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Comparison of vegetation indices to determine their accuracy in predicting spring phenology of Swedish ecosystems

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Abstract

Phenological observations of terrestrial ecosystems are useful in monitoring the changes in the local climate due to their relatively long time series and high temporal resolution. However performing field based phenological observations can be a labour intensive and time consuming process. Using satellite-based remotely sensed data can make the process much more efficient. Although the satellites do not measure the plant phenology directly they can be used to observe seasonal changes on a landscape scale and to estimate the dates of a number of phenological events, such as the onset of greenness or the beginning of the leaf senescence. The launch of new Earth observation satellites over the last decade, with improved spatial, temporal and spectral resolutions, presented an opportunity to develop new vegetation indices (VI) which could potentially be suited to the observation of phenological changes.

The present study compares four VIs on how accurately they can be used to estimate the timing of spring phenological events in ecosystems in the north, centre and south of Sweden. The indices under study are the NDVI, WDRVI, EVI2 and NDWI. The reference data comes from tower mounted or hand held instruments which measure the photosynthetically active radiation (PAR). The phenological events being looked at are the onset of the green season (when green vegetation appears in spring either through being exposed from underneath the melting snow or through fresh growth) and the onset of the growing season (when the new vegetation, especially tree leaves, begin to grow).

The results of the study indicate that NDWI is the only index that can estimate the onset of the leaf growing season in deciduous forests both in the north and south of Sweden. The other indices are only able to predict the start of the green season in this type of ecosystem. In coniferous forests EVI2 seems to be the most appropriate index to use to estimate the start of the growing season. In low vegetation ecosystems the findings are more inconclusive but it appears that EVI2 also performs the best in estimating the start of the green season. The study also found that it is necessary to use under-the-canopy upward pointing PAR sensors to observe the start of the leaf growing season in deciduous forests and over-the-canopy downward pointing PAR sensors to observe the start of the growing season in coniferous forests.

Keywords: Geography, Physical Geography, Phenology, Remote Sensing, Vegetation Indices, NDWI, EVI2, MODIS, TIMESAT.

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Contents

Introduction.....	1
Purpose	1
Theoretical Background	2
Satellite Remote Sensing	2
Phenology	3
FIPAR and FAPAR	4
Vegetation Indices.....	6
Introduction.....	6
NDVI	7
WDRVI.....	7
NDWI.....	8
EVI2.....	8
Data Acquisition and Processing	10
Introduction.....	10
MODIS Data	10
MODIS instrument description	10
Calculating indices from MODIS data	11
Field Data.....	12
Location	12
Instruments.....	14
Calculating indices from field data.....	15
Tower Data.....	15
Locations.....	16
Instruments.....	17
Calculating indices from tower data.....	19
Use of TIMESAT	19
Results	22
Field Sites	22
Dalby 1.....	22
Dalby 2.....	24
Dalby 3.....	26
Tower Sites	28
Abisko Delta Forest.....	28
Stordalen Forest.....	31
Stordalen Mire.....	33
Norunda Forest.....	35
Fajemyr Bog.....	38
Discussion.....	40
Vegetation Indices' performance	40
FIPAR and FAPAR	40
NDVI, WDRVI and EVI2.....	41
NDWI.....	42
Study Limitations and Further Work.....	43
Conclusion	45
References.....	47

Introduction

Satellite based observations of ground ecological conditions have long been recognised by a number of international committees as a useful tool in monitoring spatial and temporal changes of terrestrial ecosystems (Verstraete et al., 1996). The launch of new generation of Earth observations satellites over the last decade, such as Terra and Aqua, Envisat or SPOT, has drastically improved the spatial, temporal and spectral resolutions of the observations. Those improved tools allow the development of new indices to improve the accuracy of predictions of the functioning of ecosystems under future climatic conditions (Delbart et al., 2005).

One area where satellite remote sensing can be particularly useful is in monitoring the phenology of various ecosystems (Ahl et al., 2006). Temporal changes in the phenology of plants can be used as an indicator of the changes in the local climate. This is especially true for spring phenology as previous studies have shown that bud burst and leaf growth are strongly correlated with temperature (Zhang et al., 2004). However, ground observation of phenological changes is a time consuming and labour intensive process. Larger areas could be surveyed quicker with the help of remotely sensed data. The correlation between ground observed and remotely sensed phenological changes has been studied quite extensively in the past (Dimitrov, 2009; Fensholt et al, 2004; Huete et al., 2002; Zhang et al, 2009) but more research can still be done in this field especially since large regional variabilities are present.

Purpose

The purpose of this project is to compare four different vegetation indices to determine which gives the best correlation between the spring greening observed from satellite and from ground observations in a number of locations in north, centre and south of Sweden. The ground reference data comes from tower mounted and hand held instruments measuring surface reflectance and fraction of intercepted or absorbed Photosynthetically Active Radiation (FIPAR and FAPAR respectively) while the satellite data comes from the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument aboard the Terra satellite.

The indices to be compared are the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974), the Wide Dynamic Range Vegetation Index (WDRVI) (Gitelson 2004), the Normalized Difference Water Index (NDWI) (Gao, 1996) and the Enhanced Vegetation Index 2 (EVI2) (Jiang, 2008).

Theoretical Background

Satellite Remote Sensing

Remote sensing involves finding out about physical and chemical properties of an object from a distance. It works by measuring electromagnetic radiation that interacts with an object before reaching the remote sensing instrument.

When electromagnetic radiation, or light, reaches an object it can interact with it in three different ways: it can get absorbed by it, reflected or it or transmitted through it. The same object can interact differently with radiation in different parts of the spectrum, for example it can reflect light with certain frequency while absorbing light with another frequency. The plot of the amount of energy reflected of an object over the electromagnetic spectrum (or part of it) forms the spectral signature of this object. The spectral signatures of a number of objects are shown in Figure 1. Since different objects have different signatures it is possible to distinguish them from each other by looking at the reflectance in one or more spectral bands.

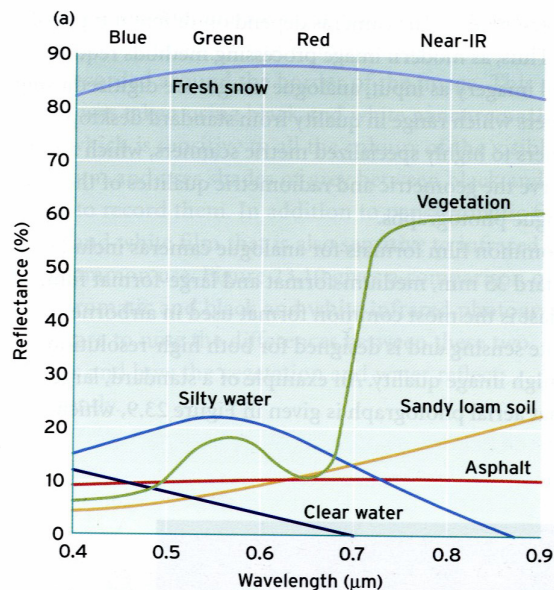


Figure 1 - Spectral signatures of surface objects (James, 2008)

There are two main types of remote sensing: active and passive. In active remote sensing the instrument uses its own energy source to illuminate the object under study. An example of the energy source could be a laser, radar or microwave emitter. Passive remote sensing, on the other hand, uses the Sun's energy for illumination. Satellite remote sensing is almost exclusively performed passively.

Phenology

One particularly useful definition of phenology is provided by Lieth (1976): “phenology is the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species”. This means that phenology is not only concerned with observing the time at which certain cyclic biological events occur but also in understanding and explaining the underlying reasons and drivers of those timings. Phenological observations are usually conducted at small scale of a couple of individual plants or species and look at the timings of actual physical changes occurring to those plants or species, such as the appearance of first buds on trees or the date of flowering.

In natural terrestrial ecosystems one of the main drivers of the phenological changes is the climatic seasonality, which is the annual pattern of rainfall and temperature. In the temperate and boreal climatic regions, in which Sweden is located, the air and ground temperature and associated measures, such as growing degree days, have the biggest influence on the timings of those changes, especially the ones related to the start of spring phenology (Menzel, 2002). This tight relation between the climatic seasonality and the ecosystem phenology together with the high temporal resolution and long time-series of phenological observations makes phenology particularly useful for monitoring the global climate change. A recent large scale study of over 125 000 time-series collected in 21 European countries over 30 years confirmed the conclusions of many previous studies that the observed shifts in the timings of spring phenological events match the measured warming of the climate over the same area and time (Menzel et al., 2006).

One problem with using phenological observations for monitoring the climate change is that the field collection of the observations is a time consuming and labor intensive process. This has led to satellite remote sensing being widely used to observe phenological changes. However due to spatial resolution (between 250 m and 8 km) of the remotely sensed data it is impossible to observe the actual phenological changes occurring on the ground. What is actually being observed is the “land surface phenology” or seasonality which refers to the “seasonal pattern of variation in vegetated land surfaces observed from remote sensing” (Reed et al, 2009). The seasonality observations occur on a landscape scale (determined by the size of the pixel of the remote sensing product) and aggregate the phenological changes of the plants and species in this landscape together with the seasonal changes in the landscape itself, such as the presence of snow cover. The landscape under study usually represents a homogenous ecosystem and the observations are usually concerned with greening or browning of the landscape as indicated by changes in the vegetation indices.

There are four phenological events which are particularly suitable for detection using remote sensing: the onset of greenness, the timing of the peak of the growing season (maximum greenness), the onset of leaf senescence and the onset of dormancy (Zhang et al., 2003). Although the accuracy of this data is not well defined due to insufficient field validation it has been shown that remotely sensed time series with temporal resolutions of between 6 and 16 days can be used to precisely estimate the terrestrial vegetation phenology (Zhang et al., 2009).

In this report a distinction is made between the beginning of the green season and the beginning of the growing season and this distinction is especially pronounced in deciduous forests. The green season begins when green vegetation starts appearing in spring. This could be caused by evergreen vegetation becoming exposed from underneath the melting snow or by growth of new vegetation. The beginning of the growing season refers to the actual growth of new vegetation in spring and especially to growth of deciduous tree leaves. The two seasons can, but do not have to, begin at the same time. This report compares a number of vegetation indices, calculated using remotely sensed data, in their ability to predict the beginning of the green and growing seasons.

FIPAR and FAPAR

FIPAR and FAPAR are defined as ratios of photosynthetic photon flux density (PPFD), which is the flux density in the visible part of the spectrum, measured above and/or below the canopy. The flux can be incident (downward) from the Sun or reflected (upward) from the ground or the canopy. As such FIPAR and FAPAR are quite suitable for measuring the changes in vegetation density by using the data collected in the field either by sensors mounted on towers and on the ground or by hand held instruments. This makes them suitable to be used as reference data and this is how they are used in this study.

FIPAR measures the fraction of PPFD that is intercepted (absorbed or reflected) by the canopy on the way to the ground. Therefore an increase in FIPAR can be indicative of the leaf growing season since the more leaves there are (and the larger they are) the more PPFD gets intercepted by the canopy. It is calculated using the incident PPFD above the canopy (I_a) and the PPFD that reaches the ground below the canopy (I_b) as follows (Gower et al., 1999):

$$FIPAR = 1 - \frac{I_b}{I_a} \quad [1]$$

Measuring I_a and I_b can be quite easily done using hand held instruments, especially in high vegetation. I_a can be obtained by measuring PPFD just outside of the forest, while I_b can be calculated by taking a number of PPFD measurements from different points inside the forest and averaging them. It is also possible to measure those two

values by having a sensor on a tower above the canopy and a sensor on the ground, under the canopy and close to the base of the tower.

FAPAR measures the fraction of PPFD that is actually absorbed by the canopy vegetation for use in photosynthesis. This is slightly different from the value measured by FIPAR since it also takes into account the photosynthetically active radiation (PAR) reflected either from the canopy or in sparse canopy cover from the ground/understory. This makes it a bit more difficult to measure in forests using hand held instruments as it is hard to get the PAR reflectance reading above the canopy. FAPAR is calculated as follows (Gower et al., 1999):

$$FAPAR_{canopy} = \frac{(I_a - R_a) - (I_b - R_b)}{I_a} \quad [2]$$

where I_a and I_b are the same as in FIPAR equation and R_a and R_b are the values of the reflected PPFD from the canopy and ground/understory respectively. Similarly to FIPAR, this FAPAR equation can be used to monitor the beginning and progress of the leaf growing season.

The above FAPAR equation, however, is not very useful when trying to compare satellite derived data with ground collected data to monitor the greening trends of the whole ecosystem, especially in forests with open canopy and rich understory vegetation. This is because it excludes the absorption of PAR by the understory or the ground. The PAR absorbed by the whole ecosystem can be calculated as follows (Olofsson & Eklundh, 2007):

$$FAPAR_{ecosystem} = 1 - \frac{R_a}{I_a} \quad [3]$$

where R_a and I_a are defined like in the previous equations. This equation can also be used to calculate FAPAR for ecosystems where the overhead canopy does not exist, for example grasslands or croplands. Because the R_a value contains the information about the PPFD reflected from the whole ecosystem below the tower it is sensitive to snow covering the ground and the greenness of the understory.

In this study the ground data is analysed using either FIPAR and/or $FAPAR_{ecosystem}$ equations, depending on its source and availability. The choice of FIPAR over the $FAPAR_{canopy}$ equation to monitor the leaf growing season does not impact the result strongly as the difference in readings between them is about 1-2% in Nordic forests (Olofsson & Eklundh, 2007). The $FAPAR_{ecosystem}$ equation is used to monitor the green season. The absolute values of FIPAR or FAPAR for each site are not as important as the relative temporal changes of those values which are indicative of the spring phenological events.

Vegetation Indices

Introduction

Vegetation Indices (VI) are measures of vegetation “greenness” obtained through combining the results of measurements of surface reflectance of the vegetation canopy in different spectral bands. They work based on the principle that vegetation reflects different amounts of electromagnetic radiation in different spectral bands. The amount of reflection also depends on the state, or “greenness” of the vegetation as shown in Figure 2. These two factors are the reason why it is possible to combine vegetation surface reflectance from two or more spectral bands, usually using a ratio or similar mathematical equation, to obtain an index indicating the state of this vegetation.

Healthy vegetation shows strong absorption in the blue and red spectral bands, as the electromagnetic energy from those two bands is used during photosynthesis. In the near infra-red (NIR) part of the spectrum there is strong reflectance due to the physical cell structure of the leaves. In the short wave infra-red (SWIR) part of the spectrum there are a couple of bands showing strong absorption. Those are the water absorption bands and they are caused by the moisture content of the vegetation.

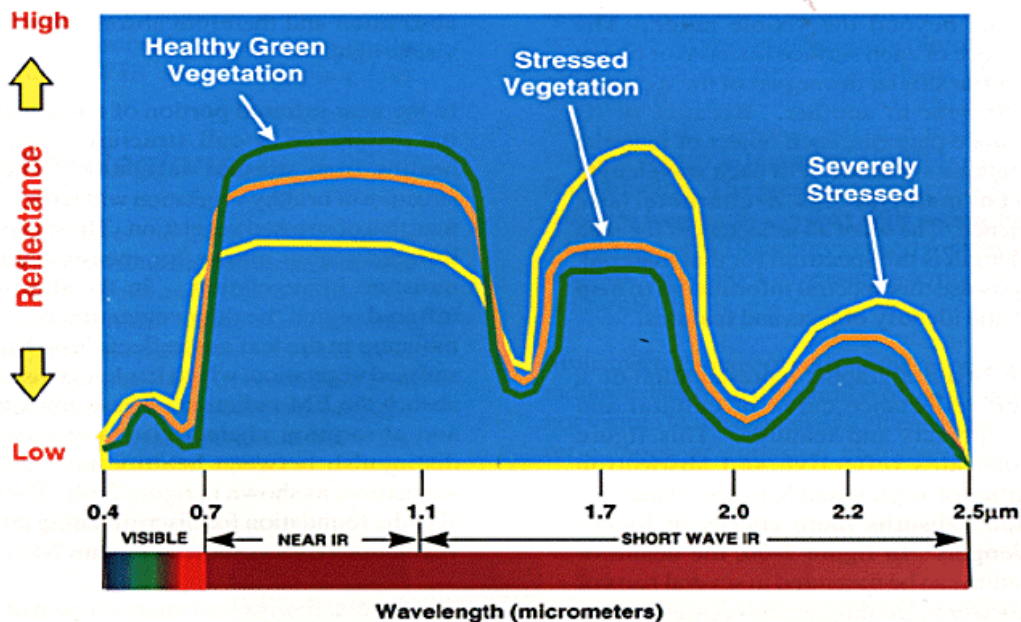


Figure 2 - Spectral Reflectance of Vegetation (NOAA, 2010)

The indices are not indicative of one particular physical property of the vegetation but represent a combination of a number of properties such as leaf chlorophyll content, canopy cover and architecture or leaf area (Jiang et al., 2008). However, they can be used as proxies for ecosystem physical properties, such as leaf area index (LAI) or

fraction of absorbed photosynthetically active radiation, which are affected by the seasonal phenological changes.

NDVI

NDVI is probably the most widely used and one of the oldest vegetation indices. It is based on the surface reflectance in two spectral bands: red (R) and near infra-red (NIR) (Rouse et al. 1974). Those two bands are used because green vegetation shows strong absorption in the red part of the spectrum (reflectance of around 3-5%) and weak absorption in the NIR part (reflectance around 40 - 60%) (Gitelson, 2004). The index value is calculated by getting a ratio of the reflected radiation in those two spectral bands in the following way:

$$NDVI = \frac{NIR - R}{NIR + R} \quad [4]$$

NDVI produces values of between -1 and 1. The negative values indicate the presence of water bodies, such as oceans, rivers, lakes and snow. Small positive values indicate bare ground with little or no green vegetation while values approaching 1 are a sign of lush green vegetation.

Although NDVI is very widely used it does have a number of problems. Firstly, the value of NDVI for vegetations with similar biophysical properties can be different depending on the soil background brightness (Huete et al., 1985). Secondly, NDVI is sensitive to atmospheric effects caused by scattering and absorption by aerosols, especially in the red band as shorter wavelengths are more sensitive to aerosols (Kaufman & Tanre, 1992). Lastly, NDVI has a limitation when it comes to determining the greenness of lush vegetation with medium to high LAI. This is because at higher LAI values NDVI saturates and the almost linear relationship between NDVI and LAI no longer holds (Gitelson, 2004).

A number of vegetation indices were introduced over the years to overcome those, and other, limitations of NDVI and to take advantage of increasing spectral resolution and range of the modern Earth observing satellites. Three of them, looked at in this study, are described below.

WDRVI

As mentioned before, NDVI is not very suitable for monitoring ecosystems with high LAI values. At LAI values above 2 the reflectance of red spectral band saturates and shows a flat response, while the reflectance in the NIR band continues to change as LAI increases. However this response of NIR has almost no effect on NDVI at higher LAI values. The Wide Dynamic Range Vegetation Index (WDRVI) developed by Gitelson (2004) tries to overcome those limitations by setting a weight coefficient on the NIR reflectance in the NDVI formulae to make it look like this:

$$NDVI = \frac{a * NIR - R}{a * NIR + R} \quad [5]$$

where $a < 1$ and is usually between 0.02 and 0.5.

The advantage of WDRVI over NDVI has been demonstrated in a study which used the MODIS 250 metre resolution data to estimate the vegetation density in crop lands (Gitleson et. al., 2007).

NDWI

Another vegetation index that might be of use, especially in the high northern latitudes, is the Normalised Difference Water Index (NDWI) introduced by Gao (1996) as a complementary vegetation index to NDVI. It is “*a measure of liquid water molecules in vegetation canopies that interacted with the incoming solar radiation*”. Compared to NDVI it is less sensitive to atmospheric scattering and does not saturate as quickly in high LAI ecosystems. NDWI uses the reflectance of two MODIS bands: one centred around 0.86 μm (NIR - MODIS band 2) and second one centred around 1.24 μm (SWIR - MODIS band 6) in the following form:

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \quad [6]$$

NDWI gives a positive value for green vegetation and negative one for dry vegetation.

Various papers have suggested that NDWI could be useful for determining the phenological dates of greening up and senescence in boreal regions where there is a lot of accumulated snow (Delbart et al., 2005; Delbart et al., 2006; Sekhon, 2010). Delbart et al. (2005) have shown that using NDWI instead of NDVI produces better estimations of the timings of phenological changes in Siberia. They noticed that in this geographical region NDWI experiences two peaks during the year: a bigger one during winter caused by snowfall and a smaller one during summer caused by leaf water content. Therefore the start of the growing season can be detected when NDWI starts increasing after reaching a minimum due to snowmelt induced decrease. The researchers used SPOT satellite data in their study but they suggest that the method could be applied also to MODIS data which has better temporal resolution.

EVI2

Enhanced Vegetation Index (EVI) (Huete et al., 1999) was developed specifically for use as a data product produced by MODIS. In addition to the red and NIR bands, used by NDVI, it also uses the reflectance information from the blue spectral band. This lets it overcome the major problems of NDVI and provide better sensitivity in ecosystems with high LAI while at the same time reducing the influence of soil background brightness and atmospheric scattering and attenuation on the index value.

However, the use of the blue band also limits the applicability of EVI, especially when working with older data. This is because data sets from older satellites, such as the Advanced Very High Resolution Radiometer (AVHRR) which has been observing the Earth since 1981, do not contain blue band information. To allow EVI to be used

also on those datasets Jiang et al. (2008) developed EVI2 – a two band enhanced vegetation index. They used a large number of field test sites to develop an index equation that uses just the red and NIR bands but produces values very similar to EVI:

$$EVI2 = 2.5 \frac{NIR - R}{NIR + 2.4R + 1} \quad [7]$$

EVI2, like EVI and NDVI, produces values ranging from –1 to 1 with negative values representing water bodies and large positive ones representing lush vegetation.

Once they developed the EVI2 equation Jiang et al. (2008) validated it by comparing the index values at global and local scales against EVI. The results indicate that EVI2 produces values within ± 0.02 of EVI over most land cover types and during different seasons, provided that the surface was ice and snow free and there was not too much atmospheric interference.

Data Acquisition and Processing

Introduction

The data for this study comes from three general categories of data sources. The remotely sensed data, used for calculating the vegetation indices, comes from the MODIS instrument aboard the Terra satellite. The ground truth data comes both from manual field measurements, mostly using the TRAC instrument, and from PAR sensors mounted on towers above the canopy and below the canopy in a number of locations in Sweden.

MODIS Data

MODIS instrument description

MODIS is an instrument aboard the Terra and Aqua satellites operated by NASA. Both satellites are placed in sun synchronous near-polar orbits with Terra passing over the equator from south to north at 10:30 a.m. and Aqua passing the equator in the other direction at 1:30 p.m. The orbits are chosen such that the MODIS instrument provides almost daily observation of the entire surface of the Earth (NASA, 2010).

MODIS consists of instruments measuring the surface reflectance in 36 spectral bands covering the visible and infrared parts of the electromagnetic spectrum. In addition the raw data from the instrument is processed into a number of data products ranging from simply atmospherically correcting the bands' reflectance, through providing aggregate values chosen as the best over a certain time period, to calculating vegetation indices or performing land cover classification. Most of the data products come with quality flags indicating the reliability of the given data (USGS, 2010).

In this study two MODIS data products from the Terra satellite were used: MOD09Q1 and MOD09A1, both containing atmospherically corrected surface reflectance (Vermote et al., 1997). MOD09Q1 contains the reflectance from red and NIR bands (bands 1 and 2) at 250 m spatial and 8 day temporal resolutions. MOD09A1 contains reflectance from bands 1 through 7 at 500 meter spatial and 8 day temporal resolutions. Table 1 shows the bandwidth of the bands used in those two products.

The surface spectral reflectance data presented in those two products has been corrected for atmospheric scattering and absorption. The data pixels, at their respective resolutions, are arranged in a rectangular grid pattern in the Sinusoidal projection. The reflectance values given for each pixel are chosen from the values collected over the 8 day period, as the best based on factors such as the viewing angle, cloud cover or aerosol loading. Adjacent pixels might have values selected from a different date during the 8 day period.

In addition to the reflectance data each pixel also contains the quality rating and other auxiliary data.

Table 1 - Selected MODIS spectral bands (NASA, 2010)

Band Number	Bandwidth	Band Name
1	620 - 670	Red
2	841 - 876	NIR
3	459 – 479	Blue
4	545 – 565	Green
5	1230 – 1250	SWIR
6	1628 – 1652	SWIR
7	2105 – 2155	SWIR

Calculating indices from MODIS data

The territory of Sweden is covered by two MODIS tiles: h18v02 covering the north and centre of the country and h18v03 covering the south. Each tile is divided into pixels with their number depending of the spatial resolution of the MODIS product being looked at. The tile and pixel of each tower location or field observation area can be calculated by entering accurate latitude and longitude of each point into an online MODLAND tile calculator (MODLAND, 2005).

Each field site was chosen such that it contained at least a 500 metre by 500 metre area of a homogenous ecosystem type. Although the position of tower sites was outside the control of this study they were also mostly placed in larger homogenous ecosystem areas. This means that that each area was covered by at least 2x2 250 metre resolution MODIS pixels (the spatial resolution of the MOD09Q1 product). This made it possible to choose from a number of schemes for calculating the value of the pixel in which the tower or centre of the field site was located. Previous studies using MODIS tiles have found that there is minimal difference in using the median or mean values of the pixels covering the area or just the value of the centre pixel (Ahl et al., 2006). Therefore, for simplicity only the value of the centre pixel was used in this study. The same approach was used when selecting the 500 by 500 metre, MOD09AQ1 product pixel.

Once the relevant MODIS pixels were located, the time-series of their reflectance and quality data spanning the period under study was extracted using a Matlab script. The reflectance data was used to calculate the vegetation indices time-series. NDVI, WDRVI and EVI2 only require the red and NIR reflectance values so they were calculated using the MOD09Q1 data at a spatial resolution of 250 metres. The NDWI requires the SWIR reflectance value and so was calculated using the MOD09A1 data with 500 metre resolution.

The quality data was used to assign a weight to each point in the time-series for use in the TIMESAT curve fitting (see chapter below). The quality of each point was calculated as the minimum of the qualities of each of the bands required to calculate a given vegetation index and the state of cloud cover, with full cloud cover being considered as minimum and clear skies as maximum. Although the MOD09Q1 product officially contains cloud cover information in reality it is not reliable (personal communication, Margareta Hellström). Therefore the MOD09A1 cloud information had to be up sampled to the 250 metre resolution.

Once the time-series of the vegetation indices and quality values for each MODIS pixel were calculated the data was imported into TIMESAT for curve fitting.

Field Data

Location

The field data collection sites were located in Scania (Skåne) in the south of Sweden. Scania lies in the temperate climatic zone, in the summer-green deciduous forest (nemoral) region. In the middle of winter the average temperature is around 0 °C and in the middle of summer it is around 16 °C with the average annual temperature of 7 °C. The average precipitation is around 660 mm/year (Barring et al., 2003).

There were three field sites in Scania which were visited at regular intervals, every 10 days on average, throughout the spring and summer of 2010 to take field FIPAR and FAPAR measurements. The sites are all located near the township of Dalby and coordinates of the centre of each site are indicated in Table 2 with the aerial photo location indicated in Figure 3.

Table 2 – Locations of the field observation sites. The MODIS rows and columns are in the h18v03 MODIS tile.

Site	Lat / Long (WGS 84)	MODIS 250m Row / Column	MODIS 500m Row / Column	Ecosystem type
Dalby 1	55.67414/13.33302	2075.91/3608.37	1037.71/1803.93	Deciduous mixed forest
Dalby 2	55.67945/13.33387	2073.36/3608.11	1036.43/1803.80	Semi-natural grassland
Dalby 3	55.67951/13.37319	2073.34/3618.74	1036.42/1809.12	Coniferous forest plantation

A number of factors were taken into account when choosing the field sites. Firstly, the field sites all had to represent different ecosystem types to ensure a broad scope of the study. Secondly, the ecosystem type had to remain uniform over an area of at least

500 by 500 metres. This is because the spatial resolution of the main MODIS data products used in this study (MOD09Q1) is 250 metres, although some data from a data product with 500 metre resolution was also used. Therefore, if a MODIS tile is selected, which covers the point in the centre of the site the whole tile should be inside the site. Thirdly, the sites had to be located reasonably close to each other and to Lund for logistical reason, since the main mode of transport to, and between, the sites was a bicycle.



Figure 3 - Field study sites. Each red square encloses an area of approximately 500 by 500 metres.

The Dalby 1 site covers the Dalby Söderskog National Park. It is a small park of 0.36 km², which was established in 1918 and lies at an altitude of 65 metres above the sea level. Before the national park was established the area was used for livestock grazing and for occasional woodcutting. Currently the tree line of the park is dominated by two species: the European Ash (*Fraxinus excelsior*) and Scots Elm (*Ulmus glabra*). Except for a number of 300 year old oak trees the age of the dominant over story trees is about 200 years. The park also contains a rich herb layer that is present throughout the spring and summer (von Oheimb & Brunet, 2007).

Dalby 2 site covers Hästhagen, a nature reserve consisting of a semi-natural grassland. In spring and summer the area is used as an open field pasture for horses and cattle.

The Dalby 3 site is located in the Skryllegården nature reserve. In the middle ages the area has been used for grazing and agriculture and was widely deforested. In the second half on 19th century a large scale planting of spruce began. This continued until quite recently when a decision was taken to replace any areas thrown down by storms by a more natural deciduous forest (Skryllegarden, 2010). However, the area

where the study was conducted was covered entirely by mature Norway Spruce (*Picea abies*)

Instruments

Two instruments were used to collect the field data: TRAC (Tracing Radiation and Architecture of Canopies) and LAI-2000 Plant Canopy Analyser. Originally it was planned to only use TRAC during the study, since it contains sensors pointing both up and down (which is required for Dalby 2 site) and is light and easy to transport. However, due to prevalence of cloudy conditions LAI-2000 had to be used on a couple of occasions.

Leblanc et al. (2002) describe TRAC design and usage. As illustrated in Figure 4, TRAC is a hand held instrument that consists of three sensors (two pointing up and one down) measuring the photosynthetic flux density (PPFD) hitting the sensors. By using the direct solar beam as a probe and taking the measurements 32 times a second TRAC can be used to measure canopy “gap size” and “gap fraction”. This allows it to estimate the FIPAR of the canopy.



Figure 4 - TRAC instrument (Leblanc et al., 2002)

TRAC should be used on day with no, or minimal, cloud cover since it requires direct solar radiation (Zheng & Moskal, 2009). It should be used along a straight transect 100 to 300 metres long, preferably running in the east – west direction and with the solar azimuth angle being between 30 to 60 degrees at the time of measurement. The operator should move along the transect at a steady speed of around 10 metres per 30 seconds while making sure that the instrument head, containing the sensors, is kept horizontally straight (Leblanc et al., 2002).

During this study the TRAC was used in a manner specified in the above instructions. The three transects through the three field sites were about 150 metres long and running east to west. The measurements were taken on cloudless days between the

hours of 2 p.m. and 4 p.m. (with the time of measurements getting progressively later as the days got longer) to maintain a solar zenith angle of between 45 and 55 degrees. At Dalby 1 and Dalby 3 a measurement was taken outside the forest stands immediately before the measurements inside the stand to provide the “above canopy” PPFDF value. Since the time to take the measurements was quite short (about 15 minutes) and the sun still quite high and not covered by clouds it was possible to obtain sufficiently accurate data without the need to take a second “above canopy” reading after the inside measurements.

Due to the requirement of taking the field measurements at regular intervals it was not always possible to wait for a cloud free day. On those occasions LAI-2000 (LI-COR, 2002) had to be used as it requires a cloudy day to take accurate measurements. LAI-2000 contains a LAI-2050 Optical Sensor which measures the attenuation of diffuse sky radiation.

LAI-2000 measurements were conducted along the same transects as the measurements taken with TRAC with under-the-canopy readings being taken on average every 10 metres. However LAI-2000 is not suitable for taking measurements at Dalby 2 site and so it was not used there. Also due to transportation issues (LAI-2000 is much heavier than TRAC), LAI-2000 measurements were sometimes taken only at Dalby 1 and not at Dalby 3. The time of taking the measurements was not important since they were conducted under light diffused through the clouds. Although ideally the instrument should be used under a uniform and thick cloud cover, that was not always possible and sometimes it had to be used under quick-moving low clouds. In those instances two “above canopy” readings were taken outside the forest stands, one just before and one just after ten “under canopy” readings, to minimise the effect of potentially variable solar radiation.

Calculating indices from field data

It is possible to calculate both FIPAR and $FAPAR_{ecosystem}$ from the measurements taken during the field observations. At the Dalby 1 and Dalby 3 sites, where FIPAR was calculated using equation [1], the I_a and I_b values were taken outside and inside the forests respectively. At the Dalby 2 site $FAPAR_{ecosystem}$ (equation [3]) was used instead and the I_a reading was obtained by using the upward pointing sensor of TRAC, while R_a reading was obtained using the downward pointing sensor which measures the amount of PAR reflected of the grassland.

Tower Data

As most of the tower PAR sensors have been mounted recently and most of the data for this study comes from the spring and summer of 2010 the calibration of values obtained from the sensors is uncertain. As such, the data should be considered as preliminary as it has not passed any quality review. However, it should still be

accurate enough to fulfil the objectives of this study, especially since it is the relative changes of the values over time and not the absolute values that are of interest.

Locations

Some of the ground truth data came from instruments mounted on five towers throughout Sweden, as shown in Figure 5. Three of them are located in the very north of Sweden: in the Abisko Delta forest, Stordalen forest and Stordalen mire. The fourth one is located in the Norunda forest in the middle of Sweden and the last tower is in the Fajemyr bog in the south of the country. The exact coordinates of the towers are shown in Table 3.

Table 3 – Locations of the radiation measurement towers. The MODIS rows and columns are in the h18v02 MODIS tile except for Fajemyr which is in the h18v03 tile.

Site	Lat / Long (WGS 84)	MODIS 250m Row / Column	MODIS 500m Row / Column	Ecosystem type
Abisko	68.36226/18.79567	785.62/3326.22	392.56/1662.86	Birch forest
Stordalen forest	68.34820/19.04980	792.49/3371.56	396.00/1685.53	Birch forest
Stordalen mire	68.35531/19.0472	788.95/3371.77	394.23/1685.63	Mire
Norunda	60.086497/17.479503	4757.98/4183.61	2378.74/2091.55	Pine, spruce forest
Fajemyr	56.265444/13.553514	1792.09/3612.41	895.79/1805.95	Bog

The Abisko and Stordalen sites are both located in the Abisko Valley in the Caledonian Mountains in north-eastern Sweden and lie close to the Abisko weather station. The climate of the valley is characterised as humid cold, close to tundra climate with the mean annual air temperature of -0.8 °C and mean annual precipitation of 299 mm for the period of 1913 – 1987. In July the mean air temperature reaches 11.0 °C while in January it falls down to -11.9 °C (Alexandersson et al, 1991). The areas around both of the forest towers are dominated by mountain birch forests (*Betula pubescens*). In 2004 growing season the Abisko valley experienced a big outbreak of autumnal moth, however by 2006 growing season the vegetation has mostly recovered to the state before the outbreak (Haapanala et al., 2009). The mire site lies on top of a discontinuous permafrost which creates a patchwork of distinct conditions and plant communities. Woody herbaceous plants dominate on top of the drier permafrost areas, the partly thawed, wetter areas are covered by peat mosses (*Sphagnum*) and sedges (*Carex*) while the wettest areas, which fully thaw in summer, are host to Common Cottongrass (*Eriophorum angustifolium*) (Backstrand et al., 2010).

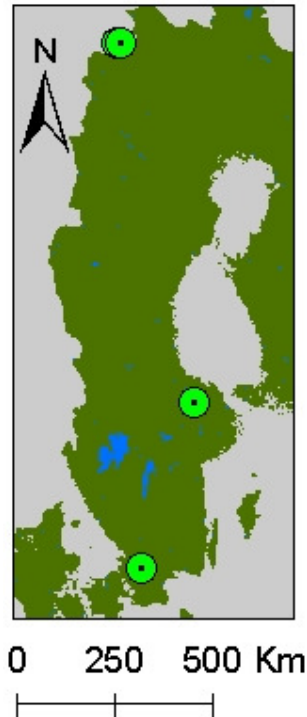


Figure 5 - Tower locations: the northern-most sites are Abisko Delta forest, Stordalen forest and Stordalen mire followed by Norunda forest in the middle of Sweden and Fajemyr bog in the south.

The Norunda tower is located in Uppland in central Sweden. The forest around the tower site is comprised in 65% by Scots Pine (*Pinus sylvestris*), 33% by Norway Spruce (*Picea abies*) with the rest being made up by deciduous trees. The trees are around 100 years old with a height of 24 to 28 metres and LAI of between 4 and 5 (Feigenwinter et al. 2010). The mean annual temperature in the area was 5.1 °C and mean precipitation was 555 mm over the period of 1961 till 1990. During the warmest month the mean temperature reaches 15 °C while in the coldest in falls down to -5 °C (Alexandersson et al., 1991).

Fajemyr tower is located in the north of the Scania province in southern Sweden. The climate in Scania was described in the chapter above, discussing the location of the field work sites. The tower is situated in an ombrotrophic bog (deriving its water and nutrients directly from rainfall) and it is considered that no significant anthropogenic activities have had an impact on the natural functioning of this ecosystem (Schubert et al. 2008).

Instruments

There are two different types of PAR sensors mounted on the towers, the LI-COR produced LI-190SZ (LI-COR, 2010) in Norunda and the SDEC produced JYP 1000 (SDEC, 2010) at all the other sites. The two types of sensors have a very similar spectral response, measuring the radiation in the 400 nanometres to 700 nanometres

wavelength band (i.e. the visible light) although the LI-190SZ is more accurately calibrated to this spectral band. The details of the spectral responses of the two sensors are presented in Figure 6. The differences between the spectral responses of the two sensors should not affect this study, firstly because no direct comparison is made between the different sites, secondly because it is the relative changes in PAR detected over time that are of interest and not the absolute PAR values and thirdly because FIPAR and FAPAR values for each site are calculated as ratios of values obtained from the same sensors types.

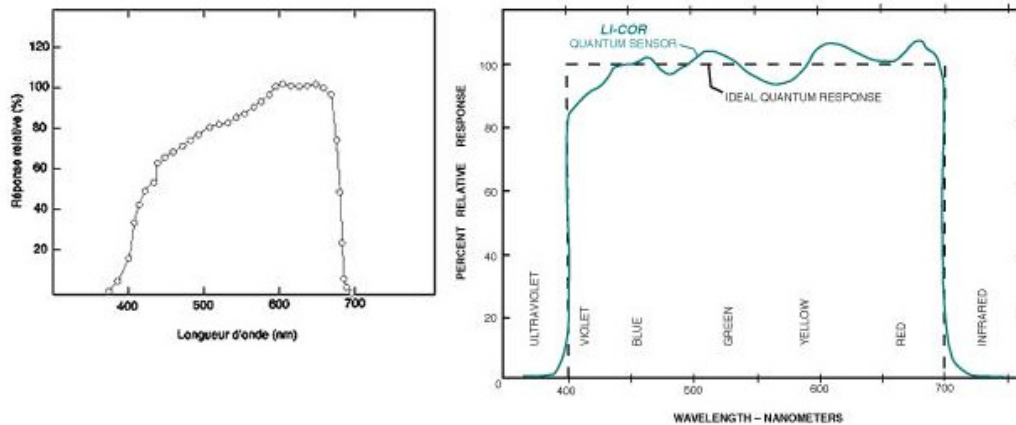


Figure 6 - Spectral response curves of the JYP 1000 (SDEC, 2010) and LI-190SZ (LI-COR, 2010) PAR sensors

All the towers have a PAR sensor pointing up to measure the incident radiation and pointing down to measure the reflected radiation. Abisko Delta forest and Norunda also have sensors on the ground to measure the radiation that got transmitted through the tree canopy. Both LI-190SZ and JYP 1000 sensors claim to have the cosine response corrected up to an 80 degrees angle of incidence. This, together with the height over the canopy or the ground of the downward pointing PAR sensor, determines the area of the ecosystem that can be observed from a particular tower. Table 4 shows the radius of the area of observation of each tower.

Table 4 - The radius of the area of observation of the downward pointing PAR sensor on each tower. The height is given over the canopy for the forest sites and over the ground for other sites (personal communication, Lars Eklundh).

Tower Site	Height of sensor (m)	Radius (m)
Abisko Delta forest	8	45
Stordalen forest	2	11
Stordalen mire	8	45
Norunda forest	70	400
Fajemyr bog	10	57

Calculating indices from tower data

The $FAPAR_{ecosystem}$ equation (equation [3]), described in section “FIPAR and FAPAR”, was used at all the tower sites. Both the incident PAR used as I_a and reflected (outgoing) PAR used as R_a were measured by sensors mounted on the towers above the vegetation canopy. At the Abisko Delta forest and Norunda sites the FIPAR equation was also used with the measurements obtained from the ground based sensor used as I_b .

The PAR sensors take their measurement at regular intervals, usually every 30 minutes. This temporal resolution is too high for the present study as phenological changes occur on timescales of days, not hours. Therefore before any more processing is done the daily incident and reflected PAR values are calculated. This is done by taking an average of the values between 10 am and 2 pm each day. The values centred around noon were specifically selected as this excludes, as much as possible, the PAR measurements taken in low light conditions and which might produce erroneous FIPAR or FAPAR values.

Before the daily PAR values are calculated and after the daily FIPAR or FAPAR values are calculated basic error detection and correction is performed. All the points are examined consecutively and each value that is above or below certain threshold levels is replaced by latest previously encountered good value. The upper threshold level is based on the visual inspection of the data and is usually selected to allow all data to pass unless there are some extreme outliers. The lower threshold level is set to a small negative value in case of PAR, and zero in case of FIPAR or FAPAR as theoretically none of those values should be less than zero. It is mostly used to detect and replace missing values which are represented as large negative numbers in the data series.

Use of TIMESAT

TIMESAT is a software tool for fitting smooth curves to time-series data (Jonsson & Eklundh, 2004). It takes a time-series of values of parameters like NDVI, each with a possible weight value specifying its importance, and fits a smooth curve to the time-series. Once the curve has been fitted TIMESAT can calculate a number of seasonality parameters such as start, amplitude or the length of the growing season. In this study TIMESAT is used to fit curves to the time series of the vegetation indices' values calculated using the data from MODIS and from the towers. No fitting was performed for the field collected data as the number of observations was limited.

TIMESAT gives the option to use one of three algorithms to perform the fitting: Savitzky–Golay filtering, least-squares fits to a polynomial and harmonic basis and least-squares fits to asymmetric Gaussian functions. This study uses the Savitzky-

Golay filtering algorithm for curve fitting as, unlike the other algorithms, it captures a large amount of detail.

The Savitzky-Golay algorithm (Savitzky & Golay, 1964) uses a moving window to smooth the input data. A traditional approach to moving window filtering involves replacing the value of each input series data point by a linear combination of the values of all the points within a window of specified width centred on that point. When this is applied to time series of, for example, NDVI values over a growing season some properties, such as position of the seasonal peak, are preserved while others, such as width and height of the seasonal curve, are changed (Jonsson & Eklundh, 2004). The Savitzky-Golay filter preserves all the important properties by using a least squares fit of the values in the moving window to a polynomial (quadratic in case of TIMESAT) and replacing the value of the input data point by the value of polynomial at that point.

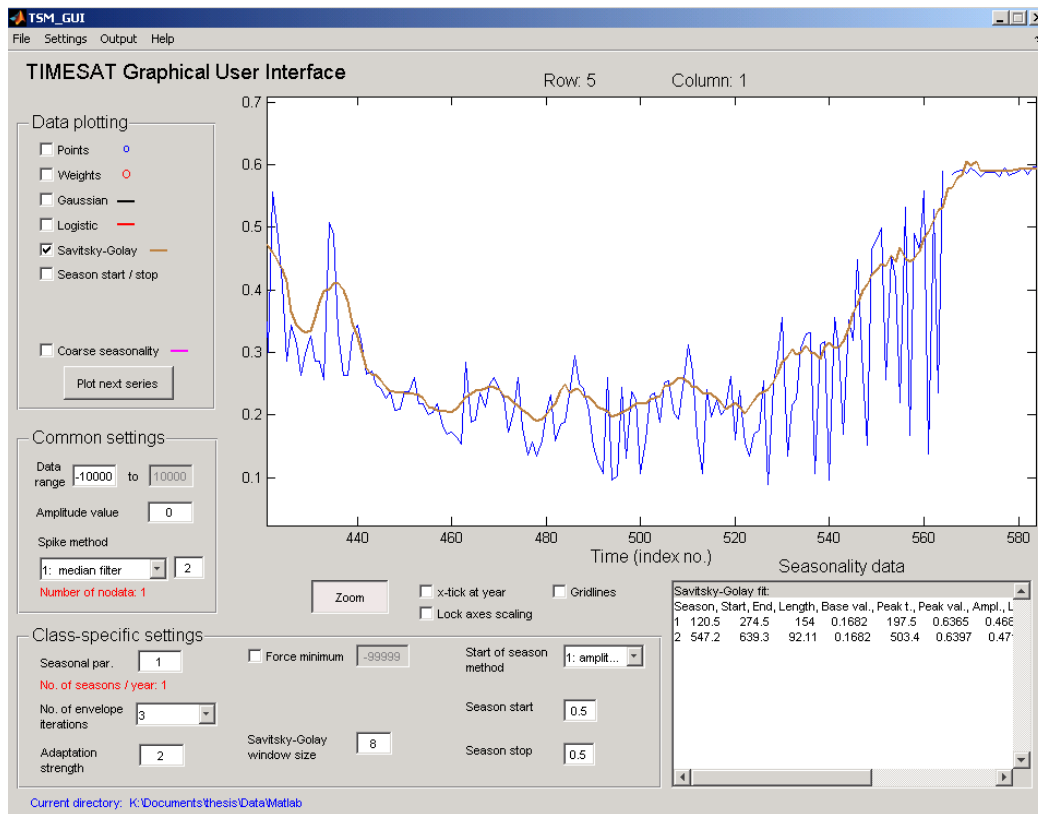


Figure 7 - TIMESAT GUI. The blue line represents the original FIPAR values for the Abisko Delta Forest during the winter and spring of 2010 while the brown line shows the Savitzky-Golay fitted curve.

Figure 7 shows the TIMESAT Graphical User Interface (GUI) which allows the user to select the curve fitting algorithm and set a number of parameters controlling this algorithm and performing basic error filtering. The main part of the GUI is taken up by the graph window showing representation of the original data (the blue line) and

the curve fitted to that data using the selected algorithm (brown line). In Figure 7 the graph window shows the FIPAR data for Abisko Delta forest and the Savitzky-Golay fitted curve and is zoomed in to display the data just for winter and spring of 2010.

TIMESAT puts two basic requirements on the input data series: it must cover a whole number of years and each year must have the same number of data points. The second requirement is already covered by the MODIS data as each full year in the MOD09Q1 and MOD09A1 products consists of exactly 46 points. In case of tower data a full year could consist of either 365 or 366 points (during leap year) so any values from February 29th were discarded if they existed.

The first requirement was not fulfilled by the MODIS data for the year 2010 where only the values up the beginning of July were present. The values after that date were copied over from one of the previous years. For most of the towers only the FIPAR or FAPAR data for the beginning of 2010 was present. The rest of the values were padded with a step function with a high FIPAR or FAPAR values during the growing season and low value in winter. Padding the data with other values does not affect the final analysis as the Savitzky- Golay filtering uses a localised window and the values away from the measured data points do not affect the curve fitting at those points. Also in the graphs presented in the report only the parts of the curves that cover the measurement time period are shown.

Results

Field Sites

Dalby 1

Dalby 1 site was located in a mixed deciduous forest. When the first field reading was taken in Dalby 1, on the 7th of April, there were no buds at all on any tree branches. The first sign of buds appeared during the second visit to the site, a week later, while the first small leaves were observed during the 4th visit, on the 5th of May. From then on the leaf growth proceeded at quite a quick pace with the leaves almost fully developed by the sixth visit, on the 26th of May, especially on the smaller, younger trees (Figure 8). By the eighth visit, on the 17th of June, it appeared that the leaves were fully developed on all the trees. The understory developed much earlier than the tree leaves and by the time the first buds started appearing it was already lush and green.

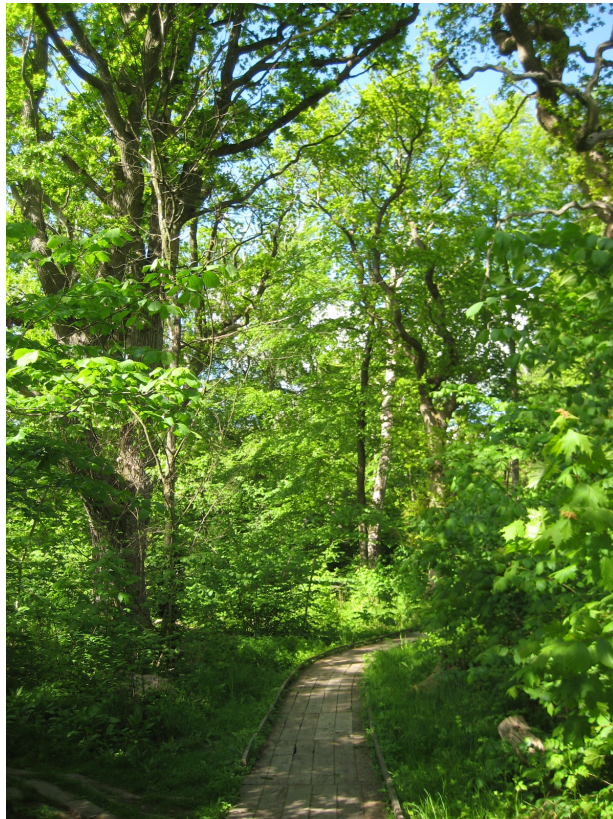


Figure 8 - Dalby 1 site on the 26th of May

The visual observations described above were noted down during each field visit, before the FIPAR values were calculated and plotted. However, this temporal pattern of the leaf growth corresponds quite closely to the temporal pattern produced by the measured FIPAR values (Figure 9). During the first month of measurements, from

early April till early May, during which the buds and small leaves started appearing, the FIPAR value increased by around 0.1 from 0.5 to 0.6. Over the second month, which corresponded to the main leaf growth spurt, FIPAR increased by around 0.3 from 0.6 to 0.9. The FIPAR plateaus on the eighth measurement, just when it was observed that the leaves have reached their full size.

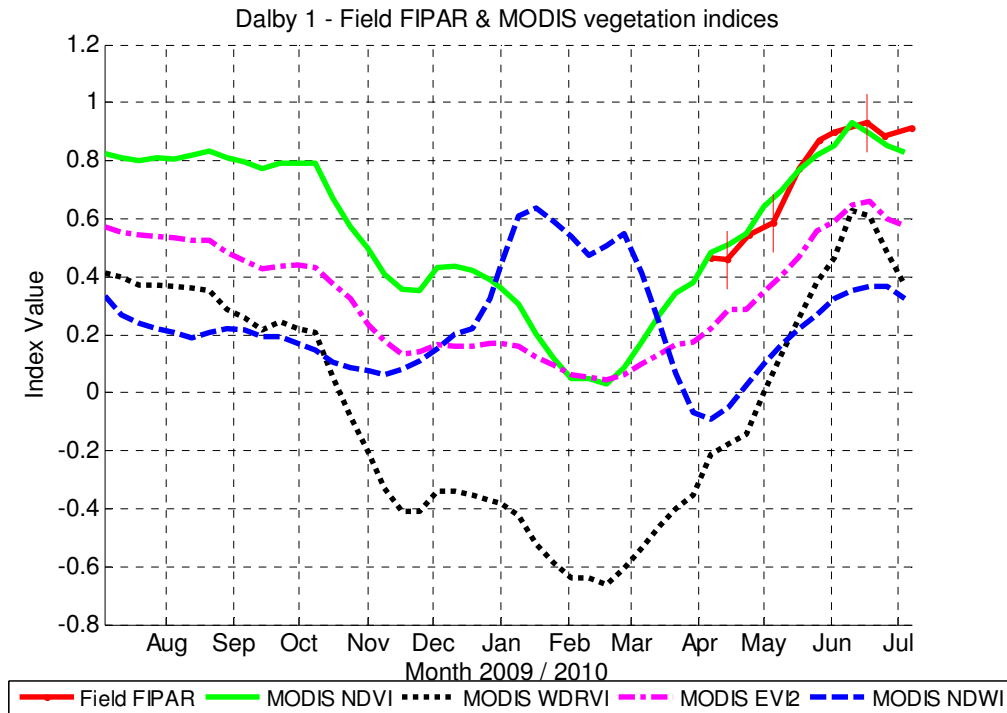


Figure 9 - Dalby 1: vegetation indices. The three red vertical lines indicate, from left to right, the visits during which: the first buds were observed, the first leaves were observed, the full development of leaves was observed.

The MODIS vegetation indices (Figure 9) correspond quite well with both the visual observation and with the measured FIPAR values once the growing season begins. NDVI shows clear linear relationships with FIPAR during the leaf growth period, as expected by theory, and it peaks at the same time. It also shows no saturation at high FIPAR values. Nevertheless, it starts increasing long before the growing season starts. It crosses the 0.2 threshold, which is usually the value of bare ground, at the beginning of March and continues to grow linearly until the beginning of June. The reason for that is that it reflects a combination of three processes: snowmelt, understory growth, and tree leaf development. The initial increase, from February till early March, was caused by the melting snow which fully disappeared at the beginning of March (SMHI, 2010). As soon as the snow melted the understory began to grow and since the MODIS-obtained NDVI measures the reflectance index of the whole ecosystem, including the understory growth, it kept on rising. Finally the tree

canopy started greening up and so NDVI continued growing. Because the three processes follow each other in quick succession it is impossible to estimate from NDVI values the beginning of the tree canopy, or for that matter the understory, growing season.

The other Red-NIR vegetation indices perform similarly, with linear relationships with FIPAR during the beginning of the growing season. However they also suffer from the same problem as NDVI, reflecting the snowmelt and understory development as well as tree leaf growth, making them unsuitable for estimating the start of the growing season.

The NDWI curve begins to decrease in February and continues to go down until the beginning of April. This corresponds quite well to the snow melting period although the decrease of NDWI continues for about a month after the snow is already gone. This could be explained by the drying up of the initially wet soil left after the snowmelt. At the beginning of April the index starts to increase again, which corresponds quite well to the timing in the increase of FIPAR and could be an indication of the start of the growing season.

Dalby 2

Dalby 2 site was located in a semi-natural grassland. According to visual observations there was not much change until the fifth field visit on the 17th of May. Until that time the grass appeared dry, brown and hay like. On that date it was, for the first time, observed that the grass was visibly greener than previously and that it contained a large number of flowers. From then on, until the end of the field measurements, no change in the visual appearance of the grassland was observed (Figure 10).

To better illustrate any temporal changes in FAPAR it was scaled before being shown on the graph with the following equation:

$$FAPAR_s = 10 * (FAPAR_m - 0.9) \quad [8]$$

where $FAPAR_s$ stands for the scaled FAPAR and $FAPAR_m$ is the measured FAPAR value. The measured FAPAR varied between around 0.92 and 0.97.



Figure 10 - Dalby 2 on the 2nd of June

The FAPAR values (Figure 11) do not reflect the observed changes. According to the measurements there was a relatively quick increase in the absorption of PAR radiation from the beginning of April till the very beginning of May. After that the absorption stayed steady until the last measurement where it experienced a sudden drop. It should be remembered that the increase in FAPAR is not as big as it appears on the graph. In reality it changed from 0.92 to 0.96. This small actual change in FAPAR may accentuate any measurement errors and skew the results. Also on two days, the 17th of May and 26th of June, there were no measurements taken at Dalby 2.

The vegetation indices obtained from the MODIS reflectance data (Figure 11) produce varied results when compared to the FAPAR values. NDVI experiences a first peak when according to visual observations the fresh grass has not started growing yet and when FAPAR was just beginning to increase. It then dips slightly just when fresh grass began to grow and FAPAR reaches its plateau before slowly increasing again. Also, it does not show any trace of the sudden drop in FAPAR values recorded during the last field visit. WDRVI and EVI2 produce a very similar pattern to NDVI.

The early increase in NDVI, WDRVI and EVI2, in February and March, once again probably reflects the snowmelt. The continued increase after the snowmelt is harder to explain. It might be possible that early spring grass and flowers began to grow right after the snowmelt but that would be impossible to verify now since no field visits were undertaken during that period. The timing of the first field visit corresponds to the beginning of the dip in the VI values which might mean that the dry, hay like grass observed during the initial couple of visits had actually grown during the spring of 2010 and not the previous year as first thought. The indices begin to rise again just

as the fresh grass begins to grow, according to field observations, indicating that it might be the second green wave of the spring. If the above explanation was true it would mean that the three indices reflect quite well the spring phenology of semi-natural grasslands and although it is not possible to estimate the timing of the first onset of greenness during the spring of 2010 the date of the second onset can be deduced from the graphs.

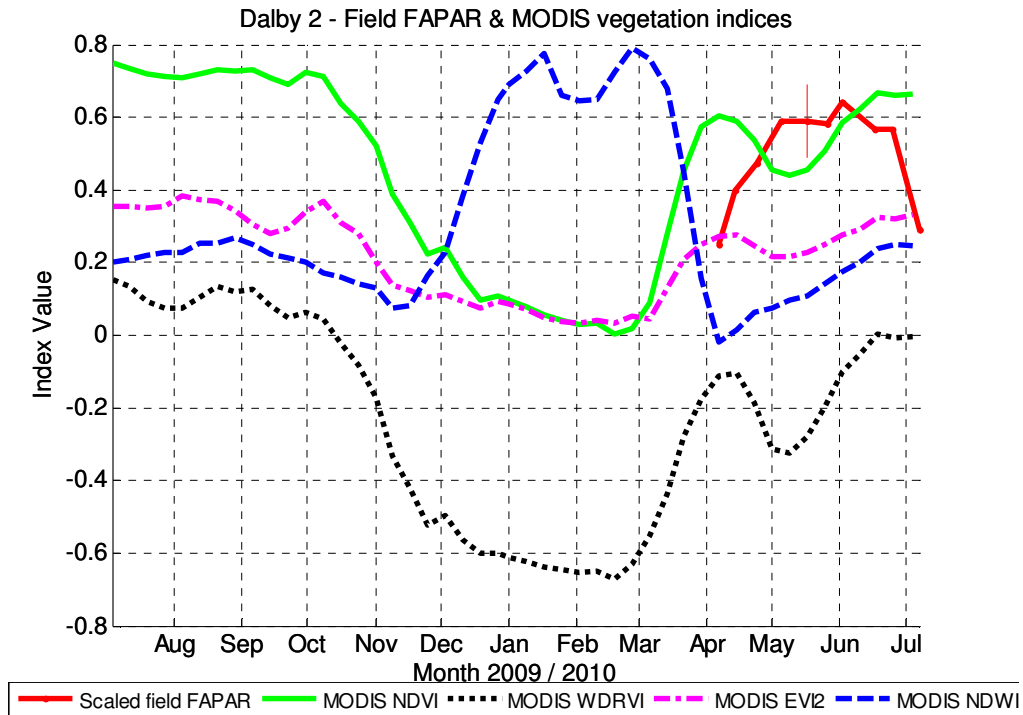


Figure 11 - Dalby 2: vegetation indices. The red vertical line indicates the visit when green grass was first observed.

NDWI shows the timing of snowmelt, although once again it keeps decreasing for quite a long period. It reaches its lowest point at the beginning of April and then shows a steady increase throughout the spring. This could be a sign of growing vegetation although NDWI does not display the dip at the beginning of May like the other vegetation indices do.

Dalby 3

Dalby 3 site was located in a temperate-zone coniferous plantation forest. As such it was expected that there would not be many observable changes in the canopy cover during the field measurement period and this has shown to be true. No change at all was detected by the visual observations during the field visits, with the same thick canopy present during all the visits (Figure 12). The FIPAR measurements (Figure

13) have also detected almost no change. The values shown in the graph have been scaled similarly to those in Dalby 2 and in reality range from around 0.985 to 0.995.



Figure 12 - Dalby 3 site on the 17th of June

The MODIS based vegetation indices (Figure 13) also reflect the fact that there was not much change in the canopy over the spring. Throughout most of the winter and spring the NDVI oscillates around 0.5, indicating that green needles were present on the trees in more or less steady amount over this period. There is a large increase starting in the second half of May, which is not shown in the FIPAR values but which might indicate that fresh, green needles have appeared at the top of the trees. WDRVI shows a similar pattern, with oscillating but steady winter values and a large increase in late spring. EVI2 remains almost steady throughout the winter and the field observation period, except for the last month when it also experiences an increase. NDWI once again showed the snowmelt during February and March but after the snow has melted it remained steady throughout May. It began to increase in early May, like the other vegetation indices, which seems to confirm the suggestion that fresh needles started growing at the top of the canopy around this time.

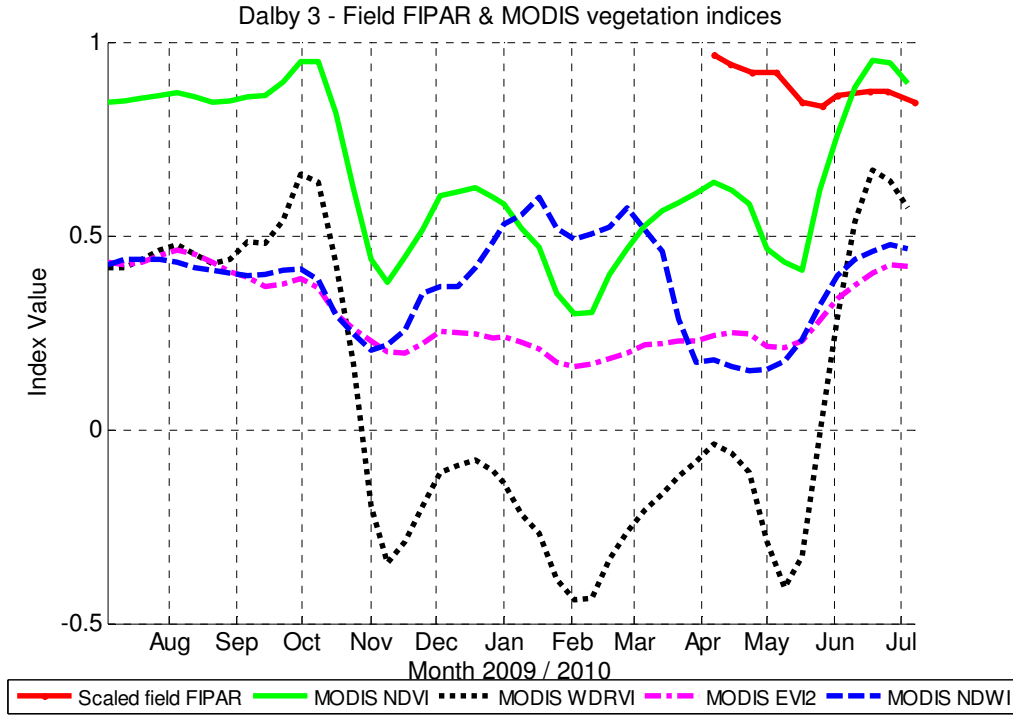


Figure 13 - Dalby 3: vegetation indices

Tower Sites

Abisko Delta Forest

The Abisko tower data came from two different towers which were located in the same ecosystem and in close proximity (around 100 metres from each other) so they were covered by the same MODIS pixel. The data from one tower contained FIPAR and FAPAR values for the spring of 2010 (Figure 14) while the data from the second tower contained FAPAR values only from the spring of 2009 (Figure 16).

The FIPAR and FAPAR curves from the 2010 growing season (Figure 14) present an interesting picture. FAPAR starts increasing at the very end of April. It rises up very quickly and by the beginning of May it reaches its maximum value and remains steady throughout the rest of spring and summer. FIPAR stays low until the first half of June, when FAPAR has already plateaued at its maximum value.

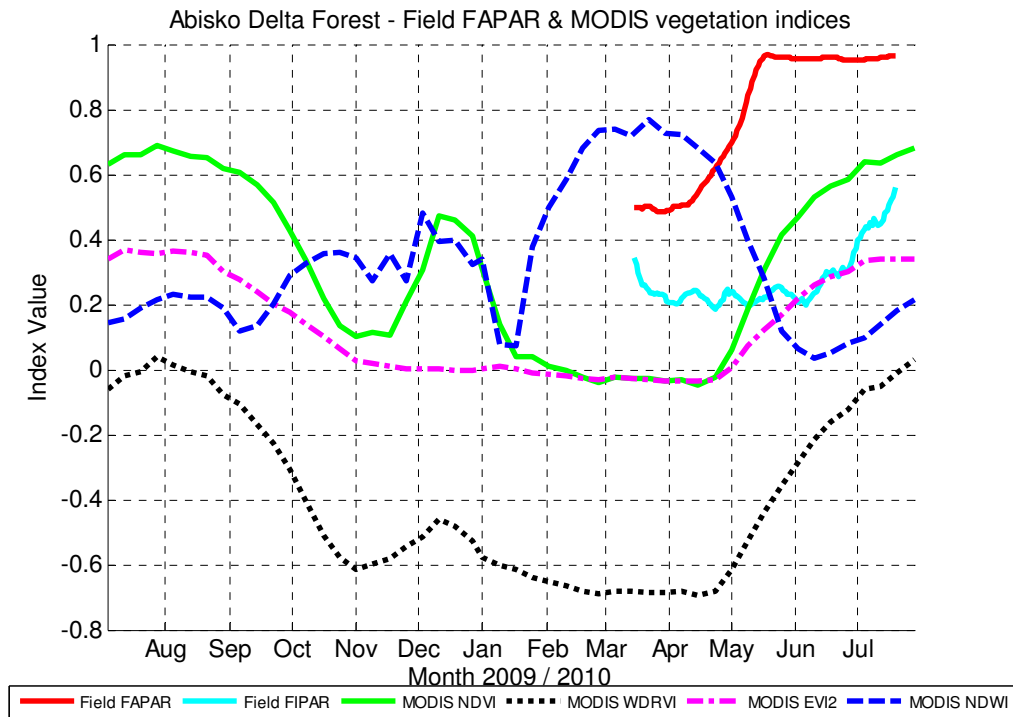


Figure 14 – Abisko Delta Forest: vegetation indices, 2010

The FAPAR equation used in this study shows the absorption of the whole ecosystem in the vicinity of the tower. This means that along with measuring the absorption of PAR by the leaves growing on trees it also measures the absorption by any understory vegetation which might be present. In Abisko Delta Forest the understory consist of quite thick, evergreen berry shrubs together with mosses and lichens (Nilsson & Wardle, 2005). Therefore as soon as the snow cover melts, the shrubs start photosynthesising and absorbing PAR. According to Swedish Meteorological Institute (SMHI, 2010) the snow around the area of Abisko in 2010 remained until the second half of May although the snowmelt started around the middle of April. This is confirmed by the average daily temperature recorded at the tower site (Figure 15), which shows positive temperatures starting in April, and this is what is reflected in the FAPAR curve.

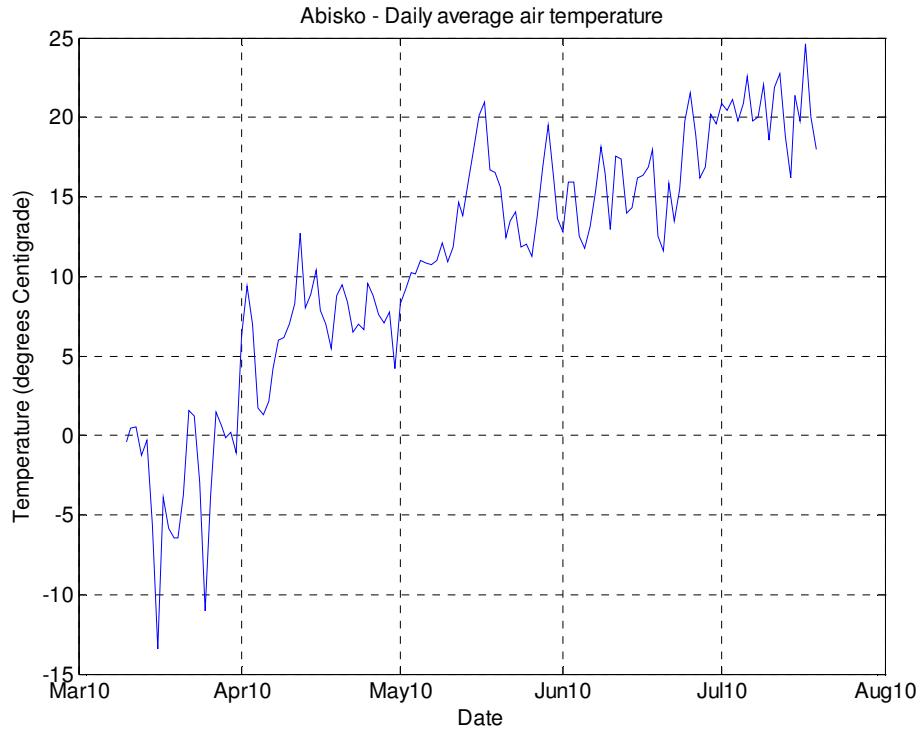


Figure 15 - Abisko Delta Forest: daily average temperature

The leaves start appearing on trees in the Abisko Delta Forest around the beginning of June (personal communication, Michal Heliasz). This is not reflected in the FAPAR curve which is saturated by that time and any PAR absorption by the leaves just replaces PAR absorption by the understory. However, the FIPAR curve, which measures the interception of PAR by the trees only, clearly shows the moment when the leaves start appearing. Throughout the early spring FIPAR undergoes small fluctuations, most probably caused by snow covering the sensors, but in the beginning of June it shows a clear rising trend which continues until the end of the available measurements in the middle of July.

The snowmelt dates for 2010 are reflected in the values of the NDWI which starts decreasing around the middle of April and does not reach its lowest value until the end of May after which it steadily increases. The timing of NDWI starting to increase again fits very nicely with the beginning of leaf growth as indicated by FIPAR.

The other vegetation indices do not fit well with the FIPAR curve but instead reflect what is happening with the FAPAR curve. Since the NDVI of snow is lower than that of a bare ground, or the forest understory, the NDVI starts increasing as soon as some of the ground and understory appears from underneath the melting snow. It continues to increase smoothly throughout the snowmelt and the greening up of the trees and

that makes it difficult to estimate when the actual leaf growth started. As can be seen in Figure 14, the same problem affects WDRVI and EVI2.

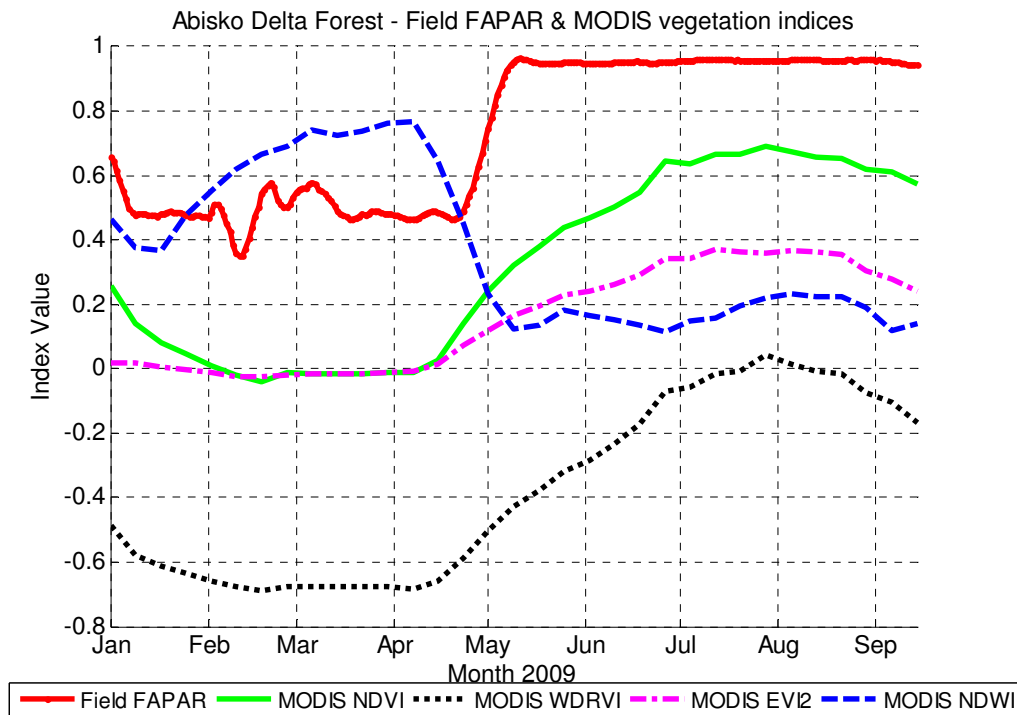


Figure 16 - Abisko Delta Forest: vegetation indices, 2009

For the growing season of 2009 only the FAPAR values were available (Figure 16). They show a similar pattern to what was observed in 2010, with a rapid increase at the end of April and beginning of May due to evergreen berry shrubs appearing from underneath the snow, and a steady value for the remainder of the summer with no indication of the start of the tree leaf growing season. NDVI, WDRVI and EVI2 also start increasing towards the end of May and reflect the same changes as FAPAR does.

NDWI has two minima during the spring of 2009, the first one around the middle of May and the second towards the end of June. This could indicate that the leaf growing season could have started earlier or later in 2009 than in 2010. Around the same time as the second increase in NDWI there is a short-lived, but noticeable, steepening of the slope of the NDVI and WDRVI curves from their otherwise steady increase since the beginning of the snowmelt. This might also indicate the beginning of leaf growth. However, without the FIPAR values this is hard to verify.

Stordalen Forest

Stordalen forest site is located in the same region as the Abisko site and covers the same type of ecosystem so it could be expected that the FAPAR and the vegetation indices would exhibit similar pattern on both sites. This proves to be true up to a point.

The FAPAR measured at the Stordalen forest site (Figure 17) starts increasing towards the end of April in both 2008 and 2009. Since the data from the spring of 2009 is available for both the Stordalen and Abisko Delta forests it is possible to make a direct comparison. At both sites the FAPAR starts its sharp increase around the 20th of April and reaches its peak towards the end of the first week of May. Since the understory of Stordalen forest also consists of evergreen berry shrubs, this increase in FAPAR can be explained by the shrubs appearing from underneath the melting snow. Unfortunately, there are no ground PAR sensors at the Stordalen forest site so no measurements of FIPAR were possible.

During the winter of 2008/2009 FAPAR experiences a number of fluctuations around the apparent baseline value of 0.6. Those fluctuations cannot be easily dismissed as noise since they are also present at the same time in the Abisko data, although centred around the FAPAR value of 0.5, and in the vegetation indices obtained from MODIS data. They are most probably caused by snow, which can decrease NDVI and the other red – NIR indices and increase the amount of PAR reflected from the ground thus also decreasing FAPAR, and very low light conditions since in winter this region is in constant state of darkness.

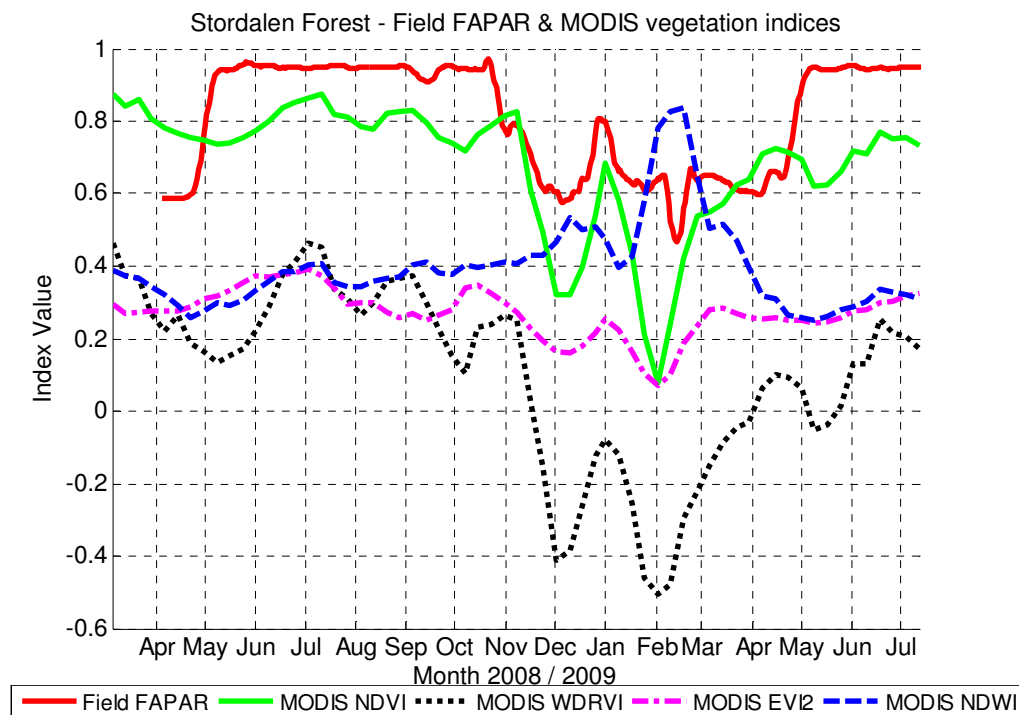


Figure 17 - Stordalen Forest: vegetation indices

The MODIS obtained vegetation indices (Figure 17) show a very curious pattern at the Stordalen Forest site. On one hand, they very closely match the timing and amplitude of the fluctuations observed in the FAPAR values in the winter of 2008/09. On the other hand, they show almost no sign of the beginning of snowmelt and appearance of the evergreen shrubs as indicated by tower obtained FAPAR values. This is especially true for NDVI and WDRVI which actually dip at the moment that FAPAR undergoes the steep increase and only increase again once FAPAR has plateaued. In case of EVI2 there is slight observable increase as the snowmelt begins, especially in 2008, but nothing to clearly indicate that it has begun.

The NDWI value peaks in the late February of 2009 and then undergoes a steep, two step decrease. The first step lasts from the end of February until the beginning of March. The temperatures are far too low for snow melt to be happening at this time. However, the tower is located at the top of a hill so the decrease could be indicative of the snow being blown away. The second step begins towards the end of March and continuous until the beginning of May. It is probably a combination of snow being blow away and melting, the second factor becoming dominating especially towards the end of the period.

Stordalen Mire

The Stordalen mire site is located a couple of hundred meters from Stordalen forest but the ecosystems are very different. Whereas forest consists of high vegetation, mire is composed of much lower plants which during winter are totally covered by snow.

This explains the two-stage increasing pattern exhibited by the FAPAR value (Figure 18). The first increase in FAPAR can be noticed at the beginning of April and lasting till the second half of that month. This is most probably caused by change in albedo of the ground surface caused by the snowmelt and has nothing to do with the beginning growing season. Dry snow has much higher reflectance then wet snow, bare soil or bare branches. Therefore, initially as the whole surface of the mire is covered by dry snow the FAPAR has a very low value (0.2). As the daily average temperature first becomes positive at the beginning of April and then from around the 10th of April remains always positive (Figure 19), the snow begins to melt and FAPAR increases to a more moderate value of around 0.4.

The second, much larger, increase in FAPAR is caused by the large increase in temperature at the beginning of May. By the beginning of that month enough ground and evergreen shrubs are exposed for the green vegetation to start absorbing PAR. Also the temperature becomes warm enough for new plants to begin to grow. This process continues throughout the first half of May, with FAPAR reaching its maximum value around the middle of that month.

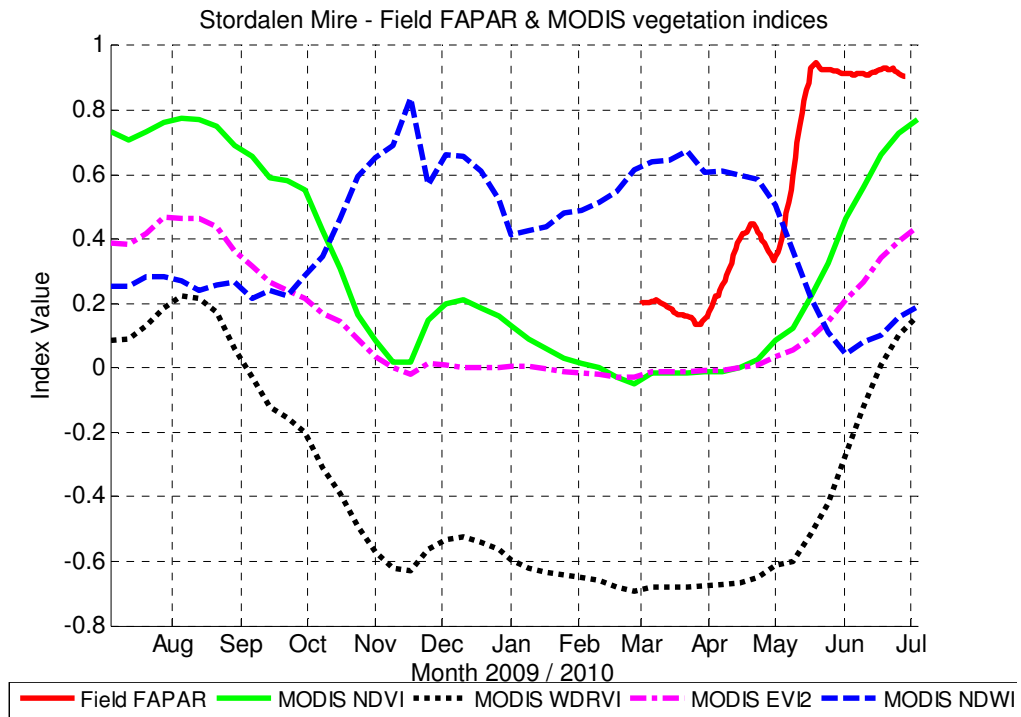


Figure 18 - Stordalen Mire: vegetation indices

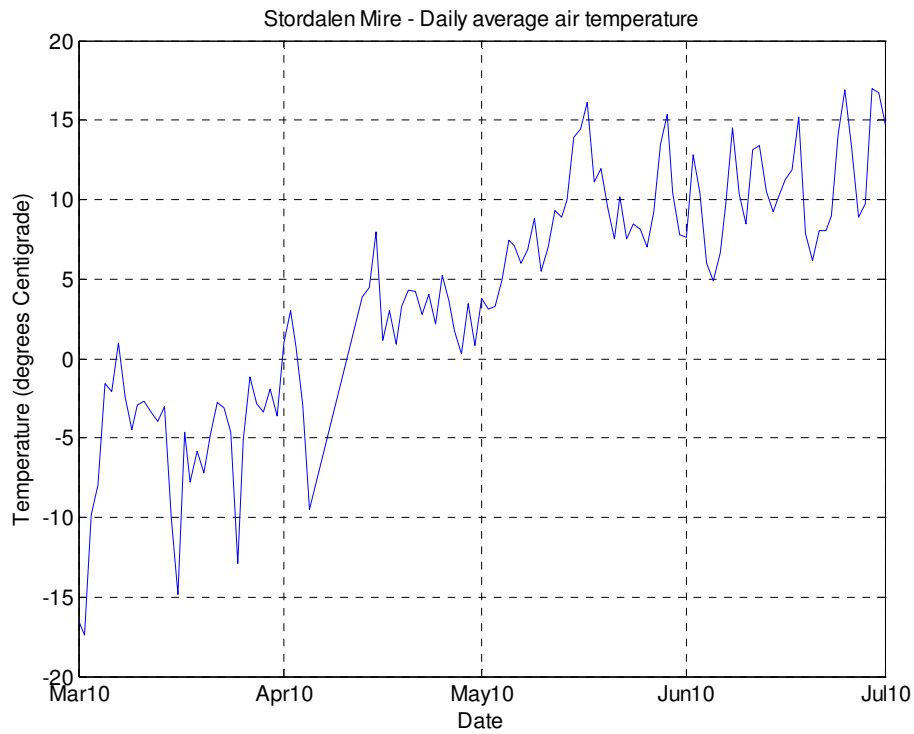


Figure 19 - Stordalen Mire: daily average temperature

NDVI, WDRVI and EVI2 remain quite steady, and quite low, throughout the winter, with NDVI and EVI2 having a slight bump in December. This also indicates that the whole surface of the mire was covered by snow throughout winter. They do not react to the first bit of snow melting in April since the ground surface is still covered by snow. Once the process accelerates and the evergreen shrubs become exposed at the beginning of May, the indices start to grow. The increase in the indices' values continues as the growing season begins making it one continuous increase caused by snow melting and greening up. However there is no indication in the indices' curves of when new vegetation begins to grow. Therefore although they do indicate the beginning of the green season, there is no indication of the beginning of the growing season.

NDWI reaches its peak in the middle of March and then shows a steep and steady decrease throughout April and May. This is in agreement with the onset of snow melting as indicated by warmer temperatures and increasing FAPAR. NDWI starts to increase again at the beginning of June which might point to the appearance of new vegetation on the mire. Nevertheless, since the mire lies in close proximity to forest covered areas, and the NDWI relies on 500 m spatial resolution data, it might also reflect leaf growth in the adjacent forest. It is hard to explain the exact cause of this increase in NDWI without field observations since FAPAR has already saturated by that time.

Norunda Forest

The data from the Norunda forest tower came in two separate time-series but was collected at the same site. This first time-series (Figure 20) covered the growing season of 2010 while the second one (Figure 21) covered the period of 2000 till 2004 although for clarity only the years 2002 till 2004 are shown.

The Norunda tower is located in an evergreen, coniferous forest. This means that the forest's green season lasts for the whole year with the PAR-absorbing needles present throughout the winter although with no photosynthesis taking place. As soon as the temperature becomes right though, the trees can start photosynthesising and at the same time fresh, green needles are grown.

There are a number of ways to determine the start of the growing season in evergreen forests like Norunda. One of them defines the start of the growing season as the date on which the average weekly air temperature crosses the 4.7 °C threshold (Sun et al., 2003). For the year 2010 that happens to be on the 15th of April. Another method uses the net ecosystem carbon exchange to estimate the start of the growing season. Using this method at the Norunda site Lagergren et al. (2008) determined the mean starting date to be in week 12 (the last week of March) for the years 1995 to 2003. Looking at the FAPAR data for 2010 it can be observed that FAPAR starts its final increase before stabilising for summer around the last week of March and actually stabilises

around the 15th of April. Therefore, in this study the beginning of the growing season can be defined as the time at which FAPAR reaches its maximum value and stabilises for summer. During winter, mostly due to low light conditions, the FAPAR signal is very noisy and unreliable.

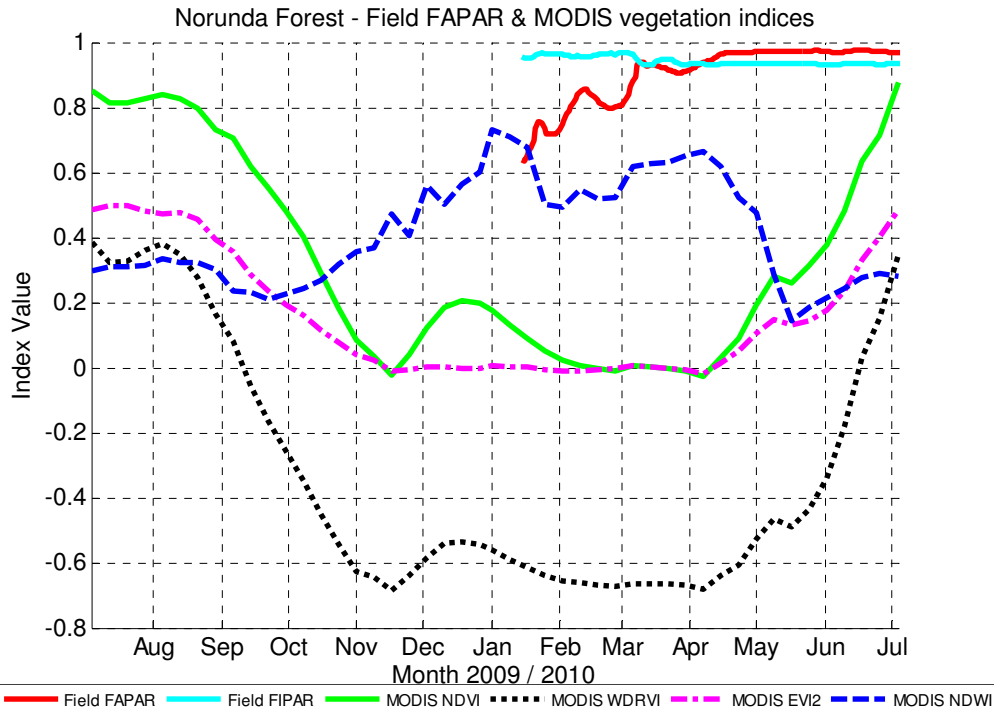


Figure 20- Norunda forest: vegetation indices 2010

It is not possible to infer much from FIPAR as it hovers around the value of 0.95 throughout the year. In winter the value is slightly higher, most probably due to snow on the tree canopy blocking even more light from reaching the ground.

By defining the start of the growing season as stated above, and looking at the FAPAR curve on Figure 21, it can be seen that the growing season begins around the middle of April in all years under study. NDVI, WDRVI and EVI2 all start growing, after remaining very low throughout the winter, almost exactly at the same time as FAPAR stabilises, except in the year 2003 when the indices remain low for a couple of weeks longer. Although they only cross the bare ground threshold value (0.2 to 0.3 for NDVI) about 2 weeks, later it still remains true that the time they start increasing coincides with the time of the defined start of the growing season.

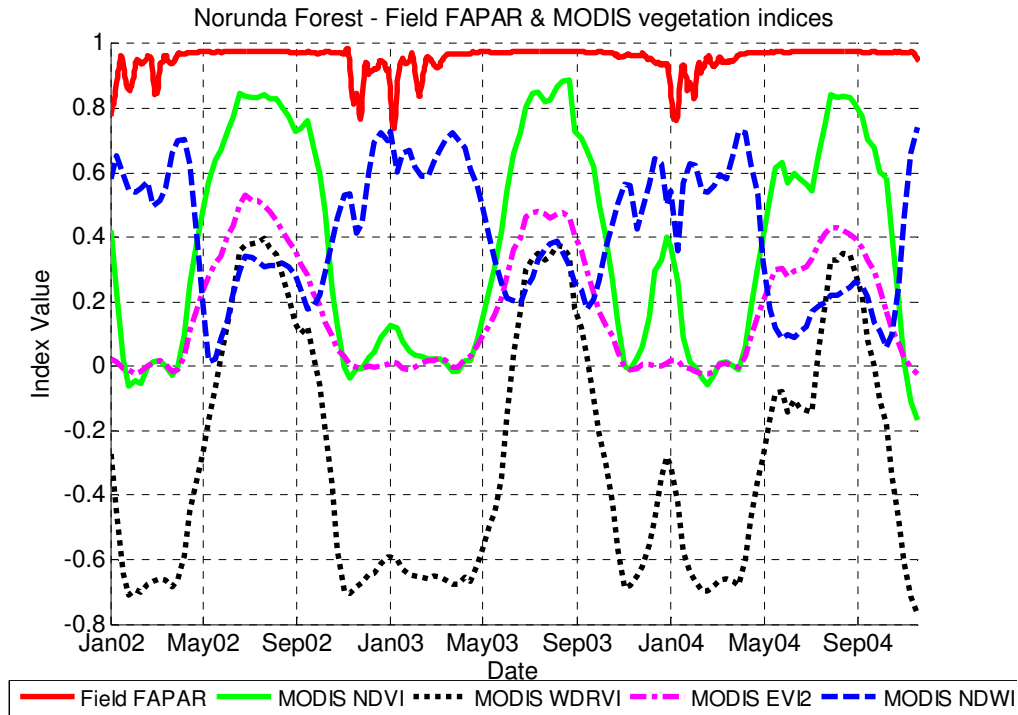


Figure 21 - Norunda Forest: vegetation indices 2000 - 2004

NDWI also shows interesting behaviour. It fluctuates around quite high values throughout the winter due to the snow cover and reaches its final peak, before declining for summer, right at the moment when FAPAR stabilises. This period should coincide with the period of snow melting and NDWI should decrease. For example, in 2010 the snow in the general area of Norunda started melting at the beginning of March and was completely gone by the beginning of April (SMHI, 2010). However, the NDWI value remains high, possibly because new needles are appearing and older needles are regaining moisture at the same time as snow is melting. Therefore the last peak of NDWI during spring could potentially also be used to estimate the start of the coniferous growing season.

It appears that in the case of Norunda forest all the vegetation indices could be used to estimate the time of the start of the growing season. Still it appears that EVI2 is the most suitable index for this task. Unlike NDVI and WDRVI, EVI2 remains stable throughout the winter without any noise signals. NDVI suffers from another drawback of saturating at the peak of the growing season, as can be clearly observed in the years 2002 and 2004. EVI2 is also more suitable than NDWI since it is a measure of photosynthetic activity of the ecosystem and not some secondary indicator of canopy growth, such as canopy water content.

Fajemyr Bog

The ecosystem greens up very quickly on the Fajemyr site, at least according to the FAPAR values (Figure 22). It takes about a week and a half from when FAPAR starts increasing on the 17th of March from a low value of around 0.25 until it reaches its maximum value of 0.97. This coincides with the period of when the daily average temperatures at the bog started to regularly exceed 5 °C (Figure 23).

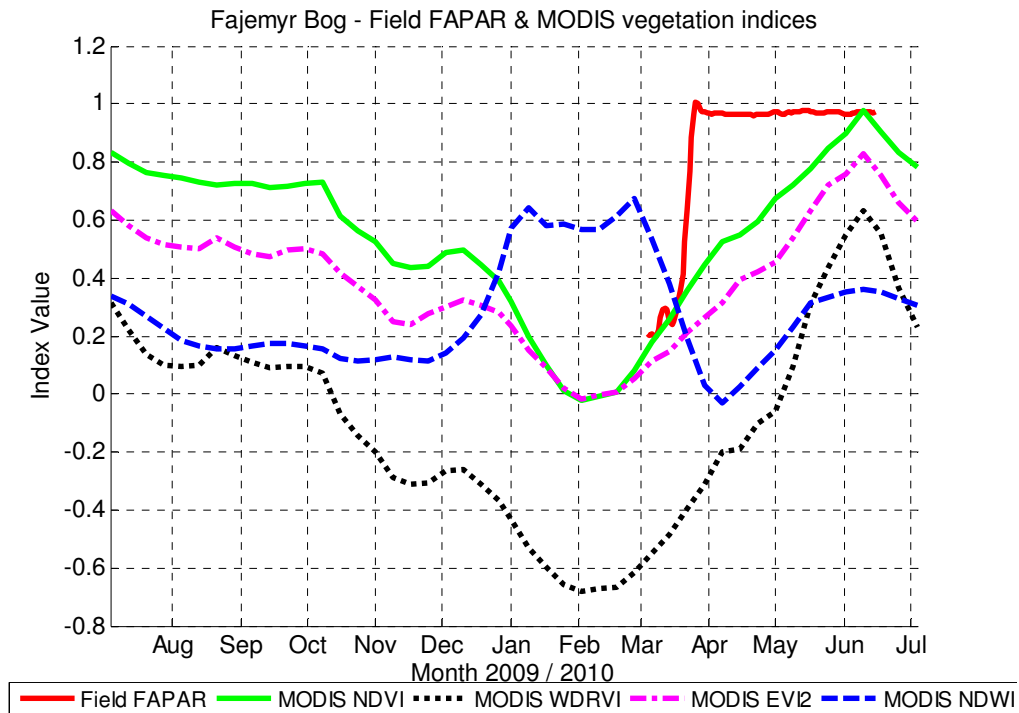


Figure 22 - Fajemyr Bog: vegetation indices

That quick pace of greening up is not reflected in any of the vegetation indices. NDVI, WDRVI and EVI2 start increasing towards the end of February when, according to the decreasing NDWI value, the snowmelt began. Then they continue to increase, almost linearly, until the beginning of June when they all peak. It is possible to observe as small inflection and a slight steepening of the slope on the EVI2 curve at the time that FAPAR values start increasing but the change is very small and difficult to detect. The NDWI curve also does not indicate the start of the green season. It begins to rise only at the beginning of April, after the FAPAR curve has plateaued, and this might indicate a new wave of vegetation growth but that is hard to verify without field observations.

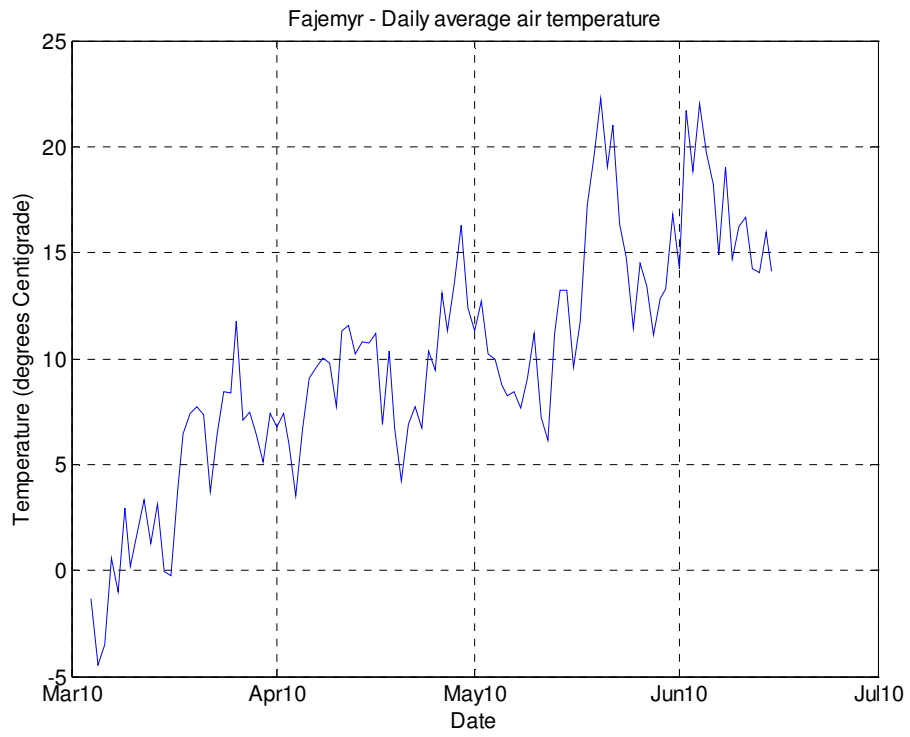


Figure 23 - Fajemyr Bog: daily average temperature

Discussion

Vegetation Indices' performance

FIPAR and FAPAR

FIPAR and FAPAR values were calculated using the tower and field collected data, and used as a ground reference data for comparing the performance of the other vegetation indices. Nevertheless, the present study shows some interesting observations as to their applicability in monitoring phenological changes in various ecosystems.

FAPAR_{ecosystem}, calculated using the equation number [3], measures the PAR absorption of the whole ecosystem underneath the tower. That means that it not only measures the PAR absorption by the tree canopy but also by the understory vegetation and the ground or snow, if snow cover exists. If, like in the case of Abisko Delta forest and Stordalen forest, there is thick winter snow cover on top of evergreen understory vegetation, than as soon the understory starts appearing from underneath the melting snow FAPAR shoots up. Soon the understory absorbs enough PAR to saturate FAPAR. When the buds and the leaves start appearing on the trees there is no indication of this in the FAPAR values because any PAR absorbed by the leaves would have been absorbed by the undergrowth anyway if the leaves were not present. Therefore, in deciduous forests with evergreen vegetation and thick snow cover the whole ecosystem FAPAR can only indicate the start of the green season but not the start of the tree growing season.

FIPAR, on the other hand, measures the amount of PAR that gets intercepted by the tree canopy on the way to the ground. If the ground PAR sensors are positioned such that they are not covered by the understory vegetation, than FIPAR can give a precise indication of when the leaves start appearing on the trees. Therefore, it can be used for monitoring the start of the growing season in deciduous forests, as shown both by the tower obtained measurements in the Abisko Delta forest and hand held instrument measurements performed at the Dalby 1 site.

The change in FIPAR values at the Dalby 1 site corresponded very closely to the visual observations of vegetation growth. This seems to validate the use of TRAC instrument (with the occasional use of LAI-2000 if cloud-free days do not occur for a long time) to measure the change of FIPAR values during the beginning of the growing season in a temperate-zone broad-leafed forests.

In evergreen coniferous forests the whole ecosystem FAPAR proves much more useful than FIPAR in observing the phenological changes. Because of the thick canopy cover, even in winter, consisting of both green needles and brown branches and dead needles, the amount of PAR reaching the ground is always low. This means

that the FIPAR value remains very high throughout the year and any changes to it due to the appearance of fresh needles are minuscule. This was obvious in both the FIPAR values obtained from Norunda and Dalby 3 sites. The almost negligible change in FIPAR values obtained at Dalby 3 might indicate that TRAC instrument is not suitable for performing FIPAR measurements in ecosystems with such dense canopy. It could also be that in such cases FAPAR measurements, with sensors placed over the canopy, should be used. The FAPAR values obtained at Norunda were also more useful than FIPAR values. Although they also remain quite high during winter, due to the presence of green, PAR absorbing needles, it is still possible to observe an increase during spring which could be indicative of fresh needles appearing and the increase in PAR absorption due to the start of photosynthesis, i.e. the start of the growing season.

In ecosystems with low vegetation, such as the Stordalen mire, Fajemyr bog and Dalby 2 grassland, FAPAR is the only practical choice since it can be hard to position ground PAR sensors to be covered by the vegetation. However, in those cases the FAPAR also saturates quickly, especially if snow covered, evergreen vegetation was present throughout winter, and so can only be used to estimate the start of the green season and not the start of the growing season.

NDVI, WDRVI and EVI2

WDRVI and EVI2 make use of the same spectral bands (red and NIR) as NDVI and were developed to overcome a number of weaknesses of NDVI such as saturation in lush vegetation and sensitivity to atmospheric effect and background soil brightness (Gitelson, 2004; Huete et al., 1999). Although none of those limitations, maybe with the exception of sensitivity to background soil brightness, should have much impact on the index's ability to estimate the date of spring phenological events, the performance of the three indices in this respect was still compared in this study.

In general NDVI, WDRVI and EVI2 perform equally well in the estimation of the onset of the green season and equally poorly in the estimation of the onset of the leaf growing season in deciduous forests. In all the locations under study the three indices started to increase in spring at exactly the same time. The timing of the increase corresponded quite closely to the timing of the increase in FAPAR in all the locations except for Stordalen forest, where the index values behaved strangely, and Dalby 2 where the FAPAR measurements were not very reliable. This shows that there is no difference between NDVI, WDRVI and EVI2 when it comes to detecting the appearance of evergreen shrubs and greening of the understory as the snow melt reveals more of the ground.

However, when it came to estimating the date of the start of the leaf growing season in the deciduous forests of Abisko and Dalby 1 all the indices performed rather poorly. As mentioned previously they started increasing as soon as understory vegetation became visible or began growing, which happened about 4 weeks before

the leaf growth. This is in broad agreement with a study by Ahl et al. (2006) which found that the MODIS products predicted the start of the growing season up to 3 weeks earlier than what field measurements indicated. The reasons given in that study, the temporal composition of MODIS data and the impact of the understory development, are equally applicable to this study. In some instances it is possible to observe a lasting change of slope, as in the case of WDRVI in Dalby 1, or a temporary kink, as in the case of NDVI in Abisko Delta forest in 2010, at the time the leaves are appearing but that is not enough to conclude that those vegetation indices are indicating the start of the growing season.

Apart from their ability to predict the start of the green season there are some noticeable differences between the three indices. Although finding those differences was not the primary objective of this study they are nevertheless worth noting. Firstly, the response of WDRVI is much larger than NDVI, especially during the peak of the growing season. This is due to NDVI becoming saturated as the vegetation becomes lush and make WDRVI better suited to observing small changes in the vegetation greenness once the growing season is already well advanced. Secondly, while both NDVI and WDRVI are affected by snow and experience some variance during winter, EVI2 is much more stable throughout the non-green season. The same has been observed for EVI (Reed et al., 2009), meaning that, at least in this respect, EVI2 works well as a two-band substitution for EVI.

NDWI

During this study NDWI proved to be quite accurate in predicting the start of the growing season both in the boreal region of Abisko and in the temperate region of Dalby. The Abisko Delta forest data from the spring of 2010 shows that the NDWI started its spring increase exactly at the moment when FIPAR indicated the beginning of leaf growth, while the other indices started increasing about a month earlier. It is harder to assess the performance of NDWI during the 2009 growing season since there is no FIPAR data available for that period. However, it looks like NDWI shows the start of leaf growth in the second half of June which is more consistent with the usual observed date of the start of the Abisko growing season (around the beginning of June) than what is indicated by other indices.

NDWI also performs surprisingly well during the 2010 growing season on the Dalby 1 site. The snowmelt is reflected in the decrease in NDWI values over February and March and although it seems to continue slightly too long after all the snow has melted this could be explained by the drying up of the soil. The timing of when the index reaches its minimum value and starts increasing again corresponds very well to the start of leaf growth as observed during field visits and illustrated with the FIPAR curve. It even obtains its maximum at the same time as FIPAR. It might be tempting to conclude that NDWI is the best VI to estimate the start of the growing season in deciduous forests in the Scania region. Nevertheless, that conclusion should only be reached after more studies over a number of growing seasons, especially since the

2009/2010 winter in Scania produced unusually prevalent snow cover (personal observations).

Although it seems like NDWI performed quite well in predicting the start of the growing season, especially of deciduous forests after a snowy winter, it does suffer from a number of limitations. According to Delbart et al. (2005), if the snow melt and greening up overlap for a long period then the changes to NDWI from the two processes interact and the result is the delay in the increase in NDWI compared to the onset of greening. This has not occurred during the 2010 or 2009 growing seasons but could be a problem during other past or future years. Another limitation of NDWI is the requirement of the SWIR spectral band to perform the index value calculation. Firstly, this limits the index's backward compatibility since that spectral band has only been used in satellite remote sensing for the last ten or so years. There are, however, possible solutions to this problem (Delbart et al., 2006). Secondly the SWIR band aboard the MODIS satellite has a 500 m spatial resolution, while the bands required to calculate the other indices have a 250 m spatial resolution. Therefore, if NDWI is to be used as the primary index in monitoring an ecosystem phenology, the site under study should be at least 1 km by 1 km. This would, for example, preclude all of the Dalby field sites which are too small.

Study Limitations and Further Work

The main limitation of this study was its limited temporal scope. In most cases the agreement between the ground and satellite measurements was only compared during one growing season. This precludes any meaningful statistical analysis of the results and any observation of longer term trends. Finding agreement (or disagreement) between the actual performance of a vegetation index during this study and the assumption of its performance as incurred from theory and previous studies cannot be treated as a definitive finding but rather as an encouragement for longer term investigation.

A second major limitation was the inability to visit the tower sites in person. The location of a tower site (e.g. on the top of a hill, shadowed by a mountain during low sun, close to water, etc.), the appearance of the ecosystem as it changes over the spring (e.g. the dominant understory and overstory species, the lushness of the vegetation, the presence of evergreen species) and other factors can prove very helpful with explaining the variations in both the measured FIPAR and FAPAR and the MODIS data derived indices. Although it is possible to obtain some of this information through literature research and conversations with the people regularly visiting those sites, this is still not as good as seeing the sites in person.

A third limitation was the lack of the proper equipment available at all the sites. For example PAR sensors mounted under the tree canopy in Stordalen forest or over the canopy in Dalby 3 forest would have allowed for measurement of FIPAR and FAPAR

respectively which are more suitable to observing the changes in those ecosystems than what was actually measured.

Any further study should address the above limitations, which mainly means extending the study over a longer period of time while reducing the scope to fewer sites and vegetation indices. The extension of the period of study is quite obvious. The purpose of the reduction in scope is to get a more in depth knowledge of the sites and indices under study.

Since the three red-NIR indices behave quite similarly there seems no point in continued analysis of all three of them. Instead EVI2, which has a number of other advantages over NDVI and WDRVI, should be chosen as the topic of further study. In addition NDWI which produced some interesting results during this study should also be continued to be looked at. There is currently a discussion in the literature on whether including snow cover information, which is what NDWI does, into the satellite phenological observations could help with better defining the phenological stages or if it is just an unnecessary complication (Reed et al., 2009). Further studies should also take this issue under consideration.

Limiting the number of sites under study would allow the researchers to get to know the sites better and to inspect them personally and at regular intervals. It would also enable the appropriate PAR sensors to be installed at the sites where they are not currently present. A good selection of sites should represent the ecosystems similar to the ones encountered in Abisko Delta forest, Norunda, Dalby 1 and Fajemyr to provide a broad cross section of environments to be analysed. However, it would be advantageous to move the smaller sites, such as Dalby 1, to different locations where larger homogenous areas are present. This would allow a comparison between the field observations and a probabilistic analysis of vegetation indices' responses from a large number of MODIS pixels. This has been proposed as a possible solution to the problem of large spatial scale differences between the field and satellite observations and the problem of comparing the discrete timings of the field observed phenological events against the continuous vegetation indices (White and Nemani, 2006).

Conclusion

There are a number of findings that can be reached as a result of this study. Firstly, when observing spring phenological events using satellite data it is important to distinguish between the green and growing seasons. This is especially relevant to forests. In deciduous forests with evergreen understory the green season starts when the understory vegetation breaks through the melting snow. The growing season starts later when the leaf growth begins on trees. Even when the understory is not evergreen the green season usually begins before the tree leaf growing season.

Secondly, the choice of FIPAR or total-ecosystem FAPAR has a large impact on what is actually observed by the field measurements. FIPAR measures the amount of PAR transmitted through the tree canopy and so can be used to observe the progress of tree leaf growth in deciduous forests. In coniferous forests it is not very useful as the amount of light below the canopy is always low. The total-ecosystem FAPAR on the other hand cannot be used to observe leaf growth in deciduous forests with lush understory because by the time the leaves appear FAPAR is already saturated. In those forests it can only be used to estimate the beginning of the green season. However, in coniferous forests with thick canopies it can be used to estimate the beginning of the growing season. In ecosystems with low vegetation it can be used to estimate the beginning of the green or growing seasons, depending on whether those ecosystems support evergreen vegetation or not.

Tied in with the above is the appropriate use of instruments. TRAC proved to be a useful instrument for measuring PAR values to be used for FIPAR calculations in the deciduous forest. Conversely, in grassland and especially in coniferous forest the use of TRAC did not result in useful data. In the tower sites the location of the PAR sensors is important. It would have been useful to have ground PAR sensors at the Stordalen forest site, while the Norunda based ground PAR sensors were not very useful during this study.

The final conclusion concerns the performance of the MODIS-data derived indices in estimating the dates of spring phenological events. NDWI proved to be very useful in predicting the start of the leaf growing season in the deciduous forests, both in the boreal and temperate climatic zones. In fact, it was the only vegetation index that could predict the start of the growing season. It also seemed to be of use when predicting the start of the growing season in the coniferous forest although that conclusion is not as strong. In the low vegetation ecosystems the results are more inconclusive.

NDVI, WDRVI and EVI2 all undergo the spring increase at the same time at all the sites. The increase coincides quite closely with the increase in the FAPAR values and so most probably is indicative of the onset of the green season. The only exception is in Norunda where it coincides with the start of the growing season. Although the three

indices perform the same when it comes to monitoring spring phenological events
EVI2 still has the advantages of staying the steadiest over winter and not saturating
during summer.

References

- Ahl, D E, S T Gower, S N Burrows, N V Shabanov, R B Myneni, and Y Knyazikhin. "Monitoring spring canopy phenology of a deciduous broadleaf forest using MODIS." *Remote Sensing of Environment*, 104, 2006: 88-95.
- Alexandersson, H, C Karlstrom, and S Larsson-McCann. *Temperature and precipitation in Sweden 1961–1990, reference normals*. Norrkoping: SMHI, 1991.
- Backstrand, K, P M Crill, M Jackowicz-Korczynski, M Mastepanov, T R Mastepanov, and D Bastviken. "Annual carbon gas budget for a subarctic peatland, Northern Sweden." *Biogeosciences*, 7, 2010: 95–108.
- Barring, L, P Jonsson, J O Mattsson, and R Ahman. "Wind erosion on arable land in Scania, Sweden and the relation to the wind climate—a review." *Catena*, 52, 2003: 173–190.
- Delbart, N, L Kergoat, T Le Toan, J Lhermitte, and G Picard. "Determination of phenological dates in boreal regions using normalized difference water index." *Remote Sensing of Environment*, 97, 2005: 26-38.
- Delbart, N, T Le Toan, L Kergoat, and V Fedotova. "Remote sensing of spring phenology in boreal regions: A free of snow-effect method using NOAA-AVHRR and SPOT-VGT data (1982-2004)." *Remote Sensing of Environment*, 101, 2006: 52-62.
- Dimitrov, P. "Investigation of dynamics of some biophysical parameters of Norway spruce stands by MODIS data." *Recent Advances in Space Technologies, 2009. RAST '09. 4th International Conference on*. Istanbul, 2009. 392 - 396 .
- Feigenwinter, C, M Molder, A Lindroth, and M Aubinet. "Spatiotemporal evolution of CO₂ concentration, temperature, and wind field during stable nights at the Norunda forest site." *Agricultural and Forest Meteorology*, 150, 2010: 692–701.
- Fensholt, R, I Sandholt, and M S Rasmussen. "Evaluation of MODIS LAI, fAPAR and the relation between fAPAR and NDVI in a semi-arid environment using in situ measurements." *Remote Sensing of Environment*, 91, 2004: 490–507.
- Gao, B. "NDWI A Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water From Space." *Remote Sensing of Environment*, 58, 1996: 257-266.
- Gitelson, A A. "Wide Dynamic Range Vegetation Index for Remote Quantification of Biophysical Characteristics of Vegetation." *Journal of Plant Physiology*, 161, 2004: 165–173.
- Gitelson, A A, B D Wardlow, G P Keydan, and B Leavitt. "An evaluation of MODIS 250-m data for green LAI estimation in crops." *Geophysical Research Letters*, 34, 2007: L20403.
- Gower, S T, C J Kucharik, and J M Norman. "Direct and Indirect Estimation of Leaf Area Index, fAPAR, and Net Primary Production of Terrestrial Ecosystems." *Remote Sensing of Environment*, 70, 1999: 29–51.
- Haapanala, S, A Ekberg, H Hakola, V Tarvainen, J Rinne, and et al. "Mountain birch – potentially large source of sesquiterpenes into high latitude atmosphere." *Biogeosciences Discussions*, 6, 2009: 5409–5430.
- Huete, A R, R D Jackson, and D F Post. "Spectral Response of a Plant Canopy with Different Soil Backgrounds." *Remote Sensing of Environment*, 17, 1985: 37-53.

- Huete, A, C Justice, and W van Leeuwen. "MODIS Vegetation Index (MOD13), Algorithm Theoretical Basis Document." *MODIS Web*. April 30, 1999. http://modis.gsfc.nasa.gov/data/atbd/atbd_mod13.pdf (accessed July 20, 2010).
- Huete, A, K Didan, T Miura, E P Rodriguez, X Gao, and L G Ferreira. "Overview of the radiometric and biophysical performance of the MODIS vegetation indices." *Remote Sensing of Environment*, 83, 2002: 195–213.
- James, T D. "Remote Sensing of Environmental Change." In *An Introduction to Physical Geography and the Environment - Second Edition*, by J Holden, 643-647. Harlow, Essex: Pearson Education Limited, 2008.
- Jiang, Z, A R Huete, K Didan, and T Miura. "Development of a two-band enhanced vegetation index without a blue band." *Remote Sensing of Environment*, 112, 2008: 3833–3845.
- Jonsson, P, and L Eklundh. "TIMESAT—a program for analyzing time-series of satellite sensor data." *Computers & Geosciences*, 30, 2004: 833–845.
- Kaufman, Y K, and D Tanre. "Atmospherically Resistant Vegetation Index (ARVI) for EOS-MODIS." *IEEE Transactions on Geoscience and Remote Sensing*, 30 (2), 1992: 261-270.
- Lagergren, F, A Lindroth, E Dellwik, A Ibrom, H Lankreijer, and et al. "Biophysical controls on CO₂ fluxes of three Northern forests based on long-term eddy covariance data." *Tellus B*, 60, 2008: 143–152.
- Leblanc, S G, J M Chen, and M Kwong. *Tracing Radiation and Architecture of Canopies, TRAC MANUAL Version 2.1*. Canada Centre for Remote Sensing: Natural Resources Canada, 2002.
- LI-COR. *LAI-200 Plant Canopy Analyzer*. Operating Manual, Lincoln, Nebraska: LI-COR, 1992.
- . *LI-190 Quantum Sensor - Measure Photosynthetically Active Radiation*. 2010. http://www.licor.com/env/Products/Sensors/190/li190_description.jsp (accessed July 20, 2010).
- Lieth, H H. "Contributions to Phenology Seasonality Research." *International Journal of Biometeorology*, 20(3), 1976: 197-199.
- Menzel, A. "Phenology: Its importance to the global change community." *Climatic Change*, 54, 2002: 379–385.
- Menzel, A, T H Sparks, N Estrella, E Koch, A Aasa, and et al. "European phenological response to climate change matches the warming pattern." *Global Change Biology*, 12, 2006: 1969–1976.
- MODLAND. *MODLAND Tile Calculator*. October 12, 2005. <http://modis-250m.nascom.nasa.gov/cgi-bin/developer/tilemap.cgi> (accessed July 20, 2010).
- NASA, National Aeronautics and Space Administration. *MODIS Web: About MODIS*. n.d. <http://modis.gsfc.nasa.gov/about/> (accessed July 20, 2010).
- NOAA, National Oceanic and Atmospheric Administration: Coastal Services Center. *Remote Sensing: The Logistics*. n.d. <http://www.csc.noaa.gov/products/sccoasts/html/rsdetail.htm> (accessed 07 20, 2010).
- Nilsson, MC, and D A Wardle. "Understory vegetation as a forest ecosystem driver: evidence from the northern Swedish boreal forest." *Frontiers in Ecology and the Environment*, 3 (8), 2005: 421–428.

- Olofsson, P, and L Eklundh. "Estimation of absorbed PAR across Scandinavia from satellite measurements. Part II: Modeling and evaluating the fractional absorption." *Remote Sensing of Environment*, 110, 2007: 240–251.
- Reed, B C, M D Schwartz, and X Xiao. "Remote Sensing Phenology: Status and the Way Forward." In *Phenology of Ecosystem Processes*, by A Noormets, 231–246. Springer Science + Business Media, 2009.
- Rouse, J W, R H Haas, J A Schell, and D W Deering. "Monitoring vegetation systems in the Great Plains with ERTS." *Third ERTS-1 Symposium NASA*. Washington DC: NASA SP-351, 1974. Vol 1, 309–317.
- Savitzky, A, and M J E Golay. "Smoothing and Differentiation of Data by Simplified Least Squares Procedures." *Analytical Chemistry*, 36 (8), 1964: 1627–1639.
- Schubert, P, M Lund, and L Eklundh. "Estimation of Gross Primary Productivity of an Ombrotrophic Bog in Southern Sweden." *Geoscience and Remote Sensing Symposium, 2008. IGARSS 2008. IEEE International*. Boston, MA, 2008. IV - 866 - IV - 869 .
- SDEC. *PHOTOSYNTHETICALLY ACTIVE RADIATION (P.A.R) SENSOR - JYP 1000*. July 01, 2010. <http://www.sdec-france.com/produits.php?numprod=46&lg=an> (accessed July 20, 2010).
- Sekhon, N S, Q K Hassan, and R W Sleep. "Evaluating Potential of MODIS-based Indices in Determining “Snow Gone” Stage over Forest-dominant Regions." *Remote Sensing*, 2, 2010: 1348-1363.
- Skryllegarden. *Skryllegarden*. August 17, 2010. <http://www.skryllegarden.se/> (accessed July 20, 2010).
- SMHI. *Snödjup*. 2010. <http://www.smhi.se/klimatdata/meteorologi/sno/snodjup-2.722> (accessed July 20, 2010).
- Suni, T, F Berninger, T Vesala, T Markkanen, P Hari, and et al. "Air temperature triggers the recovery of evergreen boreal forest photosynthesis in spring." *Global Change Biology*, 9, 2003: 1410–1426.
- USGS, U.S. Geological Survey. *MODIS Product Table*. March 2009, 2009. https://lpdaac.usgs.gov/lpdaac/products/modis_products_table (accessed July 20, 2010).
- Vermote, E F, N El Saleous, C O Justice, Y J Kaufman, J L Privette, and et al. "Atmospheric correction of visible to middle-infrared EOS-MODIS data over land surfaces: Background, operational algorithm and validation." *Journal of Geophysical Research*, 102, 1997: 17,131-17,141.
- Verstraete, M M, B Pinty, and R B Myneni. "Potential and Limitations of Information Extraction on the Terrestrial Biosphere from Satellite Remote Sensing." *Remote Sensing of Environment*, 58, 1996: 201-214.
- von Oheimb, G, and J Brunet. "Dalby Soderskog revisited: long-term vegetation changes in a south Swedish deciduous forest." *ACTA OECOLOGICA*, 31, 2007: 229 – 242.
- White, M A, and R R Nemani. "Real-time monitoring and short-term forecasting of land." *Remote Sensing of Environment*, 104, 2006: 43 – 49.
- Zhang, X, M A Friedl, C B Schaaf, A H Strahler, J C F Hodges, and et al. "Monitoring vegetation phenology using MODIS." *Remote Sensing of Environment*, 84, 2003: 471–475.
- Zhang, X, M A Friedl, and C B Schaaf. "Sensitivity of vegetation phenology detection to the temporal resolution of satellite data." *International Journal of Remote Sensing*, 30(8), 2009: 2061–2074.

- Zhang, X, M A Friedl, C B Schaaf, and A H Strahler. "Climate controls on vegetation phenological patterns in northern mid- and high latitudes inferred from MODIS data." *Global Change Biology*, 10, 2004: 1133–1145.
- Zheng, G, and M L Moskal. "Retrieving Leaf Area Index (LAI) Using Remote Sensing: Theories, Methods and Sensors." *Sensors*, 9, 2009: 2719-2745.
- .

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