of Sweden and thereby, to some degree, the NDVI value and the timing of the growing season, but most likely only on a local scale. The situation in Finland is more or less the same (FFRI 2008), while forestry occurs mainly on a smaller scale in Norway.

Several studies have mapped the trends in NDVI and onset and end of the growing season over very large areas, which also cover Fennoscandia (Myneni et al. 1997, Tucker et al. 2001, Zhou et al. 2001, Dye & Tucker 2003, Gong & Shi 2003, Slayback et al. 2003, Bunn & Goetz 2006, Zhang et al. 2008). However, most of these studies have a poor link with field phenological data, or no field data at all, and were conducted at scales that are difficult to interpret effectively for Fennoscandia. Stöckli & Vidale (2004) processed the European Fourier-Adjusted and Interpolated (EFAI) NDVI data set, a well-smoothed and calibrated data set based on NOAA-AVHRR, over all of Europe for the 1982–2001 period. They showed a trend for Fennoscandia with a similar pattern for onset of the growing season as found in the present study. In autumn, they found a heterogeneous pattern with a trend primarily of a later end of the growing season, but with no contradictions to the present study. However, they did not compare the results with field data, and they used a threshold method that would yield too early an onset and too late an end of growing season compare with the present study. Delbart et al. (2008) used both a phenological model and a remote sensing-based data set and mapped the trend in onset of the growing season in boreal Eurasia for the 1982–2002 period, and found a stable or slightly delayed trend in onset for alpine and northern continental regions of Fennoscandia, which partly supports the present study. In previous preliminary studies, Høgda et al. (2001, 2007) used an early version of the GIMMS-NDVI data set to map the trends in the growing season for the 1982–1999 period for Fennoscandia, correlated, however, with data from only a few field stations. They found a similar pattern but with a stronger trend in onset of the growing season in southern and oceanic regions. This is most likely because a threshold based on the mean NDVI value above zero was used. The threshold would then be influenced by the degree of snow cover, and some southern and oceanic regions that lack a stable snow cover each year could have an overly strong trend, with the onset more associated with the timing of snowmelt.

The present study used a pixel-specific method and a threshold from a mean summer NDVI value. Other methods that work on a pixel-by-pixel basis were also tested, for instance, using the period of steepest increase in NDVI as the timing of the onset of the growing season (White et al. 1997, Studer et al. 2007); however, they yielded a low correlation when compared with field observations in our study area. An earlier comparison of methods showed that the present method is most suitable for the GIMMS-NDVI data set of the study area (Karlsen et al. 2006). Our pixel-specific method based on a mean summer NDVI threshold has also recently been used on MODIS-NDVI data in different regions of the study area, and has shown high correlation in spring both with birch phenology (Karlsen et al. 2008) and pollen data (Karlsen et al. 2009). These MODIS-NDVI-based maps, based on the summer NDVI mapping method, have also been compared with snow maps, based on microwave data, in southern Norway (Karlsen et al. 2007b). The study from southern Norway showed that the time differences between the last day of snow and the onset of the growing season was much larger in the oceanic lowland compared with the alpine areas, indicating that our method based on mean summer NDVI values is not directly influenced by snowmelt, but with greening. However, the correlation with autumn phenophases was also low in the MODIS-NDVI-based study (Karlsen et al. 2008), which indicates that more research is needed to map the timing of autumn. Dense coniferous forest is very common in the study area, in particular in Finland and Sweden. It should be emphasized that dense coniferous forest without birch has low NDVI amplitude variation and in these regions the trends mapped for the growing season are thus likely to be more affected by noise, becoming less accurate. Also, since birch is rare in some coniferous-dominated areas, we may detect the understorey green-up from shrubs, herbs, and grasses in the forest rather than the overstorey coniferous species, but this was not further investigated. However, if the threshold value we determine is wrong in some pixels, this will influence the accuracy of the timing (too early or too late), but it is reasonable to believe that the 25 yr mapped trends in the growing season will be less influenced. The lack of birch is, of course, also the case for alpine areas where we only measured the general greening and yellowing of the species in the field layer. In general, in areas not dominated by birch it is not possible to know what we are measuring with the 8×8 km^2 pixel resolution.

White et al. (2009) investigated 10 different satellite NDVI methods for retrieving the onset of the growing season in North America. The individual methods differed by ±60 d in average day for onset of the growing season and by ±20 d in standard deviation. They concluded that the ability of satellite methods to retrieve onset of the growing season estimates was highest in northern latitudes and that, compared with ground observations, onset estimates were more related to the phenophases of first leaf and first flowers expanding. They also highlighted the importance of implementation details (e.g. how the threshold value is selected) for the onset of the growing season results. Accordingly, our confidence in the results from the present is consistent with their findings, as we worked with high latitude data, selected a NDVI threshold value so that the timing of the passing of this threshold value fit with the onset of leafing in the area investigated, and used a method specifically designed for the area we investigated. Results from the present study also showed a correlation with ground data that is moderately high in spring, and trends were similar in both ground and satellite data.

In conclusion, despite the local errors in disagreement between field phenology and NDVI data for some stations in some years, we believe that the NDVI-defined trends for onset, end, and length of the growing season are reliable in the majority of the study area. This is due to the moderately high correlation values in spring, the rather low bias in autumn, and a general agreement with comparable studies. However, there are errors on a local level due to the noise in the satellite data used, and the maps presented show only the general trends on a regional scale. We also believe that the trend in the onset of the growing season is more accurate than the trends in end and length of the growing season.

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