Assessment of Biological and Environmental Phenology at a Landscape Level from 30 Years of Fixed-Date Repeat Photography in Northern Sweden

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Abstract A 30-year series (1978–2007) of photographic records were analysed to determine changes in lake ice cover, local (low elevation) and montane (high elevation) snow cover and phenological stages of mountain birch (*Betula pubescens* ssp. *czerepanovii*) at the Abisko Scientific Research Station, Sweden. In most cases, the photographic-derived data showed no significant difference in phenophase score from manually observed field records from the same period, demonstrating the accuracy and potential of using weekly repeat photography as a quicker, cheaper and more adaptable tool to remotely study phenology in both biological and physical systems. Overall, increases in ambient temperatures coupled with decreases in winter ice and snow cover, and earlier occurrence of birch foliage, signal a reduction in the length of winter, a shift towards earlier springs and an increase in the length of available growing season in the Swedish sub-arctic.

Keywords Lake ice · Phenophase · Mountain birch · Snow cover · Swedish sub-arctic

INTRODUCTION

Phenology has become increasingly important to climate studies over the last few decades, with phenological observations now widely accepted as important indicators of change (Schwartz and Reiter 2000; Penuelas and Filella 2001; Cayan et al. 2001; Walther et al. 2002; Badeck et al.

2004), although Callaghan et al. (2011 [this issue]) challenge the generality of this concept. However, the undertaking of research employing phenological observations as a means to collect data remains expensive for aerial/satellite surveys and labour intensive for field-based observational studies. Furthermore, accurate assessment of phenophases is likely to vary from recorder to recorder (Sparks et al. 2006), whilst human error during field observations could be expected to increase during times of adverse conditions. One method currently being used to overcome such problems is citizen science (Magurran et al. 2010), such as the UK Phenological Network (<http://www.naturescalender.org.uk>), where the high number of records generated is likely to outweigh recorder error. Unfortunately, this is not a practical solution in remote regions, where low human population density prevents the use of mass public recording.

In both populated and unpopulated regions, fixed-date repeat photography could be a reliable and cost-effective alternative. In a fully automated system, the need for any human participation can be reduced to that of installation, maintenance and analysis, and such systems have been successfully used to study phenological change of many types; including development and flowering of plant species (Crimmins and Crimmins 2008), ice cover dynamics (Bourgault 2008), snow cover dynamics (Christiansen 2001) and snow melt (Hinkler et al. 2002). However, such studies were generally designed to provide high quality phenological data on a single variable, and as such are restricted in scope to delivering information on their chosen variable. A desirable alternative would be a simplified system capable of recording a wide range of biological and physical phenological variables for extended periods at both landscape and local levels. In this paper, we analyse a 30-year (1978–2007) weekly photographic series collated by the Abisko Scientific Research Station (ANS) to, (i),

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demonstrate the usefulness and reliability of using a standard digital camera for fixed-date repeat photography as an inexpensive method for studying phenological change, and (ii), report phenological change in both physical and biological systems as a response to climate change.

MATERIALS AND METHODS

Site Description

All photographs were taken at ANS situated in the Lapland region of Northern Sweden (68°21'N, 18°49'E), on the south shore of Lake Torneträsk adjacent to the Abisko National Park. Two photo-series (the Njulla Mountain and Lake Torneträsk, Fig. 1) were selected for analysis, based on their outlook, time-scale and completeness (Table 1). The Njulla series (Fig. 1a) included terrain ranging from mountain birch forest at 341 m above sea level to the upper montane slopes at 1,169 m. The second series centred on views across Lake Torneträsk (Fig. 1b), including mountain birch forest in the foreground, Lake Torneträsk in the middle distance and the mountains of Vadvetjåkka National Park some 28 km distant.

Equipment

Early photographs (1978–1999) were taken using a Canon Datamatic 40 mm camera and stored as 24 × 35 mm Kodak projector slides, to be later digitized using an Agfa Snapscan e50 scanner (1200 × 2400 dpi, 42-bit) and stored as digital media. Photographs taken after 1999 were in digital format, firstly using a Kodak DC260 (1999–2003), and thereafter a Canon Powershot G5 camera.

Image Analysis

From each photo-series, a number of biological and environmental events were chosen for study dependant on where phenophases could be clearly assigned (Supplementary Table). In all photograph series, *Betula pubescens* ssp. *czerepanovii* (mountain birch) phenology was clearly visible and six clearly identifiable phenophases were assigned for analysis. Variations in snow cover were also identifiable in each image. However, due to variation in the distance to each objective, the number of phenophases distinguishable differed between series. Lake freeze-up could also be identified from the Lake Torneträsk series, and three phenophases were assigned. To prevent pre-judgement of expected phenophase by the recorder, images were grouped by series and year then randomized within each group before scoring commenced.

Methodological Analysis

Accuracy of the phenophase score was tested through comparison with independently collected manually observed field records collated for local low elevation snow fall, lake freeze-up and birch phenology by staff of ANS. Records of local snow cover at ANS exist as a daily snow score for the period of the study; where 1 = Full snow cover; 2 = More snow than bare ground; 3 = More bare ground than snow and 4 = Bare ground. The first date of laying snow and subsequent date of spring melt were extracted from these observational records for comparison to photographic scores of local snow cover.

Field-observed records for the date of complete ice cover and the date of clear water for Lake Torneträsk are taken from the viewing platform at ANS annually. Field-observed birch phenology was recorded from 2003 onwards in both meadow and heath communities on ground adjacent to ANS. For each site, three trees were monitored weekly and scored according to Tenow et al. (2001) phenophases for birch buds/leaf development. However, because Tenow et al. (2001) phenophases could not be accurately judged from the landscape scale photographs; six clearly identifiable phenophases were assigned (see Supplementary Table), and matched to those described by Tenow.

Thermal requirement for full foliage cover was calculated according to Cannell and Smith (1983) for each year. Base temperatures of 0, 0.5, 1, 1.5 and 2°C were considered; with accumulations beginning 1st March (no instances of positive temperatures occurred prior to this date). It was not deemed necessary to include vernalization requirements into the calculations due to the extremely low winter temperatures at such northern latitudes (Myking and Heide 1995).

Daily temperature data were used to calculate length of growing season in any given year using the method described by Frich et al. (2002).

Statistical Tests

We analysed for differences between photographic and manually observed data using a linear regression model approach (GLM) (Genstat for Windows 2007, 10th Edn, VSN International Ltd., Hemel Hempstead, UK), with year fitted as a parameter in the model. Due to the non-random distribution of birch phenology data, differences between methods were analysed using repeated measures correlated by residual maximum likelihood (REML). Mountain birch data from both photographic series were tested for differences using a Kruskal–Wallis one-way analysis of variance. As no differences existed ($df = 1$, $H = 0.009$, $P(X^2) = 0.922$), they were combined and their mean used in further analyses.

Fig. 1 Example images from **a** Njulla mountain and **b** Lake Torneträsk photographic series. Early (1981/82) and late (2007) images of similar date from each series are shown. The two images of Njulla mountain were taken on the 02/06/1982 and 4/6/2007, respectively, and provide an example of the earlier onset of foliage cover found to

have occurred during the period. The Lake Torneträsk images were taken on the 25/12/1981 and 24/12/2007 and clearly show the changes in lake ice cover and low elevation snow found between the years. All photographs are property of the Abisko Scientific Research Station

Temporal changes in phenology were tested using simple linear regression. Phenophase on-set dates were then correlated with three monthly average temperatures (month of on-set, plus the two preceding months) by Pearson product–moment correlation. In all cases, relationships with a probability of 0.05 or below were considered statistically significant.

RESULTS

Data Quality and Method Analysis

In total, 1697 (of a potential maximum, 2994) photographs were available for ascribing phenophases, generating 4980 date/event data points for analysis. Of those unavailable,

Table 1 Metadata of the photographic series to which phenophases were assigned

Series	Njulla Mountain (Fig. 1a)	Lake Torneträsk (Fig. 1b)
Photographic series start date	1979	1978
Frequency	Weekly (Monday)	Weekly (Monday)
Distance to objects of observation (approx)	5 km	28 km
Altitudinal range	390–1,169 m	347–1,200 m
Image direction	West	North-West
Overview of picture	View from ANS to Njulla/Slättatjåkka. Encompasses birch forest, climatic tree line and montane landscapes.	From ANS over (Lake) Torneträsk towards Vadvetjåkka National Park. Encompassing birch forest/scrub.
Number of phenological events analysed	Two	Four
Biological phenology	<i>Betula pubescens</i> ssp. <i>czerepanovii</i>	<i>Betula pubescens</i> ssp. <i>czerepanovii</i>
Environmental phenology	Snow cover (montane)	Lake ice; snow cover (local & montane)

Both series were taken from the viewing platform at the Abisko Scientific Research Station, using standard cameras and photography techniques (see text for details)

1000 (33.4%) were missing from the archives, whilst 225 (11.2%) were impaired due to adverse weather (low cloud/rain) and 72 (3.6%) to poor light quality.

Generally, no significant differences were found between data recorded from photo-series and data recorded from field observational records. GLM regression analysis showed both photographic and field observational data to provide similar results for lake freeze-up ($F = 1.22$, $P = 0.28$), lake ice thaw ($F = 0.00$, $P = 0.99$), the on-set of low elevation winter snow fall ($F = 0.46$, $P = 0.50$) and birch phenology ($F = 2.67$, $P = 0.10$). However, photographic-derived observations were found to differ from field observations for spring snow melt ($F = 6.85$, $P = 0.013$), with snow melt occurring slightly later in the photographic observations.

Physical Environment

Using simple linear regression, annual mean temperatures at ANS were found to have increased by 2.06°C ($F = 24.11$, $P < 0.001$) between 1978 and 2007, increasing at a rate of $0.07 (\pm 0.01)^{\circ}\text{C year}^{-1}$ (Fig. 2). Over the same period, the length of available growing season has increased by 2.4 weeks, from an estimated growing season of 12.1 weeks in 1978 to 14.6 weeks in 2007.

Phenology: Lake Ice Cover

Between 1978 and 2007, the winter freeze of Lake Torneträsk was found to be occurring significantly later in the year ($F = 26.55$, $P < 0.001$), delaying surface freeze by $0.20 (\pm 0.04)$ week year^{-1} (Fig. 3a). Regression estimates show lake freeze-up to be occurring 5.8 weeks later by the end of this period (Table 2); during week 2 (15–22

Fig. 2 Temperature trend at ANS, 1980–2007, displayed as a 3 year running mean. Error bars show the standard error of the mean, calculated from monthly average temperature

January) in 2007, compared with week 48 (26 November–02 December) in 1978. The on-set of lake freeze and the average temperatures in November ($r = 0.5$, $F = 5.01$, $P = 0.041$) and December ($r = 0.73$, $F = 17.24$, $P \leq 0.001$) were found to be significantly correlated. Predictive outputs from the GLM estimate lake freeze to be delayed by $0.55 (\pm 0.25)$ weeks and $0.49 (\pm 0.12)$ weeks for every 1°C increase in November and December average temperatures, respectively. April ($r = -0.63$, $F = 11.7$, $P = 0.003$), May ($r = -0.57$, $F = 8.71$, $P = 0.009$) and June

Fig. 3 Phenological trends in the Abisko region of Northern Sweden, 1978–2007. All data were derived through analysis of two photographic series taken at the Abisko Scientific Research Station (ANS) and display the first dates of **a** full Lake Torneträsk ice cover (filled circles) and spring melt (open circles); low (b) and high (c) elevation snow cover (filled circles) and spring melt (open circles); and **d** mountain birch full canopy cover (open circles) and senescence (filled circles). Linear regression lines are displayed as the upper and lower limits of the shaded areas, which represents the decreasing period of winter conditions in the region

($r = -0.64$, $F = 12.57$, $P = 0.002$) temperatures were all found to be significantly correlated with the first date of 'ice free' water, predicting earlier melts of $0.46 (\pm 0.12)$, $0.49 (\pm 0.17)$ and $0.61 (\pm 0.17)$ weeks for every 1°C rise in respective average temperatures.

Phenology: Snow Cover

Low elevation snow cover at ANS was found to be melting significantly earlier between 1978 and 2007 ($F = 14.66$, $P = 0.001$), with the annual spring snow melt occurring $0.12 (\pm 0.03)$ week year $^{-1}$ earlier (Table 2; Fig. 3b) over

the period. No significant change was found in the on-set of full winter snow cover during the same period ($F = 2.39$, $P = 0.14$). The strongest correlation between spring snow melt and average temperature was found to be in April ($F = 12.14$, $P = 0.002$), whilst the start of winter snow fall was similarly correlated with September ($F = 5.17$, $P = 0.034$) and October ($F = 5.29$, $P = 0.032$) temperatures. Although high elevation snow melt appeared to be occurring earlier over the study period (Fig. 3c) this was not found to be statistically significant. However, the overall period of full snow cover at higher elevations was found to have reduced significantly ($F = 6.93$, $P = 0.018$).

Table 2 Significant temporal change in four phenological observations between 1979 and 2007, as derived from photographic records. To remove effects of any missing values, the displayed data are that predicted by the generalised linear model

	1978 (week)	2007 (week)	Temporal change (weeks)	<i>P</i> value	s.e.
Full Abisko snow cover					
Fall	41	43	>1.7	0.14	0.037
Melt	22	19	<3.4	0.001	0.031
Full montane snow cover					
Fall	42	44	>1.3	0.14	0.037
Melt	21	19	<1.8	0.14	0.041
Lake ice					
Freeze-up	48	2	>5.8	<0.001	0.039
Melt	24	22	<1.7	0.12	0.036
Birch phenology					
Leaf flushing	24	23	<1.1	0.16	0.025
Full canopy	26	24	<1.6	0.050	0.026
Senescence	38	39	>0.3	0.55	0.017

Table 3 Correlation coefficients between the on-set of each of five phenophases in mountain birch (see Supplementary Table) and the mean monthly air temperature for the three preceding months, for two photo-series Njulla and Lake Torneträsk between 1978 and 2007. Negative coefficients represent an earlier on-set

Photo-series	Month of temperature measurement	Phenophase				
		Leaf flushing	Full foliage cover	Some foliage yellowing	All foliage brown	Foliage thinning
Torneträsk	Mar	−0.123				
	Apr	−0.6*	−0.229			
	May	−0.857**	−0.604**			
	Jun		−0.401*	−0.301		
	Jul			−0.282	0.207	0.186
	Aug			0.243	0.271	0.255
	Sep				−0.269	−0.262
Njulla	Mar	−0.059				
	Apr	−0.28	−0.272			
	May	−0.694**	−0.564**			
	Jun		−0.44*	−0.435*		
	Jul			0.105	0.339	0.296
	Aug			0.157	0.317	0.174
	Sep				−0.257	−0.17

* $P < 0.05$, ** $P < 0.01$

Phenology: Mountain Birch

A marginal temporal shift ($F = 4.26$, $P = 0.05$) in the onset of full foliage cover was found between 1978 and 2007 (Table 2; Fig. 3d), occurring earlier by 0.05 (± 0.03) week year^{−1}, but this was not obvious for leaf flushing. Correlations between the on-set of each of the phenophases scored for mountain birch and the preceding monthly temperatures (Table 3) showed significance at the 1% limit for both the ‘leaf flushing’ (phenophase p2) and ‘full cover’ phenophases (phenophase p3). In both cases, this related to the average May temperature. Output from the regression analysis of temperature

and leaf flushing ($F = 39.42$, $P < 0.001$) and full cover ($F = 13.18$, $P < 0.001$) predict that for every 1°C increase in May temperatures, the date of on-set occurs 0.50 (± 0.08) and 0.55 (± 0.15) weeks earlier, respectively.

Thermal requirements to achieve full foliage cover best-fitted phenology data when calculated with a base temperature of 1°C ($R^2 = 0.23$). The average thermal requirement (sum) to achieve full foliage cover calculated at 391 thermal days ($n = 26$, $SD = 75.92$). Although a small increase in thermal time requirements appeared to exist for the period, this was not found to be statistically significant ($F = 0.81$, $P = 0.38$).

DISCUSSION

Data Quality and Method Analysis

The image quality determines whether data can be reliably extracted for analysis. As a photograph is just a snapshot of a particular point in time, it is greatly affected by climatic conditions at the moment of capture. Light variation can be a major obstacle to such experimental setups as high contrast not only overshadows the image, but subtle light variation could distort subjective measurements. Despite 48% of the potential available images being missing or of poor quality, the strong correlations between data collection methods suggest this did not have a considerable impact on the results. This is most likely a result of missing or unusable images largely covering periods of relative phenophase stability, such as mid-winter when snow/ice cover is complete, and birch growth dormant.

Weekly images were for the most part found to be an accurate measure of field-based phenology. The mean date of lake freeze-up and subsequent melt on Lake Torneträsk using data derived from photographs were found to be broadly similar to those reported by Blenckner et al. (2004), using data derived from the Swedish Meteorological and Hydrological Institute between 1961 and 2002. Blenckner reported the mean onset of lake freeze-up as day 355 (SD = 12) and mean date of ice break-up as day 163 (SD = 9), equating to week 51 (SD = 1.71) and week 23 (SD = 1.29), respectively. Photographic records closely matched this providing a freeze-up date of week 52 (SD = 2.26) and melt during week 23 (SD = 1.24). The marginally later freeze-up date for the photographic data is symptomatic of the increase in temperatures that occurred during the two date ranges (Blenckner = 1961–2002; Photographic = 1978–2007). Long-term observations (1913–2008) analysed by Callaghan et al. (2010) further showed recent accelerated change in Lake Torneträsk ice cover. This accelerated change coincides with the study period of this study and shows freeze-up and subsequent break-up dates to be similar to those derived from photographic archives.

Due to differences in the viewing area between field-observed and photo-derived lake ice data (whole lake, and western quarter, respectively), differences between methods could have been expected. However, this was not found to have occurred, and ice cover data obtained from photographs appears a robust measure of the general periods of ice cover for Lake Torneträsk. Although not seemingly a problem in this study, the issue of reduced viewing area could be considered a limitation of the repeat photography technique. Fortunately, this can be easily mitigated for through wide-angle or multiple-imaged landscape photography and using systems such as Gigapan

(<http://www.gigapan.org>) to create high quality gigapixel images.

The methodological success highlights the importance of photographic archives as holding large amounts of accessible environmental data, which when extracted could provide valuable information on landscape scale phenological change in areas where conventional records are not currently collected.

Phenological Change in the Abisko region, Northern Sweden

Lake Ice Cover

Results indicate phenological change in lake ice cover is strongly correlated to preceding monthly temperatures, most significantly with the temperature of the month of mean freeze (December) and mean melt (June). Annual trends show lake freeze-up to be occurring significantly later in the winter months from 1979 to 2007. As current regionalized climate models forecast increasing winter air temperatures over the coming decades (Rummukainen et al. 2001), it is expected that the length of winter ice cover will further decrease. Regression analysis of Lake Torneträsk data shows that a 1°C increase in ambient temperatures could delay lake freeze-up by 0.5 week year⁻¹, whilst also accelerating ice melt by 0.6 week year⁻¹. This melt rate is similar to that suggested by Weyhenmeyer et al. (2004) for lakes in Northern Sweden.

Although the results on lake ice dynamics analysed from repeat photography presented here do not differ from the manual observations published by Callaghan et al. (2010), far more detail (not presented here) is potentially extractable from the photographs for analysis. These include gradual changes of the ice coverage within each year and the short-term dynamics of ice break-up and re-formation as a response to meteorological (rather than climatological) conditions such as wind and air pressure.

Snow Cover

Snow cover at high elevation appeared variable throughout the study period, but visible trends towards later onset (0.04 week year⁻¹) and earlier spring melts (0.06 week year⁻¹) were not found to be significant (Table 2; Fig. 3c). However, there has been a general decline in the period of full winter snow cover at high elevations in the Abisko region (0.1 week year⁻¹) between 1978 and 2007. At lower altitudes, the on-set date of snow cover was found to be more or less stable for the period, whereas the spring snow thaw was found to be occurring significantly earlier at a rate of 0.12 week year⁻¹ (Table 2; Fig. 3b). Although the data are not shown, tendencies towards increased

variability in the permanence of winter snow cover were also found for the latter years, indicating periods of shallower and more transient snow cover. Such decreases in snow depth coupled with the earlier spring thaw but stable on-set dates, is consistent with a springtime snow albedo feedback kicking in at lower elevations. Overall, these declines in length of snow cover at both low and high elevation contradict projected increases in long-term snow depth suggested by Kohler et al. (2006), whilst supporting data showing rapid decreases in snow depth since the 1980s (Callaghan et al. 2010).

The implications of reduced snow cover on ecosystems have been widely discussed. Snow cover protects both plants and soils from the extreme low temperatures experienced during winter in arctic areas (Sokratov and Barry 2002; Darmody et al. 2004), and from grazing by both large and small herbivores (Kohler and Aanes 2004). Furthermore, it is widely considered that at higher latitudes the timing of snow melt determines the on-set of the subsequent growing season (Walker et al. 1995; Dunne et al. 2003; Aerts et al. 2006). A future reduction in snow depth or an advanced snow melt could eventually lead to changes in species assemblages (Galen and Stanton 1995; Scott and Rouse 1995; Wipf et al. 2005) through effects on plant phenology (Dunne et al. 2003), growth (Walker et al. 1995; Kudo et al. 1999; Wipf et al. 2009) and species–species interactions (Callaway et al. 2002; Wipf et al. 2006).

Mountain Birch Phenology

Onset of full foliage cover was found to be occurring 1.5 weeks earlier by the end of the 30-year study period, which could well reflect the increased length of the available growing season, although no significant temporal change was recorded for leaf flushing or autumn senescence. These results are similar to the regional approach used by Karlsen et al. (2009), using NDVI satellite-derived data between 1982 and 2006 to show birch phenology in the Abisko region as being relatively stable for this period. Despite these similarities, the earlier onset of full foliage cover found in this study is likely to infer some advantages to birch trees in that they can use more of the available growing season, which in turn may provide the birch forests with a competitive advantage. The general stability in the onset of senescence is likely a consequence of its strong association with photoperiod (Partanen and Beuker 1999), although the new analyses also showed a significant correlation between average June temperatures and the onset of leaf yellowing, suggesting temperature has at least some involvement in senescence of birch foliage. This may provide some backing to the findings of Shutova et al. (2006) who reported that a period of cool temperatures may be necessary to trigger yellowing in birch leaves.

Correlations between mean May temperatures and leaf flushing showed that a 1°C increase in temperature could bring flushing forward by 0.5 weeks (c 3.5 days). The Karlsson et al. (2003) analyses also showed changes in May temperature to be the most influential on the timing of budburst, with budburst occurring 5–6 days earlier for every 1°C increase in mean May temperature. The necessary use of leaf flushing in this study, rather than the more traditional budburst, is due to the landscape nature of the photographs, and is also the likely cause of the variation in rates of change between the two studies even on the same individual trees.

As the thermal requirement for leaf flushing was not found to have changed, it is most likely that the mountain birch is responding directly to changes in the physical environment, rather than undergoing a physiological change in its thermal requirements. Wielgolaski (2001) demonstrated the importance of day and night temperature to growth, showing nighttime temperatures to be most strongly correlated with budburst, whilst day-time temperatures correlate more strongly with the generative stages of phenology. Temperature, however, although crucially important, is only one of many factors acting upon birch growth, as precipitation, humidity and soil moisture have also been correlated with budburst (Wielgolaski 2001).

CONCLUSIONS

Digital photography has made the collection and storage of photographic archives an inexpensive and uncomplicated process. Large amounts of useable environmental data can be quickly extracted from these archives by non-specialist researchers, and as such we would strongly encourage the creation and management of such records by researchers and non-researchers alike. Our approach also demonstrated the added benefit that photographic archives can be interrogated at any time as new questions become relevant; whereas field-recorded observations remain specific only to the intended subject and time of recording.

For the Abisko region of Northern Sweden, the assessment of photographs has highlighted significant reductions of winter duration between 1978 and 2007. Ice cover on Lake Torneträsk was reduced by 7.5 weeks over the period, whilst low and high elevation snow cover were reduced by 5.1 and 3.1 weeks, respectively, providing evidence that contradicts other analyses of short- and long-term increases in arctic snowfall (Pettorelli et al. 2005; Kohler et al. 2006). Changes in birch phenology were smaller with leaf cover occurring 1.6 weeks earlier for the period. Effectively, these findings signal a decrease in the length of the winter season and a subsequent increase in the length of the growing season, in arctic regions of Northern Sweden.

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