HIGH RESOLUTION MAPPING OF VEGETATION DYNAMICS FROM SENTINEL-2

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ABSTRACT

The aim of this work is to develop and test a method for generation of information on vegetation dynamics from high-spatial resolution data, such as Sentinel-2. In order to accomplish this, Sentinel-2 data were simulated from existing SPOT HRG and HRVIR scenes over Sweden. We used TIMESAT, a well-tested computer package for generating smooth seasonal profiles and generation of seasonality parameters, like start and end, length, amplitude, integrated values, seasonal maximum, derivatives, etc. The processing works on a pixel-by-pixel basis and is resistant to clouds and noise. Data gaps are handled, and quality information can be included to increase the fidelity of the fits. The pilot study demonstrated that TIMESAT was successful in fitting smooth model functions to the data, and generating seasonality parameters for the test area at 10 x 10 m resolution. We conclude that TIMESAT will be useful for generating vegetation dynamics data from high-spatial resolution data such as Sentinel-2. The smooth seasonal profiles will be extremely useful for driving high-resolution biophysical vegetation models, and the seasonality parameters will be excellent for change detection, and for studying trends in vegetation productivity and seasonality.

1. INTRODUCTION

Vegetation dynamics denotes long- and short-term variations in vegetation properties over time. These variations are regulated by environmental drivers such as temperature, radiation, humidity, nutrients etc. Monitoring of vegetation dynamics is essential for observing changes and trends in these drivers, and subsequent consequences for vegetation resources and human use of them. The concept includes not only gradual changes but also more rapid natural and human-induced disturbances, such as those caused by fire, clear-cutting, insect infestation, storms etc. *Plant phenology* is the response of plants to seasonal variations in environmental drivers and is manifested as flowering, leaf emergence, leaf shedding, etc. Phenology responds to the joint effects of several environmental drivers, and monitoring these variations is an important part of climate change research [1].

Earth observation data provides invaluable information on vegetation dynamics at a range of scales. A large body of scientific literature exists on the use of vegetation indices, such as the NDVI, for long-term monitoring of vegetation growth at regional to global scales, and across different climate zones [2-4]. Also phenology and its changes have been extensively studied [5-7]. It has, furthermore, been demonstrated that these types of data represent ecosystem-scale variations in fractional absorbed photosynthetically active radiation (fAPAR) and may be used for estimating net or gross primary productivity (NPP or GPP) as evidenced by relationships with eddy-covariance data of carbon fluxes [8-12]. These studies are generally based on data from coarse-resolution sensors as the high time-resolution of the data allows for consistent inter-annual comparisons. Some authors have also used these data for mapping shorter-time anomalies or disturbances during parts of the season due to e.g. drought or insect attacks [13-15].

The coarse spatial scale of coarse-resolution data makes it difficult to draw any conclusions at the scale of individual vegetation stands or for particular plant species, since measurements represent pixel sizes from 250 m to several kilometres squared, hence relating more to the scale of the "ecosystem". Relationships with carbon fluxes and other environmental measurements may also be more complex due to the mismatch in spatial scale. A few recent studies have explored vegetation dynamics using higher-resolution data, e.g. from Landsat and SPOT sensors [16-19]. Though certain aspects of dynamic variation can be monitored, the low time resolution prevents accurate mapping of phenology or disturbances to the seasonal profile.

The planned Sentinel-2 satellites will generate invaluable data for mapping phenology and seasonal dynamics at high spatial resolution, thus overcoming many of the problems related to the use of coarse-resolution data. However, several problems have to be solved before reliable methods for processing of these data have been developed.

The aim of this paper is to test and develop methodology for mapping and monitoring of vegetation dynamics at high spatial resolution, such as that generated by the future Sentinel-2 data. The method should be general in nature and allow for fast processing of large data amounts.

2. TIMESAT FOR TIME-SERIES PROCESSING OF IMAGE DATA

We have chosen to use an existing platform for processing of satellite data, TIMESAT. This program was developed by Jönsson and Eklundh [20, 21] for estimating growing seasons from satellite time-series, as well as for computing phenological metrics from the data. TIMESAT consists of several mathematical methods for smoothing data, including Gaussian and logistic model fits, and Savitzky-Golay filtering. Seasonality metrics (beginning and end of the growing season, length of the season, amplitude, integrated value, asymmetry of the season etc.) are extracted for each image pixel and output to file.

TIMESAT has been used in a number of applications for data smoothing and estimation of phenology [4, 7-10, 15, 22-24]. It is used by the North American Carbon Program, and for generation of the new generation of MODIS LAI and fAPAR data by Boston University (R. Myneni, pers. comm.). One advantage of TIMESAT is that it can fit functions to the upper-envelope of data, thereby reducing the influence of negatively biased noise due to clouds. It is resistant to noise and data gaps by least-squares fits and the use of quality weights. TIMESAT has a large user community (> 1700 registered users) and has been tested for many years using a variety of input data. It has, to the authors' knowledge, not previously been tested with high spatial resolution data.

Phenology is estimated in TIMESAT by extracting seasonality parameters (Fig. 1) for each image pixel location.

TIMESAT runs on Windows and Linux platforms and is well suited to processing in parallel. For fast processing the algorithms are programmed in FORTRAN. A general version of TIMESAT is freely available for research (http:\\www.nateko.lu.se\TIMESAT).

TIMESAT has primarily been used with coarse-resolution data and needs to be tested and further developed for use with high spatial-resolution data.

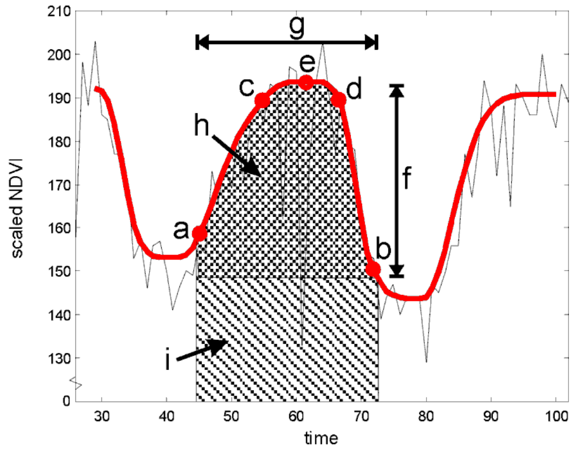

Figure 1. Some of the seasonality parameters computed in TIMESAT: (a) beginning of season, (b) end of season, (c) left 90% level, (d) right 90% level, (e) peak, (f) amplitude, (g) length of season, (h) integral over growing season giving area between fitted function and average of left and right minimum values, (i) integral over growing season giving area between fitted function and zero level. [21]

3. METHOD

3.1. Data preparation

Multispectral imagery from the Système Pour l'Observation de la Terre (SPOT) satellites was acquired from the Swedish mapping, cadastral and land registration authority Saccess database (http://saccess.lantmateriet.se). Each SPOT image used in this study covers an area of approximately 4000 km^2 and is defined in the Swedish Reference Frame 1999 Transverse Mercator (SWEREF 99 TM). In this study red (0.61-0.68 µm) and near infra-red (0.78-0.89 µm) bands from a total of seven images from SPOT-4 (20 m

Table 1. Table describing SPOT acquisitions used in the study including image acquisition date, grid reference, sun zenith and sun azimuth angle, cloud fraction percentage (estimated through visual inspection) and satellite.

Imaging Date	Grid Reference	Sun zenith angle	Sun azimuth angle	Cloud %	Resolution	Satellite
2008-05-11	057-236	39.4º	158.3º	0%	10 m	SPOT-5
2010-06-02	054-236	34.0º	173.3º	0%	10 m	SPOT-5
2009-06-14	057-236	33.3º	165.4º	0%	10 m	SPOT-5
2005-07-04	057-236	33.1º	172.5º	10%	10 m	SPOT-5
2008-07-26	057-237	36.4º	167.6º	0%	10 m	SPOT-5
2005-09-06	054-236	50.1º	164.3º	0%	10 m	SPOT-5
2005-09-16	054-236	53.0º	177.9º	0%	20 m	SPOT-4

resolution) and SPOT-5 (10 m resolution) were used (Table 1).

Radiometric processing was applied to the SPOT-imagery and digital numbers (DN) were converted to top-of-atmosphere reflectance (ρ) according to the following equation:

$$\rho = \frac{DN \cdot \pi \cdot d^2}{G \cdot \cos(\theta_s) \cdot ESUN_\lambda} \qquad (1)$$

where d is the Earth-Sun distance (astronomical units), G is the sensor specific calibration gain (W m^{-2} sr^{-1} μm^{-1}), θ_s is the sun-zenith angle and $ESUN_\lambda$ is the band specific mean solar exoatmospheric irradiance (W m^{-2} sr^{-1} μm^{-1}). G and θ_s where provided in the metadata for each SPOT acquisition whereas $ESUN_\lambda$ was provided by CNES/SPOT Image [25]. Computed layers of SPOT normalized difference vegetation index (NDVI) were then radiometrically adjusted to at-surface NDVI using the moderate resolution imaging spectroradiometer (MODIS) bidirectional reflectance distribution function (BRDF) reflectance product (MCD43A4, collection 5) by registering each SPOT acquisition to its MCD43A4 16-day counterpart and establishing linear regressions for cloud-free land surface targets (Figure 2).

3.2. Data processing

Images of SPOT NDVI were stacked by acquisition month and day order at 16-day intervals to enable the creation of seasonal NDVI profiles. Within vegetation season gaps between August 1 and August 31 (e.g. two 16-day intervals) were filled by linear interpolation whereas off-season gaps (January 1 to April 30 and October 1 to December 31) were filled by fitting SPOT NDVI to MCD43A4 data. The SPOT scenes were then examined for a suitable representative study area, and a 1235 × 704 pixel subset of the full scenes was selected for the generation of smooth time series of NDVI as well as to estimate the phenology parameters by using the TIMESAT program. A logistic model function was used in TIMESAT.

4. RESULTS

Seasonal profiles were successfully extracted from the simulated data set for all areas, except where there was large inter-annual variation in the input data, such as in cropland. In these areas the simulated data did not reproduce the seasonal profiles realistically due to widely different cropping calendars between the different years. For forest, grazing land, and natural vegetation this was not a problem and TIMESAT generated smooth functions (Fig. 3). Note that off-seasonal NDVI were generated in a somewhat crude way causing very similar off-seasonal values for the different classes. An example of an image created from one of the extracted TIMESAT seasonality parameters is shown in Fig. 4. The map shows the amplitude of the growing season, which is the variation between off-season and peak season. The amplitude is lowest for artificial surfaces, slightly higher for areas dominated by heath vegetation (*Calluna vulgaris* etc.), higher again in coniferous forest (*Picea abies and Pinus sylvestris*), and highest in deciduous forest (*Quercus robur*, *Fagus sylvatica*, *Betula* spp. etc.), and open grassland. Fig. 5 zooms in on one of the areas showing how the

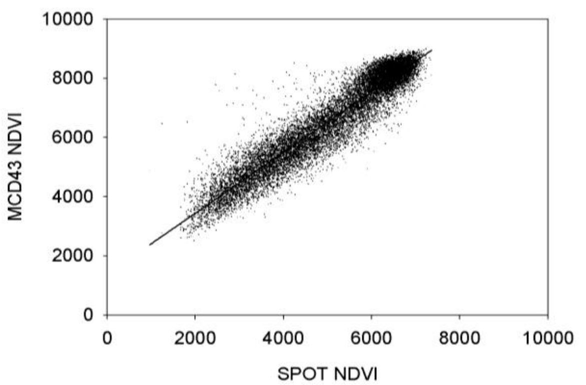

Figure 2. Scatter plot between SPOT NDVI (acquisition date 2005-09-06) and MCD43A4 NDVI (2005-09-06 composite). SPOT NDVI are 500 m averages. Solid line represents the linear regression: y = 1.03x + 1385 (r^2= 0.90).

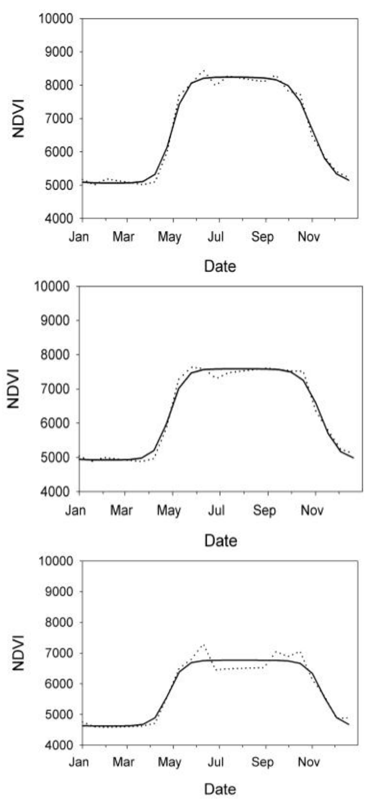

*Fig 3. Seasonal profiles for pixels in deciduous forest (top), coniferous forest (middle), and heath (bottom) (units: NDVI * 10000).*

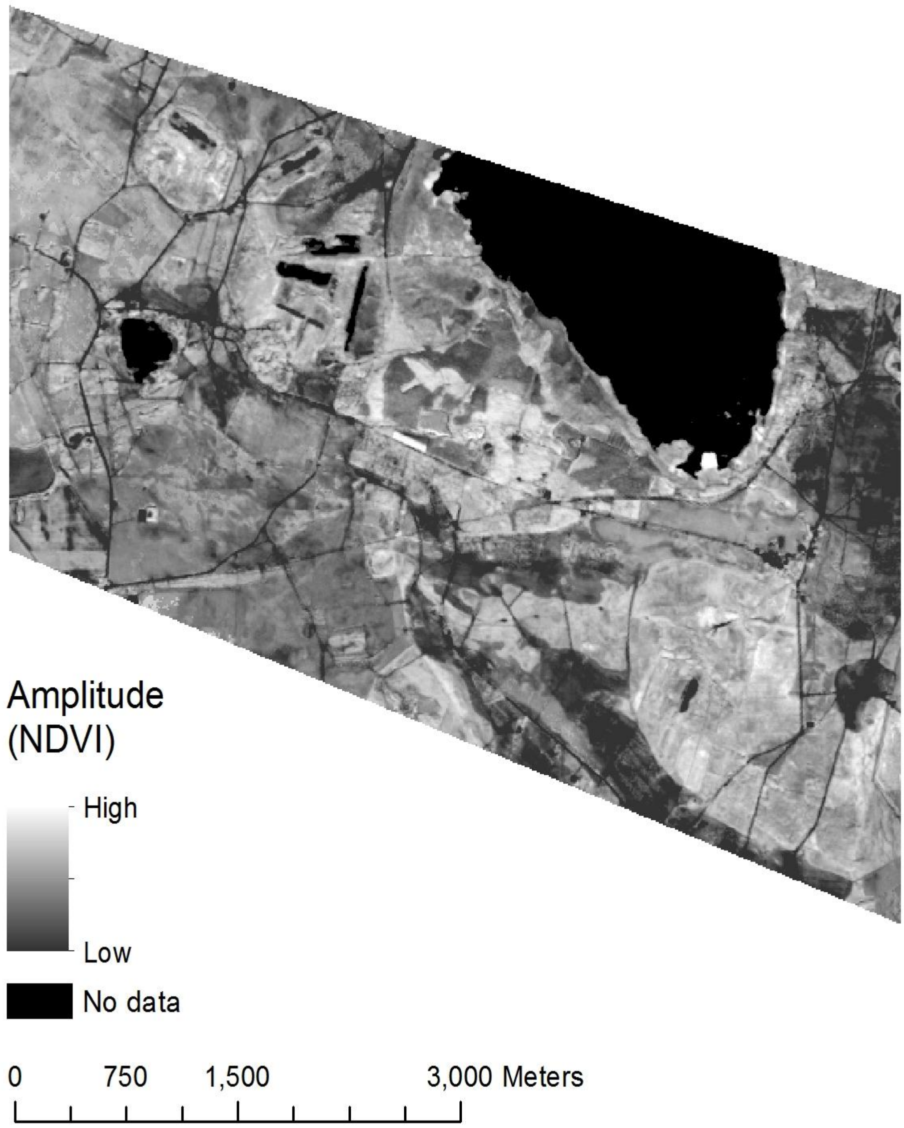

Figure 4. Amplitude of growing season, estimated with TIMESAT.

amplitude is distinctly different between coniferous and deciduous stands.

Other data generated with TIMESAT were e.g. the integrated NDVI, which is a measure that is strongly related to the productivity of the vegetation; the dates of the start and end of season; the length of the seasons; and the rates of increase and decrease of the seasons. These are not shown because of space limitations.

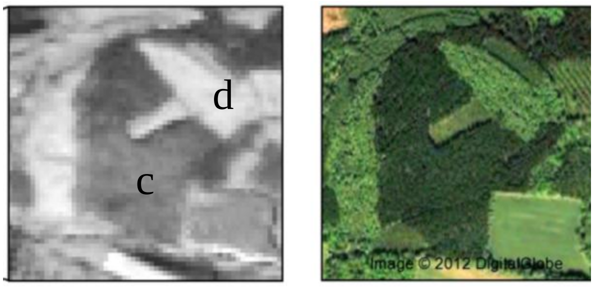

Figure 5. Zoom in from Figure 3 on areas covering coniferous (c) and deciduous (d) forest stands (left). A comparison with very-high resolution data from Google Earth is shown for comparison (right)

5. DISCUSSION

The combination of TIMESAT and high-resolution data from Sentinel-2 will be excellent for extracting precise and spatially detailed information on growing season dynamics. The simulation with SPOT data clearly demonstrated the potential of the approach.

It should be noted that the parameters extracted in this pilot study were derived from stacked data made up from a series of SPOT images from different years. They depict the average seasonality of the landscape but naturally failed in areas where strong inter-annual variations had occurred, such as in croplands. Furthermore, more subtle inter-annual differences in forest stands may have introduce some noise. These problems would not occur with real data.

The aim of the pilot study was fulfilled in the sense that the application of the TIMESAT algorithms to the data was very reliable. Some particular experiences gained during the project implementation are:

- The method relies on accurate geometric pixel-to-pixel fit between images, and this will be well met by Sentinel-2.
- Radiometry must be uniform for the images, although TIMESAT handles noise and unwanted variation between pixels in time. The use of Sentinel-2 Level 2a data (bottom-of-atmosphere reflectance) will be ideal, although Level 1c (top-of-atmosphere reflectance) will be sufficient in many cases. In our pilot study we used BRDF corrected data as normalization target, which worked very well.
- Input images do not need to be completely cloud-free, however clouds (and cloud shadow) should preferably be masked out. The Sentinel-2 cloud masks will useful. It should be noted that TIMESAT is very resistant to cloud interference by fitting to the envelope of data. Extended cloudy periods can cause some problems, and innovative approaches possibly including synergistic data from Sentinel-3 OLCI or other high-temporal resolution sensors (e.g. MODIS) might be necessary.
- Variations during the winter season may be challenging, particularly in northern areas where snow is prevalent and sun-angles are low during the winter season. More experience has to be gained in order to solve this fully.
- The precise number of scenes necessary for achieving a good fit needs to be investigated further, and varies with the specific fitting algorithm used. The selection of algorithm will depend on the data frequency, cloudiness, and will be a trade-off between portraying the data accurately and resisting noise.
- Some modification of the current TIMESAT version is necessary to handle unequal time steps in the input data.
- The Sentinel-2 satellites will generate huge amounts of data. The ability of TIMESAT to process data in parallel will be necessary for any operational applications.

The smooth seasonal profiles generated by TIMESAT are useful for biophysical modeling, as has been demonstrated by the numerous studies based on coarse-resolution data [8-10]. The ability to do this at high spatial resolution from Sentinel-2 means that models can be adapted specifically for plant stands, plant-functional types, or individual species. This will strengthen the accuracy of the models considerably.

The phenological profiles generated in TIMESAT are useful for inter-annual comparisons and analyses of trends in productivity and phenology, such as growing season lengths, start of growing season etc. They can also be used for identifying short-term variations, such as logging and other forest management practices, and natural disturbances like drought, storms, and insect infestations [15]. An added benefit is the possibility to use phenological parameters to aid in vegetation and land cover classification.

6. CONCLUSIONS

The main conclusion of this pilot study is that TIMESAT is excellent for generating smooth seasonal profiles and seasonal parameters from high-spatial resolution data such as Sentinel-2. The processing works on a pixel-by-pixel basis and is resistant to clouds and noise. Data gaps are well handled, and quality information can be included to increase the fidelity of the fits. The output data will be extremely useful for driving high-resolution biophysical vegetation models, for change detection, and for studying trends in seasonality parameters.

7. ACKNOWLEDGEMENTS

SPOT data were downloaded from the Saccess database, maintained by the Swedish Land Survey (Lantmäteriet). We acknowledge the support of the Swedish National Space Board for funding of three of the authors.

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