LIFE Project Number

ENV/FIN/000133

Progress report on extracted features (2001-2008)

Reporting Date

31/08/2010

Action

Action 7: Methodological development and implementation

LIFE+ PROJECT NAME or Acronym

SNOWCARBO

Author

Name Beneficiary	Finnish Environment Institute (SYKE)
Contact person	Ms Kristin Böttcher
Postal address	P.O. Box 503, FI-00101 Helsinki, Finland
Telephone	+358-401-876447
Fax:	+358-9-40300690
E-mail	Kristin.Bottcher@ymparisto.fi
Project Website	http://snowcarbo.fmi.fi

Table of contents

List of abbreviations

ASD	Analytical Spectral Devices
FGS	Flux Growing Season
FMI	Finnish Meteorological Institute
MERIS	Medium Resolution Imaging Spectrometer
METLA	Finnish Forest Institute
MODIS	Moderate Resolution Imaging Spectrometer
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
NEE	Net Ecosystem Exchange
RMSE	Root Mean Square Error
SCA	Snow Covered Area
SYKE	Finnish Environment Institute
WDRVI	Wide Dynamic Range Vegetation Index

Summary

This report documents progress on the extraction of carbon-balance related features from time-series of vegetation indices in SnowCarbo action 7.

Time-series of NDVI, NDWI and SCA from different land cover classes (coniferous forest, open bogs and deciduous forest) are examined for the extraction of spring phenological events, such as the start of photosynthetic activity, start of height growth of pine and bud burst of birch.

Methods for determination of these events from satellite data are described and satellite-derived spring phenological events are compared with *in situ* data.

Introduction and objectives

Time-series of vegetation index data, mostly the Normalized Difference Vegetation Index (NDVI), have been widely used for the extraction of phenological key-stages of vegetation, such as onset of greening. Many different methods were applied for the determination of phenological events and only few examples will be given here. Some authors used thresholds values based on yearly NDVI amplitude (White *et al.*, 1997; Badeck *et al.*, 2004; White and Nemani, 2006) for the detection of onset of greenness. In other works, double logistic functions were fitted on the temporal course of NDVI to describe seasonal behaviour of vegetation and the ascending and descending inflection points were used to extract phenophases [e.g. Fischer (1994) for agricultural crops and Soudani *et al.* (2008) for deciduous stands, both in France].
Good correspondence was obtained between satellite-derived bud burst day and field observations of bud burst of deciduous trees for the temperate region when using the midpoint of the NDVI-amplitude (Duchemin *et al.*, 1999; Badeck *et al.*, 2004) or the inflection point of a double logistic function (Soudani *et al.*, 2008).
For the boreal region, it was found that satellite derived beginning of cycle, based on NDVI, corresponds rather to the date of snow melt than to the beginning of greening-up (e.g. Moulin et al. (1997). Also Delbart et al. (2005) reported that snow melt and real green-up can not be well distinguished in NDVI temporal profiles in northern latitudes. Therefore, they developed a method for the extraction of onset of greening based on the Normalized Difference Water Index (NDWI) and applied the method to SPOT Vegetation data in Siberia. The NDWI-based method showed better results for the detection of start of greening-up than NDVI-based methods.

Another approach was used by Karlsen et al. (2008) for the determination of length of growing season in Northern Fennoscandia based on 16-day MODIS-NDVI composites. In order to avoid influences from snow-covered ground, they based a threshold for the detection of onset of greenness on the 7-year mean value for the period from 12 July to 28 August. The method was further combined with decision-rule based mapping. They found good correspondence between satellite-derived onset of season and observed bud burst of birch. Regarding the end of the growing season correlations between observation of yellowing of birches and satellite-derived end of season were low (<0.45) for 6 out of 12 stations.

In contrast to deciduous trees, seasonal changes in conifers are not easily observed. Photosynthesis is inhabited in winter, but close-to-full photosynthetic capacity can be reached after few days with optimal environmental conditions and is mainly driven by air temperatures (Suni *et al.*, 2003).
Richardson et al. (2009) compared four spring onset phenological indicators with surface-atmosphere CO_2 exchange data for conifer-dominated Howland forest and deciduous-dominated Harvard forest belonging to AmeriFlux network. At the coniferous Howland forest, the ecosystem switches from source to sink before bud burst occurs indicating the independence of spring recovery from changes in canopy structure, whereas in the deciduous Harvard forest the source-sink transition takes place several weeks after bud burst.

Very recently, Jönsson et al. examined the possibility to monitor seasonal changes in coniferous forest in Sweden by time-series of MODIS eight-day vegetation composites in comparison with temperature dependent phenology measures (length of snow season, modelled onset of vegetation period, tree cold hardiness level and timing of bud burst). The relationship between those measures and two vegetation indices (NDVI and Wide Dynamic

Range Vegetation Index; WDRVI) were analysed. Both, NDVI and WDRVI temporal profiles were to a large amount defined by the occurrence of snow. They concluded that thresholds, which are commonly used for the extraction of phenological stages, were not applicable for Swedish coniferous forest.

The aim of action 7 is the extraction of carbon-balance-related indicative features from vegetation index time-series, which include i) date of the beginning of growing season; ii) date of seasonal vegetation peak and ii) date of end of seasonal vegetation growth.

In this deliverable, we focus on the extraction of spring phenological events.
The start of the growing season can be defined in different ways. Based on discussions between SnowCarbo action 4, 6 and 7, the time when photosynthetic activity begins in the ecosystem is the most relevant date regarding the modelling work. Therefore, the start of photosynthetic activity, as determined from CO_2 flux measurement, will serve as reference value. For coniferous forests also the later stage, when new shoots actually start to grow will be examined.
For deciduous forest only observations of bud burst are available and will be used as reference value for the start of season.

Data sets used will be shortly described in the next section. In chapter 3, temporal profiles of NDVI, NDWI and SCA for coniferous forest, open bogs and deciduous forest will be compared with the above mentioned *in situ* observations. The methodology for the extraction of spring events will be given in chapter 4, followed by validation with *in situ* measurements.

Data sets

MODIS time-series

MODIS NDVI and SCA time-series used in this report were described in report "1st Document on existing datasets" (SYKE composite products and time series data, p.27).
Filtering and interpolation of NDVI and SCA time series was specified in a previous deliverable of action 7 "Progress report on filtered time series (2001 -2008)".

Filtering and interpolation of the NDVI time-series was further improved by using a pixelwise 'dry snow NDVI', which was derived from spring images in 2010. Missing NDVI values in winter during dry snow conditions were set to this value.

In addition to NDVI, also the NDWI is used for comparison with phenological events. NDWI was first developed by Gao (1996) for monitoring of vegetation liquid water from space. In the original work, Gao used radiance at wavelength 860 nm and 1240 nm for the calculation of NDWI. Both channels are located in the reflectance plateau of vegetation canopies and sense therefore similar depth through vegetation canopies in contrast to NDVI, for which the red channel is located in the strong chlorophyll absorption region.

In spring, NDWI temporal profiles show a decrease during snow melt and an increase when vegetation is greening up, which allows a free of snow-effect detection of start of greening-up (Delbart et al.,2005).

NDWI was calculated using MODIS bands 2 and 6 with the following equation:

$$NDWI = \frac{ch2 - ch6}{ch2 + ch6}.$$

MODIS band 6 is centred at wavelength 1640 nm, where liquid water absorption is stronger than at 1240 nm (Gao, 1996). The same wavelength region was used by Delbart et al. (2005).

Calculation of NDWI and further processing was done by action 3.
Similar to NDVI processing, NDWI data were further composited to daily products by selecting the maximum of the observed NDWI values for each cloud-free pixel.

In situ data

Details on selected *in situ* sites were given in deliverable "Progress report on filtered time series (2001 -2008)". Table 1 from the mentioned report is repeated here.

Table 1. Measurement sites used for time-series analysis.

Site	Observation/ Organisation	Latitude/ Longitude [°]	Vegetation type	Number of pixels NDVI/ SCA*	CLC 2000 class (class number**)	Threshold for LC fraction [%]
Kevo	Phenology/ METLA	69°45' N 27°01' E	broadleaved forest (birch)	24/9	broadleaved forest (17,18)	90
Parkano	Phenology/METLA	62°01' N 23°03' E	coniferous forest (Scots pine)	11/8	coniferous forest (19,20,21)	90
Paljakka	Phenology/METLA	64°40' N 28°03' E	coniferous forest (Scots pine)	65/17	coniferous forest (19,20,21)	100
Äkäslompolo	Phenology/METLA	67°35' N 24°12' E	coniferous forest (Scots pine)	472 / 70	coniferous forest (19,20,21)	100
Saariselkä	Phenology/METLA	68°24' N 27°23' N	coniferous forest (Scots pine)	69/21	coniferous forest (19,20,21)	90
Hyytiälä	CO_2 flux/ University of Helsinki (CARBOEUROPE)	61° 51' N 24°17' E	coniferous forest (Scots pine)	175/23	coniferous forest (19,20,21)	100
Sodankylä	CO_2 flux /FMI	67°21.712'N 26°38.270'E	coniferous forest (Scots pine)	27/9	coniferous forest (19,20,21)	100
Kenttärova	CO_2 flux /FMI	67°59.234'N 24°14.583'E	coniferous forest (Spruce)	19/8	coniferous (19, 20,21)	95
Lompolojänkkä	CO_2 flux /FMI	67°59.832'N 24°12.551'E	Aapa mire	8/-	open peat land (38)	70
Kaamanen	CO_2 flux /FMI	69°08.441'N 27°16.230'E	Aapa mire	30/7	open peat land (38)	70
Jokionen	CO_2 flux /FMI	60°53.956'N 23°30.933'E	Agricultural peat field, managed	11/10	arable land (13)	90

* Pixel size for NDVI 0.0025 degrees and for SCA 0.005 degrees
** Class number according to CORINE Land Cover 2000 Finland

Start and end of the growing season were derived from CO_2 flux measurements according to the method by Suni et al. (2003). As a criterion for the final recovery of photosynthesis, the date when the daytime Net Ecosystem Exchange (NEE) first falls below 20 % of the maximum summer uptake (most negative NEE) is used. The end of growing season was defined in a similar way. The time period is hereafter called growing season and denoted Flux Growing Season (FGS) following Thum et al. (2009).

FGS dates for Sodankylä, Hyytiälä and Kenttärova were taken from Thum et al. (2009). In addition, SnowCarbo action 4 provided FGS dates for Kaamanen and further data for Kenttärova and Sodankylä.

Phenological observations were compiled by Finnish Forest Institute (METLA). Details on the data are given in deliverable "Action 5 – In situ data collection and processing by SYKE". The following phenophases were used in this report (BBCH codes in brackets; Meier (1997)), the date of bud burst (BBCH07), full-sized leaves (BBCH15) of birch (*Betula pubescens)* and beginning of height growth (may-shoot, BBCH30) and end of height growth (BBCH39) of Scots pine (*Pinus sylvestris*).

Information on seasonal evolution of snow cover was obtained from Finnish Meteorological Institute (FMI). Observations include fractional snow cover (e-codes) and snow depth for selected stations (see deliverable "Action 5 – In situ data collection and processing by SYKE" for detailed description).

Comparison of satellite data with *in situ* observations

In this chapter, temporal profiles of NDVI, NDWI and SCA for different land cover classes (coniferous forest, open bogs, deciduous forest) are compared with start of FGS and observed phenophases.

Figure 1 shows temporal profiles of SCA, snow depth, NDVI and NDWI in conjunction with start of FGS at Sodankylä for the time period from February until mid-July 2006. Start of FGS occurred at the time when SCA decreased below 100 %. Snow height was about 30 cm and e-code of 7 was observed at the meteorological station, which means that snow is wet or re-frozen, but covers still 100 % of the terrain. According to e-code observation, snow cover was less than 100 % but more than 50 %, 6 days after the beginning of FGS.
This agrees with findings by Thum et al. (2009). They observed that the start of snow melt, estimated from surface albedo, was a good estimator for the beginning FGS in boreal coniferous forest.
Regarding the evolution of NDVI in spring, NDVI showed a minimum at the time of start of FGS before the actual rise of NDVI. In contrast, NDWI showed maximum values at time of start of FGS and decreased afterwards.

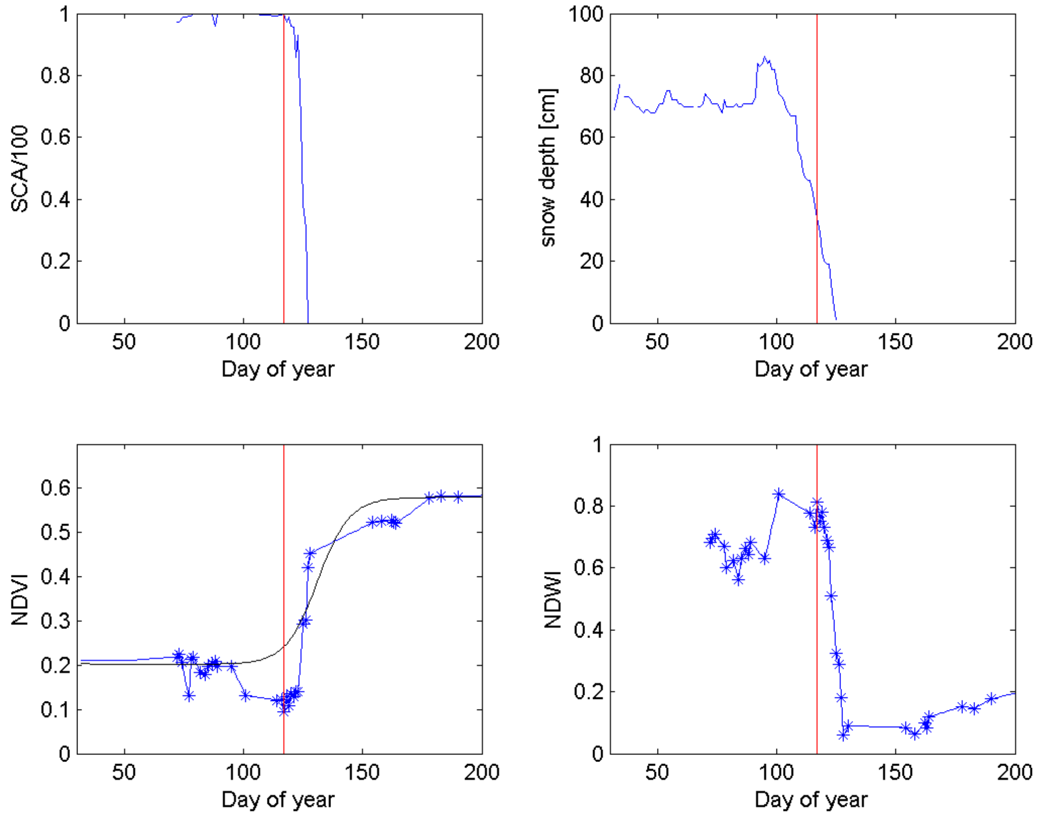

Figure 1. Temporal profiles at Sodankylä 2006 and CO_2 flux measurement derived start of season (red line) (a) SCA; (b) Snow depth measurement; (c) NDVI original values after cloud filtering (blue stars) and fitted logistic function (black line) and (d) NDWI original values after cloud filtering (blue stars).

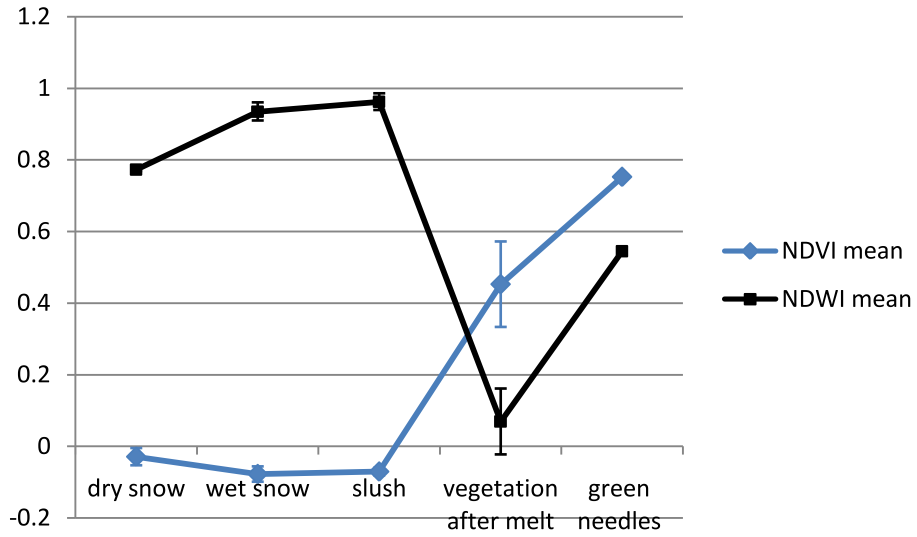

Figure 2. NDVI (blue) and NDWI (black) values for dry snow, wet snow, slush, ground vegetation after snow melt and green needles. Error bars indicate standard deviation for spectral measurements.

For comparison, NDVI and NDWI values of dry snow, wet snow, slush, ground vegetation after snow melt and green needles are shown in Figure 2. NDVI and NDWI were derived from field reflectance measurements with an ASD spectrometer, which were resampled to

MODIS spectral characteristics. Spectral reflectance curves of green needles (needles of Blue Spruce and Pinon Pine) were taken from the spectral library of U.S. Geological Survey (http://speclab.cr.usgs.gov/). Mean values and standard deviation were derived from 8 measurements of dry and wet snow, 2 measurements of slush and 4 measurements of ground vegetation after snow melt.

NDVI shows a slight decrease during snow metamorphoses from dry snow to slush and an increase when vegetation on the ground is snow-free, but not yet green. On the contrary, NDWI increases slightly during snow metamorphoses from dry snow to slush and decreases strongly, when snow has melted. Both indices show an increase when vegetation is actually greening up.

This corresponds to the temporal profiles shown in Figure 1. NDVI increases already when there is still a proportion of the area covered by snow and brown vegetation starts to be visible, whereas NDWI declines until all snow has melted and increases only when vegetation is greening up.

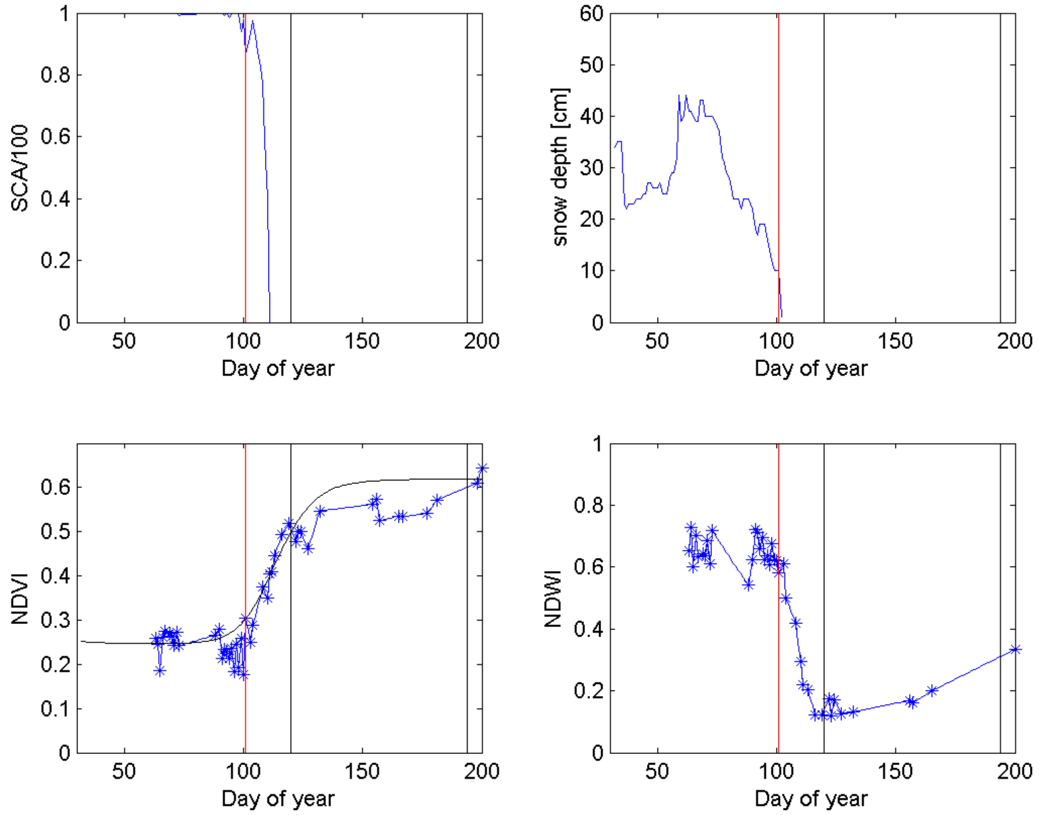

Figure 3. Temporal profiles at Hyytiälä in 2004, CO_2 flux measurement derived start of season (red line) and may-shoot pine (black line) and end of height growth pine (black line) (a) SCA; (b) Snow depth measurement; (c) NDVI original values after cloud filtering (blue stars) and fitted logistic function (black line) and (d) NDWI original values after cloud filtering (blue stars).

Temporal profiles of vegetation indices, SCA and snow depth for station Hyytiälä during spring 2004 are shown in Figure 3. The start date of FGS, as well as phenological events for pine trees are indicated in the temporal profiles. Phenological observations were taken from station Parkano.

Similar to observations in Sodankylä, start of FGS occurred during snow melt, when SCA decreases from full coverage to patchy snow cover. Snow e-codes from station Niinisalo indicate wet snow with coverage between 0 and 50 %. As illustrated in the figure, NDWI had a minimum at time of start of FGS. Start of growth of new shoots occurred later, after snow has melted and NDVI profile has reached more than 50 % of its yearly amplitude.

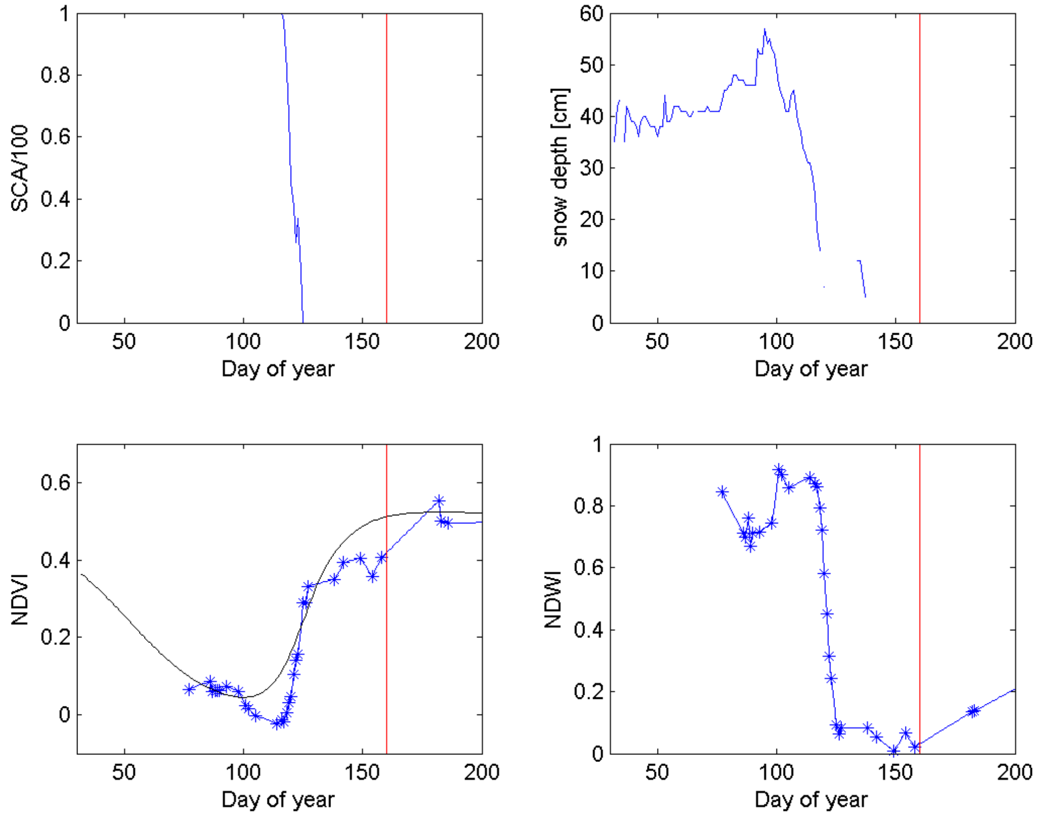

Figure 4. Temporal profiles at Kaamanen 2006, CO_2 flux measurement derived start of season (red line) (a) SCA; (b) Snow depth measurement station Kevo; (c) NDVI original values after cloud filtering (blue stars) and fitted logistic function (black line) and (d) NDWI original values after cloud filtering (blue stars).

In contrast to coniferous forest, the start of FGS occurred after complete snowmelt at the bog site Kaamanen in 2006 (see Figure 4). NDVI reached already about 75 % of its yearly amplitude. The NDWI temporal curve showed minimum values at the beginning of FGS and increased after that.

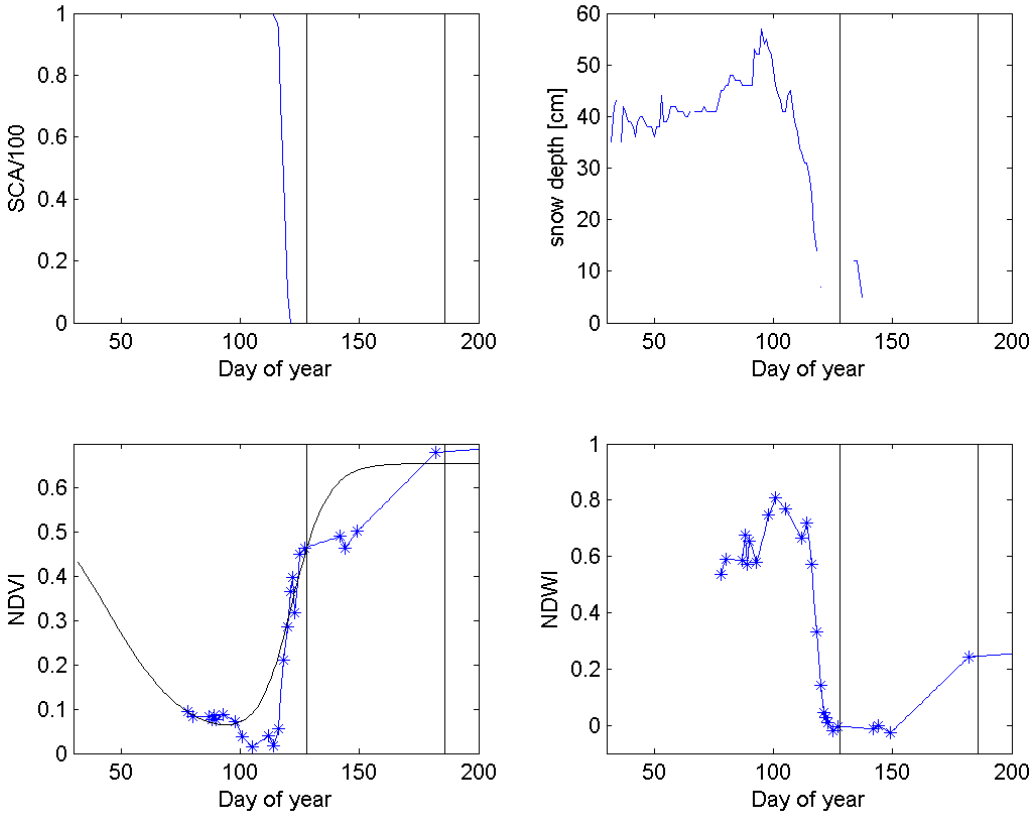

Figure 5. Temporal profiles at Kevo in 2006, day of bud burst and day with maximum size of leaves (black line) (a) SCA; (b) Snow depth measurement station Kevo; (c) NDVI original values after cloud filtering (blue stars) and fitted logistic function (black line) and (d) NDWI original values after cloud filtering (blue stars).

In Figure 5 temporal profiles for deciduous forest in Kevo are compared with observations of bud burst and the maximum size of leaves of birch trees. Bud burst occurred when NDVI profile reached more than 50 % of its yearly amplitude and NDWI had a minimum.

Extraction of phenological events

Methods for the extraction of spring phenological events will be described in this chapter. According to observations made in the previous chapter, different methods have to be applied for the extraction of the start of FGS for coniferous forest and open bogs. Furthermore, the determination of phenophases bud burst in deciduous trees and start of growth in conifers from satellite observations will be shown.

Coniferous forest

Start of FGS for coniferous forest is determined based on time of minimum of NDVI before the strong rise of NDVI in spring. For the determination of NDVI minimum daily interpolated NDVI profiles were smoothed with a Savitzky-Golay filter (Savitzky and Golay, 1964) using a window size of 5 days. The software Timesat (version 2.3) was used for smoothing (Jönsson and Eklundh, 2004).

The algorithm first detects the minimum NDVI and all days when NDVI is lower than the minimum NDVI plus an estimate of the noise level (ε). Afterwards, starting from the last day retained before NDVI reaches half of its amplitude, NDVI values are evaluated for

fluctuations, which may indicate that there is more than one minimum in spring. This was mainly observed for the station Hyytiälä and is probably due to snow melting and new snow fall events in spring.
In case there are no fluctuations in the profile, the time when NDVI has its minimum is retained as start of FGS. In the other case, the last value which fulfils the condition below is retained as start of FGS:

$$t_{start\ FGS} = \max(t \in [0{,}200]) \mid (NDVI(t) < NDVI_{min} + \varepsilon))$$

with t day of the year, $NDVI_{min}$ is minimum of NDVI from day 0 to 200 and ε = 10 % of NDVI amplitude.

The algorithm developed by Delbart et al. (2005) for the detection of the start of greening up based on NDWI time-series is applied for the determination of start of new shoots in pine trees (start of growth pine; SGP). According to Delbart et al. (2005), NDWI minimum in spring corresponds to the vegetation state before greening up. NDWI may show a plateau between snow melt and vegetation greening up.
Since from observations, SGP occurs slightly earlier than the greening up, the algorithm was modified and SGP is determined as follows:

$$t_{SGP} = \min(t \in [0{,}200]) \mid (NDWI(t) < NDWI_{min} + \varepsilon \ ))$$

with $NDWI_{min}$ is minimum NDWI and ε is set to 10 % of NDWI's spring amplitude. Here, the first record, which fulfils the condition, is retained as time of SGP.

Open bogs
According to observations in chapter 3, the method by Delbart et al. (2005) seems to be applicable for the determination of start of FGS for open bogs. That indicates that time of greening up corresponds with start of FGS for the open bog site. Additionaly, start of FGS is determined from NDVI profiles when NDVI reaches 75 % of its yearly amplitude.

Deciduous forest
The method by Delbart et al. (2005) is applied for the extraction of bud burst day in deciduous forest. The method was validated for central Siberia against *in situ* observations of leaf appearance of birch and larch trees.

Validation of satellite-derived phenological events

In this chapter satellite-derived timing of spring phenological events for the years 2001 to 2008 are compared with *in situ* observations.

Coniferous forest
Satellite-derived start of FGS for stations Hyytiälä, Sodankylä and Kenttärova and reference values derived from CO_2 flux measurements are presented in Table 2.

Table 2. Start of growing season for selected CO_2 flux measurement sites in coniferous forest. Start day of FGS was defined from CO_2 flux according to Suni *et al.* (2003) and provided by T. Thum [see Thum et al. (2009)] and M. Aurela. Satellite-derived start dates were derived from time-series of NDVI (see previous section for details).

Site and year	start day FGS	satellite-derived start day
Hyytiälä		
2001	97	96
2002	103	100
2003	108	101
2004	101	97
2005	95	92
2006	104	109
2007	82	83
2008	91	*
Sodankylä		
2001	117	115
2002	113	*
2003	*	105
2004	121	118
2005	118	122
2006	117	119
2007	113	115
2008	119	*
Kenttärova		
2001	ND	119
2002	ND	*
2003	108	106
2004	*	120
2005	130	120
2006	114	119
2007	114	113
2008	107	*

* undefined due to insufficient data, ND no data available

Start of FGS could not be derived for all years from satellite data due to long periods with missing data, mainly due to cloud masking, in spring. An improved cloud masking algorithm is currently examined in action 3, which may increase number of observations. In addition, data gaps due to missing data files will be filled by observation from MERIS.

For validation *in situ* data from Sodankylä (5 years), Kenttärova (4 years) and Hyytiälä (7 years) were used. The satellite-derived start of FGS corresponds well with *in situ* observations (see Figure 6). An R^2 of 0.88 and a Root Mean Square Error (RMSE) of 4.16 days was obtained. Largest difference between observation and satellite estimates (-10 days) was found for the year 2005 in Kenttärova.

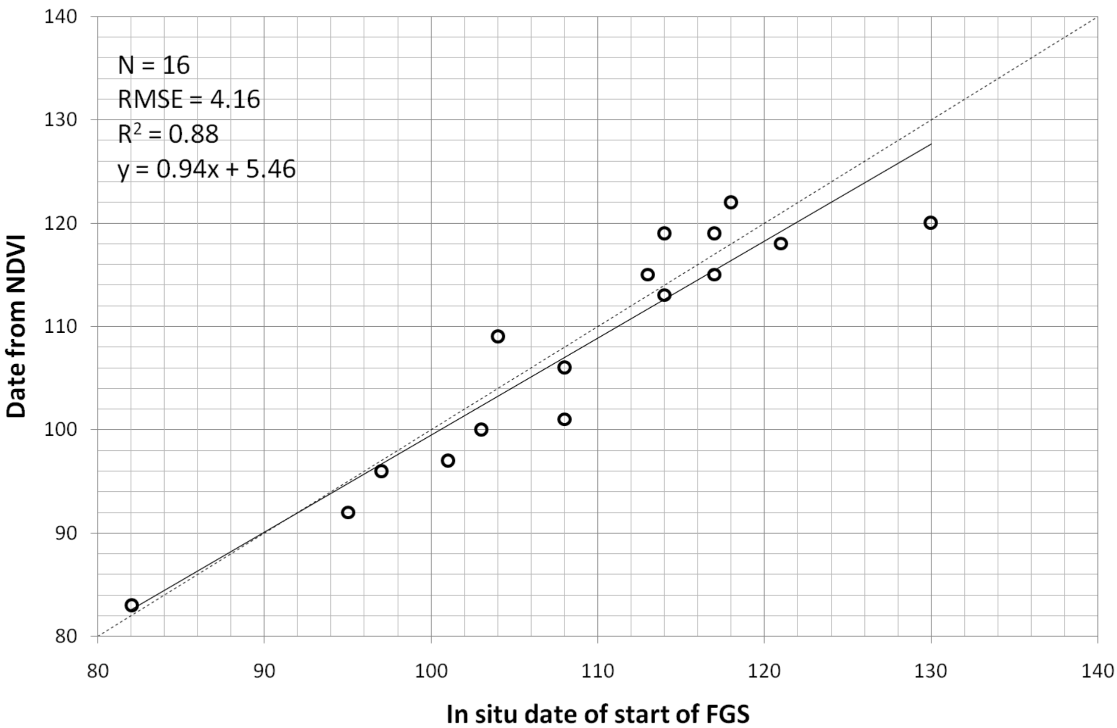

Figure 6. Comparison of *in situ* measurements of start of FGS with estimates derived from time- series of NDVI.

Satellite-derived SPG was compared with *in situ* data from stations Parkano, Paljakka, Äkäslompolo and Saariselkä, representing southern, middle and northern boreal zone. Correspondence for the SPG is lower (R^2 of 0.57 and RMSE of 9.8 days) than for the start of FGS. This may be partly due to larger observation errors for the phenological observations. For example, the result is influenced by one observation point from station Paljakka, which shows very late onset of pine growth in year 2001 (day 155). In comparison, for northern stations Äkäslompolo and Saariselkä the onset of pine growth was observed at the same time (day 158 and 155 respectively). Correspondence improved to R^2 of 0.71 when leaving out this observation (not shown).

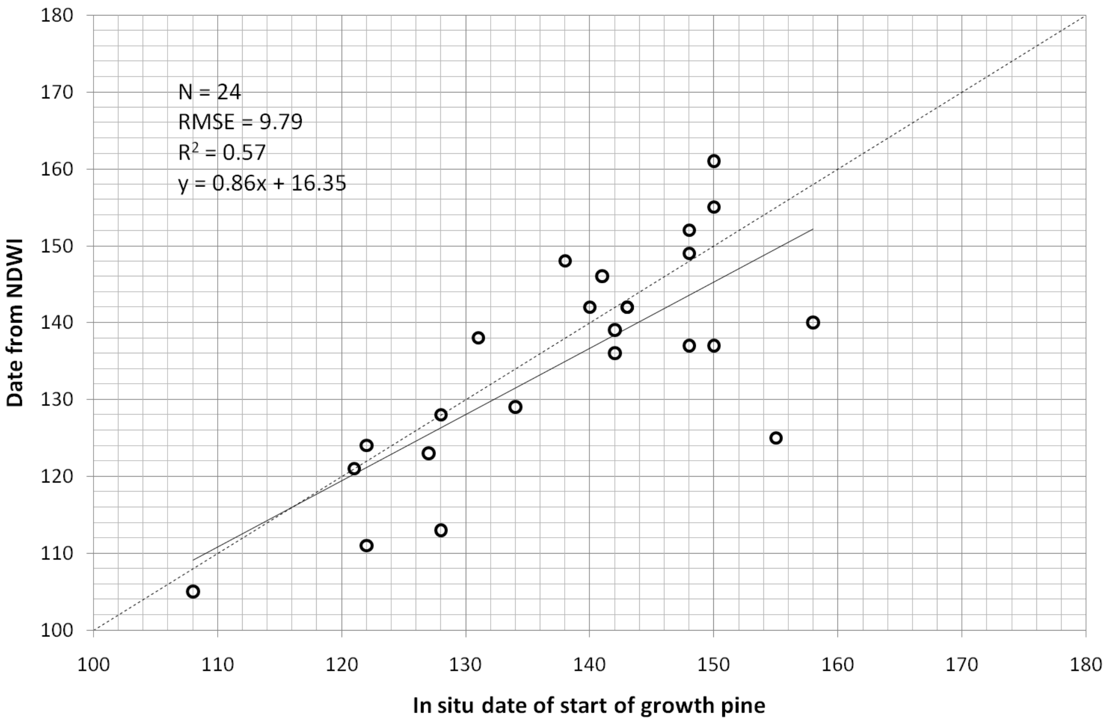

Figure 7. Comparison of *in situ* measurements of start of pine growth with estimates derived from time-series of NDWI.

Open bog

Differences in days between satellite-derived start of FGS and the *in situ* observation for Kaamanen are shown in Figure 8. In general, dates retrieved based on the NDVI threshold show lower deviation from reference date than with the method based on NDWI.

In particular, a large deviation from *in situ* date is obtained for the year 2003. For this year NDWI showed nearly no increase during summer. One reason for larger discrepancy between observation and satellite estimates, compared to coniferous sites, could be a higher heterogeneity of the area seen by the satellite. For the selection of pixels for the Kaamanen site a threshold of 70 % was used (see Table 1). That means that 70 % of each MODIS pixel is classified as open bog according to CORINE Land Cover classification. Therefore, also other land cover types could influence the temporal evolution of NDVI and NDWI. Furthermore, the bog site itself may show higher heterogeneity in its phenological development than a coniferous stand due to different vegetation species and also due to standing water at the surface after snow melt.

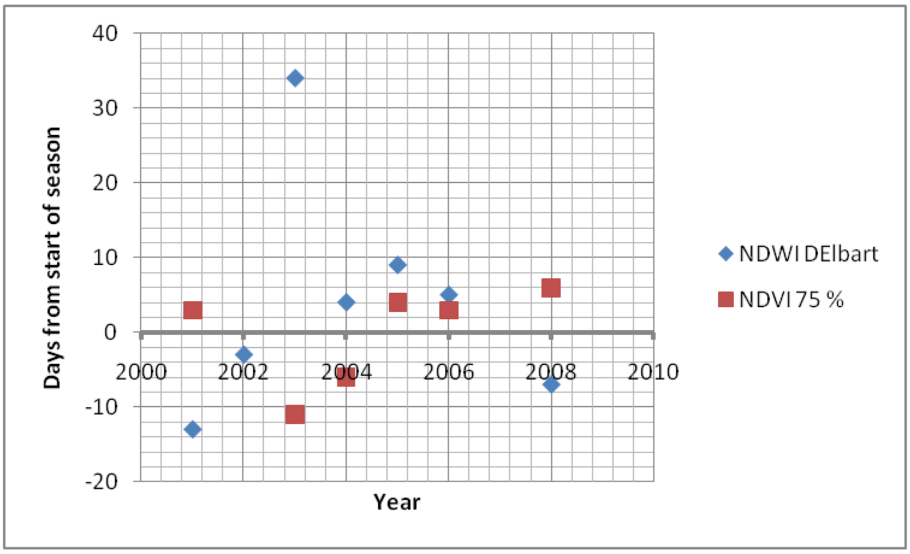

Figure 8. Difference between satellite-derived start of season by different methods compared with *in situ* dates of start of FGS at Kaamanen. NDWI Delbart is start of season derived by the method of Delbart et al. (2005) and NDVI 75 % is start of season derived with a NDVI threshold of 75 %.

Deciduous forest
Satellite-derived time of bud burst was compared with phenological observations from Kevo. Due to missing phenological observations and periods of missing data in the satellite data, comparison was done only for three years. In the work by Delbart et al. (2005), results were validated for 5 test sites in Siberia. They obtained an R^2 of 0.75 and an RMSE of 8.7 and almost no bias (-0.7). In this work, the largest error was +12 days for the year 2003. For the other two years the error was within 5 days.

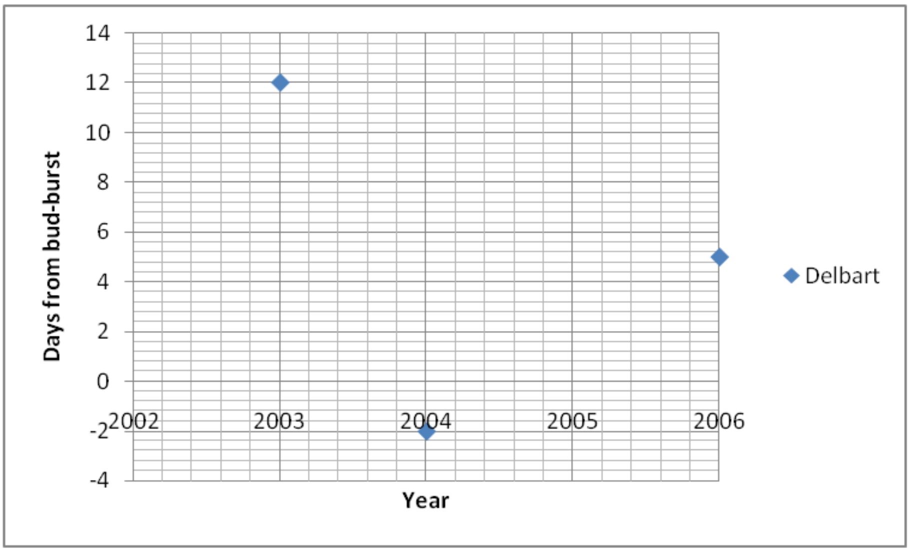

Figure 9. Difference between satellite-derived start of season using method by Delbart et al. (2005) with *in situ* dates of bud burst at Kevo.

Conclusions and outlook

In this report extraction of spring phenological event from time-series of vegetation indices for different land cover classes in the boreal region is described. Start of growing season is defined at the time when photosynthetic activity begins in the ecosystem and reference values for this event were determined from CO_2 flux measurements. Different methods have to be applied for the extraction of the start of season in coniferous forest and open bogs. Photosynthetic activity in coniferous forest starts already during snow melt, whereas in the open bog the start of the season occurs later, after snow has melted.

The start of season (FGS) in coniferous forest was extracted from NDVI time-series and good correspondence between satellite estimates and *in situ* observations was achieved based on two sites in the northern boreal zone and one site in the southern boreal zone.

Lower correspondence was obtained between satellite-derived start of FGS and *in situ* observations for open bogs. Validation is based only on one test site and further investigations are needed.

Furthermore, the start of growth in pine trees was retrieved from NDWI time-series for four test sites in Finland for the years 2001 – 2008 and compared with phenological observations.

Bud burst dates in deciduous forest were extracted from NDWI time-series based on the method developed by Delbart et al. (2005).

Next steps will be the application of algorithms to larger area and the extraction of the maximum and end of growing season from time-series of satellite observations.

References

Badeck, F.-W., Bondeau, A., Böttcher, K., Doktor, D., Lucht, W., Schaber, J., Sitch, S., 2004. Responses of spring phenology to climate change. New Phytologist 162, 295-309.
Delbart, N., Kergoat, L., Le Toan, T., Lhermitte, J., Picard, G., 2005. Determination of phenological dates in boreal regions using normalized difference water index. Remote Sensing of Environment 97, 26-38.
Duchemin, B., Goubier, J., Courrier, G., 1999. Monitoring Phenological Key Stages and Cycle Duration of Temperate Deciduous Forest Ecosystems with NOAA/AVHRR Data. Remote Sensing of Environment 67, 68-82.
Fischer, A., 1994. A model for the seasonal variations of vegetation indices in coarse resolution data and its inversion to extract crop parameters. Remote Sensing of Environment 48, 220-230.
Gao, B.-c., 1996. NDWI-A normalized difference water index for remote sensing of vegetation liquid water from space. Remote Sensing of Environment 58, 257-266.
Jönsson, A.M., Eklundh, L., Hellström, M., Bärring, L., Jönsson, P., Annual changes in MODIS vegetation indices of Swedish coniferous forests in relation to snow dynamics and tree phenology. Remote Sensing of Environment In Press, Corrected Proof.
Jönsson, P., Eklundh, L., 2004. TIMESAT-a program for analyzing time-series of satellite sensor data. Computers & Geosciences 30, 833-845.
Karlsen, S.R., Tolvanen, A., Kubin, E., Poikolainen, J., Høgda, K.A., Johansen, B., Danks, F.S., Aspholm, P., Wielgolaski, F.E., Makarova, O., 2008. MODIS-NDVI-based mapping of the length of the growing season in northern Fennoscandia. International Journal of Applied Earth Observation and Geoinformation 10, 253-266.
Meier, U. (Ed), 1997. BBCH-Monograph. Growth stages of mono- and dicotyledonous plants. Blackwell, Berlin.
Moulin, S., Kergoat, L., Viovy, N., Dedieu, G., 1997. Global-scale assessment of vegetation phenology using NOAA/AVHRR satellite measurements. Journal of Climate 10, 1154-1155.
Richardson, A.D., Hollinger, D.Y., Dail, D.B., Lee, J.T., Munger, J.W., O'keefe, J., 2009. Influence of spring phenology on seasonal and annual carbon balance in two contrasting New England forests. Tree Physiol 29, 321-331.
Savitzky, A., Golay, M.J.E., 1964. Smoothing and differentiation of data by simplified least squares procedures. Analytical Chemistry 36, 1627-1639.
Soudani, K., le Maire, G., Dufrêne, E., François, C., Delpierre, N., Ulrich, E., Cecchini, S., 2008. Evaluation of the onset of green-up in temperate deciduous broadleaf forests derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data. Remote Sensing of Environment 112, 2643-2655.
Suni, T., Berninger, F., Vesala, T., Markkanen, T., Hari, P., Mäkelä, A., Ilvesniemi, H., Hänninen, H., Nikinmaa, E., Huttula, T., Laurila, T., Aurela, M., Grelle, A., Lindroth, A., Arneth, A., Shibistova, O., Lloyd, J., 2003. Air temperature triggers the recovery of evergreen boreal forest photosynthesis in spring. Global Change Biology 9, 1410-1426.
Thum, T., Aalto, T., Laurila, T., Aurela, M., Hatakka, J., Lindroth, A., Vesala, T., 2009. Spring initiation and autumn cessation of boreal coniferous forest CO_2 exchange assessed by meteorological and biological variables. Tellus B 61, 701-717.
White, M.A., Nemani, R.R., 2006. Real-time monitoring and short-term forecasting of land surface phenology. Remote Sensing of Environment 104, 43-49.

White, M.A., Thornton, P.E., Running, S.W., 1997. A Continental Phenology Model for Monitoring Vegetation Responses to Interannual Climatic Variability. Global Biogeochem. Cycles 11, 217-234.