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Article

Evaluating Phenological Metrics derived from the MODIS Time Series over the European Continent

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Keywords: MODIS, Whittaker smoother, phenology, start of season, change detection

Summary: Regularly updated and consistent time series of the normalised difference vegetation index (NDVI) are important data sources for environmental monitoring. BOKU has setup an operational processing chain for a large European window (40° x 40°) using the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI with a 16-day compositing period and 250 m ground resolution from the year 2000 onwards. Recently, this MODIS time series has been compared with the newly released GIMMS NDVI3g dataset derived from National Oceanic and Atmospheric Administration (NOAA) satellites with (1/12)° spatial and bi-monthly temporal resolution (Atzberger et al. 2014). The NDVI time series has shown an overall moderately good agreement. However, when deriving phenological metrics from both time series, the start of season exhibited large discrepancies, which could be partly related to differences in the temporal NDVI profiles. With the present study, the validation efforts are continued. We focus on evaluating the start of season (SOS) data derived from MODIS NDVI from 2003 to 2011 with (1/12)° spatial resolution using the extraction algorithm implemented at BOKU. The study particularly considers the spatial and temporal variability over the European continent and Maghreb by comparing them with other published results. The spatial pattern of the SOS at a continental level showed a good agreement with previous work of Han (2012). A moderate (R^2 = 0.53) and good (R^2 = 0.79) relationship between SOS and altitude could be established along transects in Scandinavia. Inter-annual SOS anomalies derived for the island of Ireland coincided very well with the research results of O'Connor et al. (2012). A good agreement (R^2 = 0.90) for all pixels and years in Europe and Maghreb could be reported when compared with results of the state-of-the-art TIMESAT software (Jönsson & Eklund 2004).

Zusammenfassung: *Ableitung und Evaluierung phänologischer Kenngrößen aus MODIS-Zeitreihen für den Europäischen Kontinent.* Regelmäßig aktualisierte und konsistente Zeitreihen des normalisierten differenzierten Vegetationsindex (NDVI) sind eine wichtige Voraussetzung für die Überwachung und Modellierung von Umweltprozessen in großen Untersuchungsgebieten. Basierend auf NDVI-Zeitreihen des Moderate Resolution Imaging Spectroradiometer (MODIS) wurde an der BOKU eine Prozessierungskette für ein Europäisches Fenster (40° x 40°) aufgesetzt. Die MODIS-NDVI-Zeitreihen liegen seit 2000 als 16-Tages-Komposite mit einer räumlichen Auflösung von 250 m vor. Diese Zeitreihe wurde unlängst mit den GIMMS NDVI3g Daten der National Oceanic and Atmospheric Administration (NOAA) Satelliten verglichen, die zweimonatlich mit (1/12)° räumlicher Auflösung zur Verfügung stehen (Atzberger et al. 2014). Die NDVI-Zeitreihen zeigten eine gute Übereinstimmung. Allerdings ergaben sich relativ große Unterschiede bei dem daraus abgeleiteten Wachstumsbeginn, die sich nur z. T. auf Unterschiede in den NDVI-Profilen zurückführen lassen.

In der vorliegenden Arbeit werden diese Untersuchungen fortgesetzt. Es wird der Wachstumsbeginn (start of season, SOS) der Jahre 2003 bis 2011 näher analysiert. Die SOS-Daten wurden aus den räumlich degradierten MODIS-NDVI-Zeitreihen (1/12)° für Europa und Maghreb extrahiert. Im Fokus der Analyse steht dabei die Beurteilung der in den Daten abgebildeten räumlichen und zeitlichen Variabilität durch den Vergleich mit bereits veröffentlichen Studien. Auf europäischer Ebene zeigte das räumliche Muster des SOS eine gute Übereinstimmung mit den Ergebnissen von Han (2012). Weiterhin konnte eine mäßige (R^2 = 0.53) und gute (R^2 = 0.79) Abhängigkeit des SOS von der Geländehöhe entlang von zwei Profilen in Skandinavien festgestellt werden. Zwischenjährliche SOS-Anomalien in Irland stimmten sehr gut mit den Ergebnissen von O'Connor et al. (2012) überein. Schließlich wurden die SOS mit Ergebnissen der State-of-the-Art TIMESAT-Software (Jönsson & Eklund 2004) verglichen. Auch hier wurde eine gute Übereinstimmung über alle Pixel (R^2 = 0.90) in Europa und Maghreb erreicht.

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1 Introduction

The University of Natural Resources and Life Sciences in Vienna (BOKU) has setup an operational processing chain for a large European window (40° x 40°) using the Moderate Resolution Imaging Spectroradiometer (MODIS) normalised difference vegetation index (NDVI) with a 16-day compositing period and 250 m ground resolution from the year 2000 onwards. It provides consistently back-processed and near real-time NDVI products with quality information on a weekly basis. This NDVI time series is used at BOKU to derive regularly updated thematic products such as land cover (Vuolo & Atzberger 2012, 2014), phenological metrics (Atzberger et al. 2014) or drought indicators. At the same time, efforts are undertaken for creating 'combined' historical archives of NDVI from different sensors and adding new sensors such as Proba-V and Sentinel-2 to yield long lasting consistent time series.

To support these activities, we have started to compare and evaluate the NDVI products of the processing chain in several aspects. Recently, this MODIS time series has been compared with the newly released Global Inventory Modeling and Mapping Studies (GIMMS) NDVI3g dataset derived from National Oceanic and Atmospheric Administration (NOAA) satellites (Pinzón 2013). The GIMMS NDVI3g time series is covering the time period from 1981 to 2011 with (1/12)° spatial and bi-monthly temporal resolution. The comparative analysis comprised the data distribution, the spatial and temporal agreement of the NDVI itself as wells as derived phenological metrics such as the start and maximum of growing season (Atzberger et al. 2014). The NDVI time series has shown an overall moderately good agreement. The same holds for the maximum of season. However, the start of season (SOS) exhibited large discrepancies which were partly related to the fact that the temporal GIMMS NDVI3g profiles start rising earlier in the year than those of MODIS. The results suggested that further analysis and validation of phenological indicators is necessary.

The present paper addresses this issue while continuing the analysis previously undertaken when comparing the GIMMS and MODIS data (Atzberger et al. 2014). Its aim is to extract and evaluate phenological metrics from MODIS NDVI time series at the spatial resolution of GIMMS over Europe and Maghreb for the years 2003 – 2011. In contrast to ground based phenological observations, these time series refer to the aggregated response of a particular vegetated land surface extent (pixel) that comprises different levels of phenology e.g. individual plant, community, population and landscape. The time series also includes influences of atmospheric contamination, cloud cover, snow cover, soil wetness, and bidirectional viewing effects. Thus, we conceptually distinguish between plant phenology and land surface phenology (LSP). The present study follows the definition of White et al. (2009), who consider LSP as the study of the spatio-temporal development of the vegetated land surface as revealed by satellite sensors. The start of season is retrieved from the NDVI time series by means of the widely used relative threshold approach e.g. Jönsson & Eklundh (2002), Delbart et al. (2006), van Leeuwen (2008), White et al. (2009).

The objective of the study is to examine the plausibility of spatial and temporal patterns in the calculated SOS in the study area. Results are also checked against published results of other research teams.

2 Materials and Methods

The time series of satellite derived NDVI has been used for extracting land surface phenology metrics in many previous studies such as Reed et al. (1994), Moulin et al. (1997), Jönsson & Eklundh (2002), Stöckli & Vidale (2004), Beck et al. (2006), White et al. (2009), de Beurs & Henebry (2010). Most frequently derived metrics are displayed in Fig. 1. The current study focuses on retrieving SOS with the relative threshold approach that is implemented at BOKU. Its principle is illustrated in Fig. 1**.** The timing of the start of season occurs when the NDVI increases 20% of the seasonal amplitude from the seasonal minimum. It was out of scope of this study to explore more than one algorithm. Nevertheless, a comparison against the results obtained with the TIME-

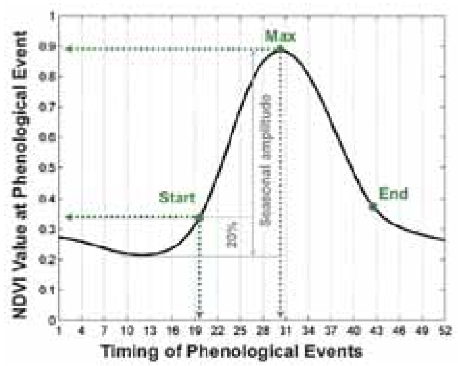


Fig. 1: Basic phenological metrics that can be extracted at particular events of a growing season (start of season, maximum/peak of season, end of season) from time series of satellite data (NDVI = normalised difference vegetation index). The principle of extracting start of season (SOS) by means of the relative threshold approach (20% of seasonal amplitude) is also displayed.

SAT software Jönsson & Eklundh (2002, 2004) is part of the current study. The TIMESAT software includes the relative threshold approach as well. Moreover, it can be considered as state-of-the-art and has been widely used in studies e.g. Beck et al. (2007), van Leeuwen (2008), O'Connor et al. (2012).

2.1 *Satellite Data and Pre-Processing*

The study's dataset included MOD13Q1 and MYD13Q1 NDVI collection 5 products of the MODIS Terra and Aqua satellites from the Land Processes Distributed Active Archive Center (LP DAAC) from the year 2000 onwards. These products are gridded level-3 data in approximately 250 m spatial resolution in Sinusoidal projection with a temporal resolution of 16 days (Terra 16-day period starting Day 001, Aqua 16-day period starting Day 009). The level-3 data are calculated from the level-2G daily surface reflectance gridded data (MOD09 and MYD09 series) using the constrained view angle – maximum value composite (CV-MVC) compositing method (Solano et al. 2010).

The MODIS products were processed within an operational BOKU processing chain comprising the following main steps:

1. downloading, mosaicking, re-projecting to geographic coordinates (datum WGS84) using nearest neighbour resampling, and image cropping to a dedicated tile system with a spatial resolution of approximately 0.002232°;
2. application of a standardised filtering for reducing the possible impact of undetected clouds and poor atmospheric conditions. The entire NDVI time series per pixel is smoothed in a single step.

The operational filtering step uses the Whittaker smoother (Eilers 2003, Atzberger & Eilers 2011a, 2011b) for smoothing and interpolating the data to daily NDVI values. It takes into account the quality of the data and the compositing day of the year for each pixel and time step based on the MODIS VI quality assessment science dataset (Solano et al. 2010). For a detailed description of the filtering procedure and settings see Atzberger et al. (2014). Only every seventh image corresponding to "Mondays" is stored as a 7-day dataset out of the resulting daily NDVI values. The 7-day interval reduces the storage load of the archive but permits an easy restoration of daily data for further applications at a later time, e.g. assuming a linear trend between consecutive Mondays. For instance, phenological metrics were extracted from daily NDVI time series allowing a better description of the timing of events.

Similar to the study reported in Atzberger et al. 2014, we used a spatially aggregated MODIS dataset consistent with the recently released GIMMS dataset at (1/12)° resolution. The spatially degraded dataset diminished the computational load that is needed to derive and evaluate phenological metrics at European scale. The spatial aggregation comprised the following processing steps:

1. averaging/resampling the smoothed MODIS data to the (1/12)° grid excluding pixels flagged as water;
2. masking all pixels that represent water in at least one time step of either MODIS or GIMMS time series (ignoring inland water bodies);
3. expanding the mask by one pixel to avoid possible artifacts.

2.2 *Study Area*

The study region covers an area of approximately 18 million km², of which more than 12 million km² is land surface (Fig. 2). The climate in the area varies between polar and arid according to the Koeppen climate classification (Kottek et al. 2006). Precipitation and temperatures show a large gradient from the fully humid to very dry Sahara desert and from polar tundra to cold/hot arid (Kottek et al. 2006). Land cover comprises a large number of different classes including cropland, deciduous, evergreen and mixed forest, shrub cover, grassland and bare areas (Friedl et al. 2010, Vuolo & Atzberger 2012).

Resulting from this huge spatial variability of the landscape and climatic conditions, one can identify a variety of growing seasons that are reflected in the spatio-temporal pattern of the NDVI. Fig. 2 depicts typical spatial patterns of the NDVI values at four different

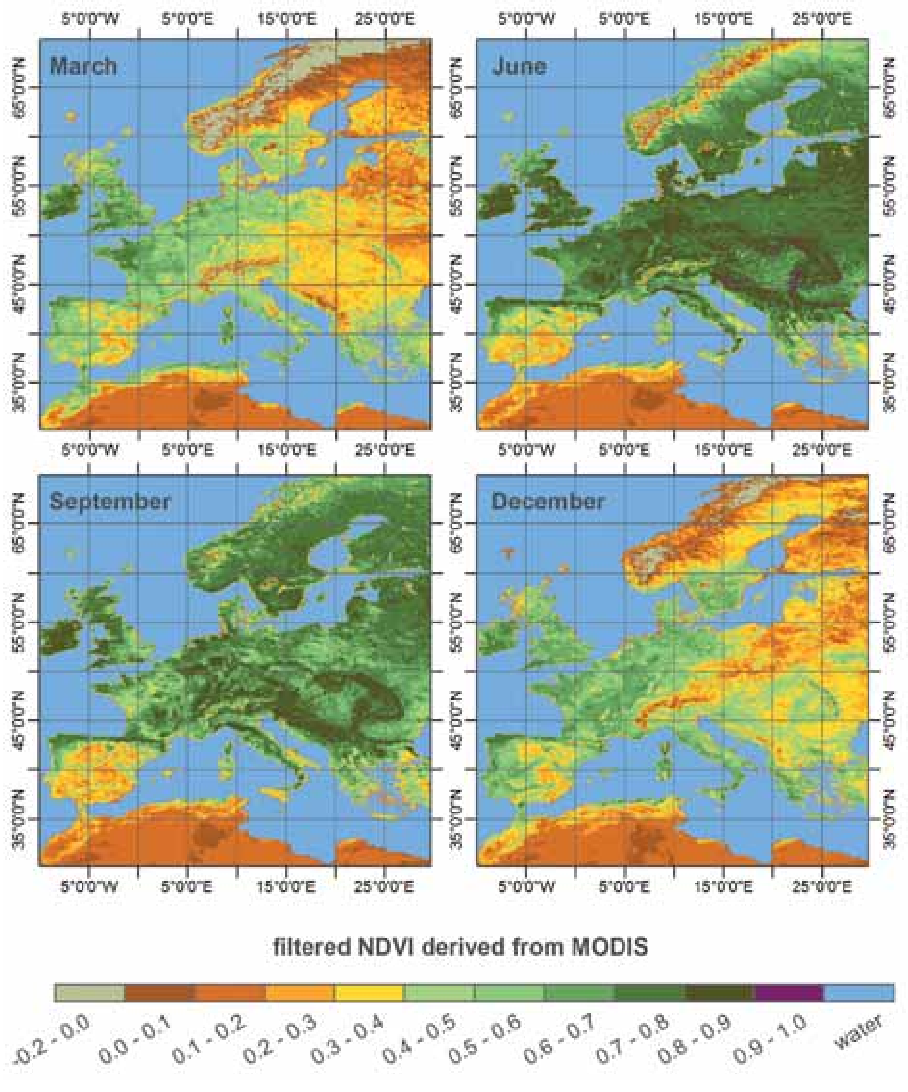


Fig. 2: Observed NDVI (normalised difference vegetation index) pattern in Europe/Maghreb throughout the year 2005 derived from MODIS, top left: March (week 12), top right: June (week 24), bottom left: September (week 37) and bottom right: December (week 50).

times in the year of 2005. It is complemented by exemplary temporal profiles of different land cover/land use types in different parts of the study area (Fig. 3).

The typical growing season of vegetation, e.g. deciduous forest, shrub cover, grassland, in wide parts of Central, Northern and Eastern Europe exhibits the onset of greenness in spring, maximum in summer and end of season in autumn. However, there are special cases such as shifted (earlier) seasons in Southern Europe/Maghreb, the occurrence of bimodal growing seasons and mixed cases, i.e. no clear distinction between growing seasons from year to year/strongly varying seasons, that should be considered when implementing a method for extracting land surface phenology. Particularly mixed cases will always be difficult to treat, but the present study focuses on distinguishing three basic cases:

- unimodal season: starting in spring/summer spanning to autumn, e.g. Fig. 3 mixed forest profiles of Sweden and Austria, crop in Italy;
- unimodal season: starting in autumn spanning to spring, e.g. Fig. 3 crop in Morocco;
- bimodal season: 1st cycle starting in spring spanning to summer, 2nd cycle starting in summer/autumn to winter, e.g. Fig. 3 mixed cropland and natural vegetation in France.

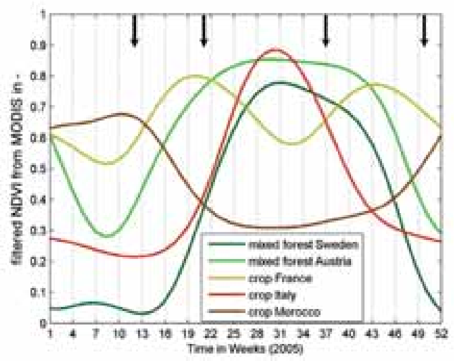


Fig. 3: Typical NDVI (normalised difference vegetation index) time profiles in Europe/Maghreb throughout the year 2005 derived from MODIS (black arrows indicate the timing of the NDVI maps in Fig. 2).

2.3 *Extraction of Phenological Metrics from the NDVI Time Series*

BOKU implementation

Land surface phenological metrics were extracted for areas having a maximum NDVI of at least 0.3. The implemented approach allows detecting both uni- and bimodal growing seasons. In case of bimodal growing seasons, however, we extracted/evaluated only the metrics of the first season. The selected approach is able to manage seasons spanning over different years. For this paper, the extraction has been summarised in four steps, yet a detailed description can be found in Atzberger et al. (2014):

1. detecting the number of cycles by means of auto-correlation information;
2. focussing on the first cycle of the season in case of multiple cycles;
3. defining a temporal search window for each growing season depending on the number of detected cycles based on the moment of minimum and the moment of maximum; so to identify a reasonable and reproducible minimum. We decided to use the steepest preceding increase as a criterion;
4. detecting start and end of season (SOS/EOS) using a relative threshold of 20% of the seasonal amplitude (Fig. 1).

The extraction procedure detected the growing seasons from 2003 to 2011. This restriction was necessary as growing seasons might span different in the years as shown in Fig. 3 for Morocco. For example, valid starts of the growing season of 2003 can range from beginning of July 2002 (-183) to end of June 2003 (181) counted in days of the year (DOY). If values occurred outside the defined start ranges, it was checked if they could belong to a different season.

TIMESAT implementation and data processing

The TIMESAT software (version 3.0) (Jönsson & Eklundh 2002, 2004) was employed to derive a second SOS dataset for comparison. The software provides an adaptive Savitzky-Golay filtering, an asymmetric Gaussian or double logistic model fit for filtering the data.

The number of potential annual seasons is determined by analysing a fitted model function. It can be controlled by a user defined threshold (season parameter) that can be applied region-specific by using a land cover map and setting a different season parameter for the land cover classes (for details see Eklundh & Jönsson 2009). The seasonality parameters such as the time of the start and end of the season are calculated for each growing season respective the number of annual time steps. The SOS is extracted at the time, when the NDVI has increased to a user defined level of the seasonal amplitude. The results of the processing are stored in a binary file. To retrieve annual SOS images, a time window containing the season must be defined.

As the MODIS NDVI data were already filtered and stored as a 7-day dataset, the parameters of the Savitzky-Golay filter were set to a window size of one using the NDVI time series from 2002 to 2011 with 52 annual time steps and adding 2011 as additional year to the end of the time series. To make sure that the growing seasons of each pixel were treated in the same way as with the BOKU approach, the season parameter was defined for two land cover classes separately: 1 for unimodal growing seasons and 0 for bimodal growing seasons. In both cases, the relative threshold of 0.2 was applied. The time window of the annual growing seasons was fixed for the entire study area in a way that it accounted for seasons spanning two calendar years. For instance, to cover the growing seasons of 2003, the window was defined from the first week of July 2002 until the last week of June 2004.

Due to different approaches in defining the timing of the growing season in both implementations, the SOS had to be adjusted before comparing them. Thus, both SOS datasets were re-assigned to the calendar day and year when they actually occurred. The resulting SOS images ranged between 1 and 366. Special attention was paid when inter-comparing years for pixels where starts may fall into different years (see section 3.3).

3 Results and Discussion

3.1 *Spatial Consistency of the Start of the Growing Season*

Maps of the start of season (SOS) were derived for each year from 2003 to 2011 yielding up to nine SOS estimates per pixel (see section 2.3). The median of SOS across Europe/Maghreb is shown in Fig. 4 left. As an example for the observed inter-annual variability, the SOS of 2005 is also displayed (Fig. 4 right).

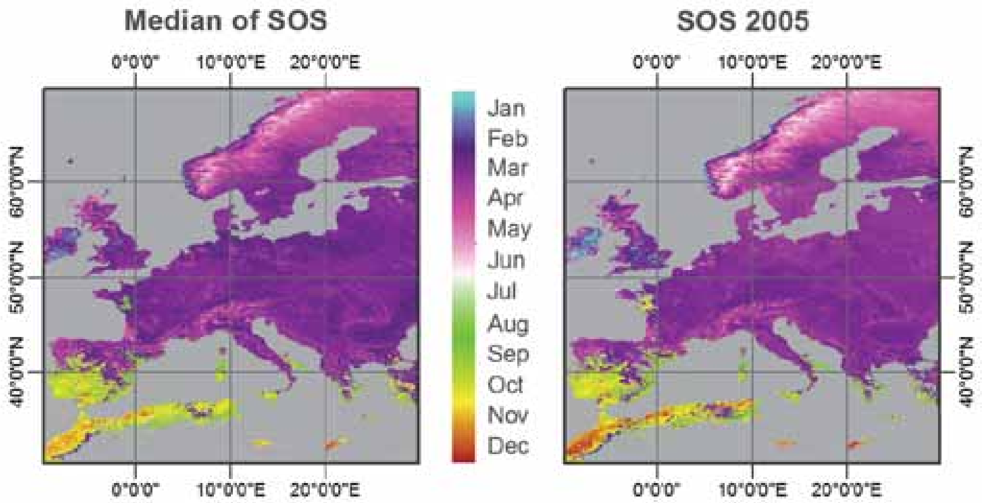


Fig. 4: Spatial pattern of the start of season (SOS) derived from MODIS NDVI time series, left: median of the SOS over the years (2003 – 2011), right: SOS of the year 2005.

Overall, the observed spatial pattern shown in Fig. 4 reflects well existing gradients within Europe resulting from the combined impact of land cover, latitude, altitude, temperature and rainfall regimes (Stöckli & Vidale 2004). Light purple to white colours indicate late starts from May to June and predominantly appear in forests, shrub cover or grassland in mountainous areas e.g. Scandinavia, the Alps, the Pyrenees and the Carpathian Arc. Earlier starts with dark purple colours (March to April) appear at lower altitudes e.g. to the north of the Alps and to the east of the Carpathian Mountains. Very early starts (January to February) are visible in oceanic Ireland. Southern Spain, the coastal regions of southern Europe and Maghreb show a distinct earlier SOS due to their particular temperature and precipitation patterns (October to December). A very similar map was derived from a SPOT-VEGETATION NDVI time series averaged over seven years (1999 – 2005) at 1 km spatial resolution by Han (2012), confirming the results of this study. Interestingly, both studies reveal a SOS as late as August/September for a distinct patch in the Pays de la Loire region of France (see small yellowish spot at the Atlantic coast of France).

O'Connor et al. (2012) examined the spatio-temporal patterns of the SOS across Ireland using medium resolution imaging spectrometer (MERIS) global vegetation index (MGVI) at 1.2 km spatial resolution (2003 – 2009) and the TIMESAT software. The derived map highlights SOS variations according to CORINE land cover 2000 and 2006. Considering the differences in spatial resolution between our study and O'Connor et al. (2012), we found again a close agreement in the spatial pattern of the mean of SOS. In addition, the spatial link between the SOS and the land cover type is apparent. Later SOS (April – May; pink colours) in the west and southeast of the island agree with the land cover types peat bogs as well as moors and heaths. On the contrary, pastures show the earliest SOS (January – February) with turquoise to purple colours.

To further examine the plausibility of our SOS map, the relation between altitude and SOS was analysed for two transects in Scandinavia (Fig. 5). In Scandinavia, GIMMS data already have been successfully used by Karlsen et al. (2002, 2009) to derive phenological maps and to relate them to traditional vegetation zone maps. To examine the relation between altitude and the SOS in the present study, the SOS pixels were chosen based on a simplified (recoded) land cover type 1 product MCD12Q1 v005 from MODIS (Friedl et al. 2010, Vuolo & Atzberger 2012). Only pixels

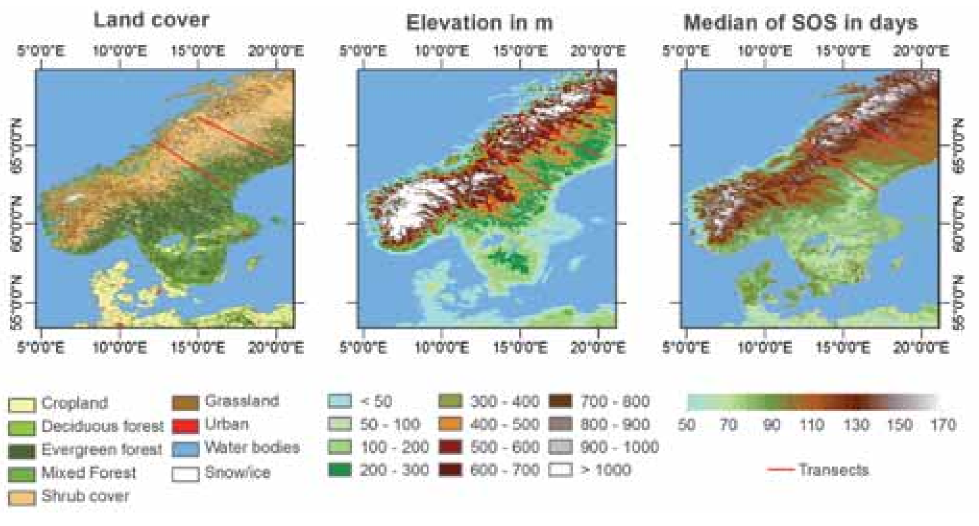


Fig. 5: Left: spatial pattern of recoded land cover type 1 product MCD12Q1 v005 from MODIS (Friedl et al. 2010, Vuolo & Atzberger 2012), centre: mean elevation (NOAA 1988), right: median of SOS (start of season) for Scandinavia. In all maps, the location of the transects is included.

labelled as deciduous forest, mixed forest or shrub cover were selected from this simplified map. Fig. 5 shows the location of transects, the land cover types (left), the average elevation map (NOAA 1988) (centre) and the derived median of the SOS (right). For this figure, the SOS colour scheme has been adopted to resemble the elevation map.

Similar spatial patterns can be observed in Fig. 5, centre and right, between elevation and SOS. The starts extracted by the BOKU approach are found to vary between March and May (DOYs 60 – 151) and generally increase with altitude. Compared to the results of Karlsen et al. (2002), our SOS results appear anticipated by about one month. However, the overall spatial pattern of SOS (as shown in Fig. 5 right) agrees with their results very well. The observed bias can be related to diverse definitions of the relative threshold when extracting the SOS. Karlsen et al. (2002) used the 18 year mean NDVI value for each pixel whereas our approach identifies the 20% seasonal amplitude, which is reached earlier.

The relationship of the median of the SOS (2003 – 2011) and the altitude along the two transects of Fig. 5 are plotted in Fig. 6. The southern and northern transects yield moderate (0.53) and good results (0.79) respectively in terms of R^2. For the northern (southern) transect, we found for each 100 m elevation difference a 6 days (7 days) increase of the SOS. This supports Hopkins' empirical law (for the US) between the timing of spring growth and elevation which states that the SOS is delayed 3 – 4 days for every 100 m increase (Hopkins 1920, Reader et al. 1974, Fisher & Mustard 2007). Our results also compare well with Dunn (2009) reporting equally high numbers of up to 7 days delay for study sites in the Rocky Mountains derived from MODIS data at 1 km spatial resolution.

The lower R^2 for the southern transect (Fig. 6 left) was confirmed when regressing individual years to altitude. The annual R^2 values range between 0.41 and 0.56. The lower R^2 result from stronger variations of the SOS at lower altitudes (eastern part of the southern transect) cannot primarily be explained by a change of elevation.

3.2 *Temporal Consistency of the Start of the Growing Season*

The analysis of the temporal consistency of the SOS was checked for the period 2003 to 2011. As already shown in Atzberger et al. (2014), the range of the SOS per pixel across the nine years varies between 17 and 35 days (25th and 75th percentiles) in Europe, with a median of 24 days. Again, we checked our data against the study of O'Connor et al. (2012) in Ireland, where a 10-day composited time series of MGVI data from 2003 to 2009 was used. For the comparison, the mean SOS of the MODIS data was plotted for the same years (2003 – 2009) in Fig. 7. It was found that the individual years of both studies fit visually quite well (not shown). Likewise, when annu-

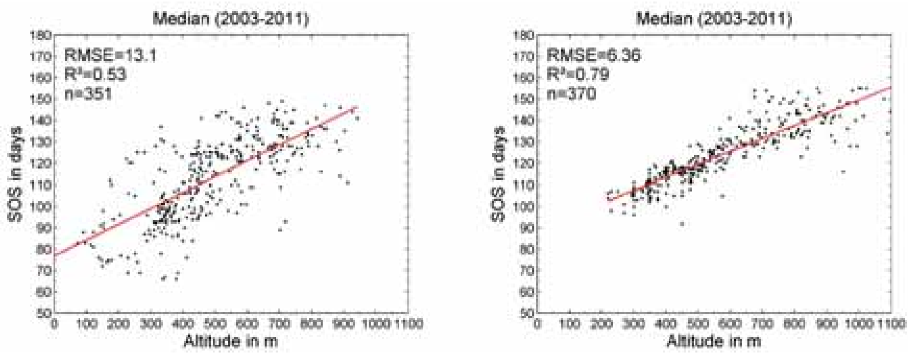


Fig. 6: Scatterplot between the SOS (start of season) and the altitude for the two transects shown in Fig. 5, left: southern transect, right: northern transect. The resulting linear regression lines are displayed in red.

al anomalies were calculated with respect to the mean SOS and grouped into classes of ten days, spatio-temporal patterns similar to the ones described in O'Connor et al. (2012) were found (Fig. 7). Individual years highlighted by O'Connor et al. (2012) were also evident in our data. For example, O'Connor et al. (2012) highlighted an SOS later than average in 2004 and 2006 due to an unusual cold winter and/or spring. For 2009, a later SOS in the south and an earlier SOS in the north was reported by O'Connor et al. (2012). A noticeably early SOS occurred in 2005 and 2007. The mentioned anomalies can be well retrieved in the MODIS derived SOS maps (Fig. 7).

The most striking event in our data was found in 2010, when the SOS of the entire island was strongly delayed by 38 days on average due to an exceptionally cold winter as reported by the Irish Meteorological Service (Met Éireann 2010). However, this year was not covered by the data of O'Connor et al. (2012).

3.3 *Comparison with the Results of TIMESAT*

To highlight similarities and differences between our approach and alternative methods, the widely used TIMESAT software (Jönsson & Eklundh 2002, 2004) was employed to extract the SOS from the MODIS data with respect to the growing seasons from 2003 to 2011. The SOS derived from TIMESAT and BOKU are compared by calculating the difference between the median of SOS in both datasets (Fig. 8, left).

Particularly in regions with SOS at the end/at the beginning of the year, e.g. Maghreb, starts may fall into different years for the compared approaches resulting in anomalous great differences, e.g. SOS differences > 100 days. Thus, special attention was paid to these cases. Before calculating the SOS difference, 365 (days) was subtracted from the SOS values close to the end of the year yielding in negative starts.

As shown in Fig. 8 left, light to dark blue colours indicate an earlier SOS in the TIMESAT results compared to the BOKU results, whereas orange to dark red colours represent later SOS for TIMESAT. As both implementations use the relative threshold approach, one can observe very similar results in large parts of Central and Eastern Europe with differences within ± 5 days (ca. 85% of pixels). Larger differences (ca. 15%) result from earlier SOS for TIMESAT, which occur predominantly in Northern and Central Europe, e.g. Scotland, Norway, Sweden, Germany, Poland, but also in Southern Spain and Maghreb (Fig. 8,

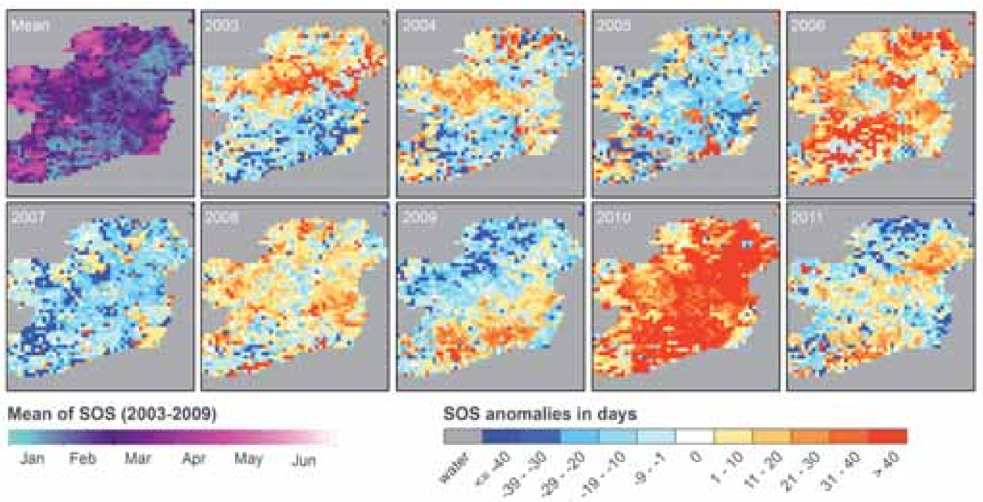


Fig. 7: Mean SOS (start of season) (2003 – 2009) and annual SOS anomalies (year – mean) for the island of Ireland. Note the two different colour scales.

left). The average absolute difference between TIMESAT and BOKU over all years and pixels is only four days.

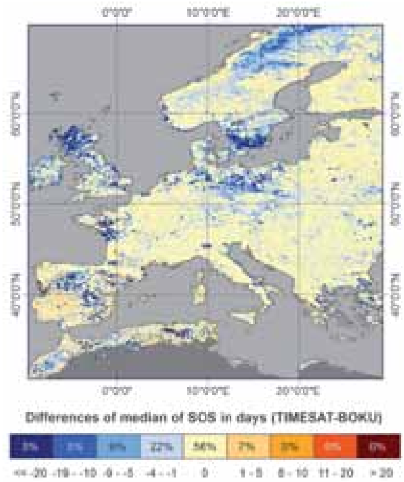
A scatterplot of the SOS from both implementations for all pixels of all considered years is shown in Fig. 8, right. Only the ordinate of the scatterplot ranges from negative to positive SOS values, as most of the above mentioned SOS corrections affected the starts extracted from TIMESAT. The calculated R^2 between both SOS time series of 0.90 confirms their good agreement. Most of the cases that diverge from the 1:1 line have earlier SOS for TIMESAT and thus appear below this line.

The SOS differences between both implementations can be related to different approaches of dealing with seasonal minima. TIMESAT always refers to the minimum between the consecutive maxima of two growing seasons. The seasonal amplitude is calculated respective the average of the left and right minimum values (Jönsson & Eklundh 2004). The BOKU algorithm tries to consider possible "noise" at the beginning of the season, e.g. small green peaks in winter due to the growing of winter crops. Thus, the algorithm searches for the steepest preceding increase and defines the minimum at the beginning of the identified increase (see section 2.3). The amplitude is just determined relative to the left minimum.

4 Conclusions

The present study was meant to continue research regarding phenological metrics from MODIS NDVI time series previously described in Atzberger et al. (2014). The study focused on the start of the growing season from 2003 to 2011 and results are compared against other published results. To exclude misinterpretations solely due to an erroneous implementation of the selected threshold approach, the SOS results of the BOKU implementation have been compared with results of the state-of-the-art TIMESAT software. The intention here was to check the plausibility of the own results as well as highlight existing differences and agreements worth to consider in further developments and work at BOKU. From the above, the main findings and conclusions can be summarised as follows:

- The averaged SOS (median) in Europe showed a good agreement with a previous work of Han (2012). This confirms the spatial consistency of the derived SOS.
- The relationship of the median of the SOS and the altitude at pixel level along two transects in Scandinavia yielded moderate ($R^2 = 0.53$) to good results ($R^2 = 0.79$). The observed positive correlation between altitude and SOS is well documented in the literature.



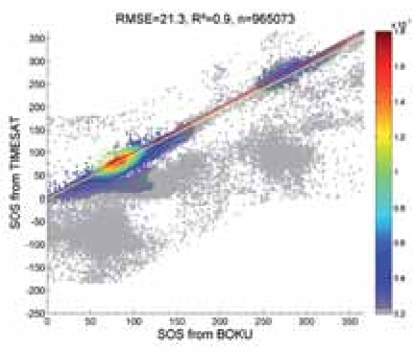


Fig. 8: Comparison of the start of season (SOS) derived from MODIS 2003 – 2011, left: difference of median SOS between TIMESAT and BOKU; right: scatterplot of SOS between TIMESAT (y-axis) vs. BOKU (x-axis) derived from the full image extent, also shown are the 1-to-1 line (red) and the regression line (light yellow), increasing densities from light grey to blue to yellow to red.

- Very good agreements of the inter-annual anomalies were found for the island of Ireland respective the study of O'Connor et al. (2012). The given resolution of (1/12)° of the MODIS time series deemed suitable for visual and magnitude comparison. However, this spatial resolution cannot fully reflect the same spatial variation as shown in O'Connor et al. (2012) with 1.2 km.
- The particularly cold winter of 2009/2010 and its impact on the SOS in Ireland, with an average delay of more than 30 days, could be successfully reproduced with the MODIS time series. This shows that such events can be possibly detected and mapped in near-real-time.
- A good agreement with minor differences for 85% of the temporally averaged SOS pixels over Europe and Maghreb with results of the TIMESAT software was found. The average absolute difference to the TIMESAT results over all years and pixels is only four days. This indicates that the derived SOS maps would not be markedly different using another algorithm.
- Difference in the SOS to TIMESAT result from different implementations of the relative threshold approach. Their impact has to be carefully analysed in the future.

A first attempt was made to evaluate the BOKU implementation for extracting SOS with ca. 8 km spatial resolution NDVI data. This exercise will be repeated at full spatial resolution of MODIS NDVI with 250 m. Future studies should focus on validating satellite-derived land surface phenological indicators. Long lasting and relatively dense phenological networks, e.g. Austria, Germany, could be used to evaluate satellite-derived maps against field observations as already shown by e.g. Soudani et al. (2008), Bradley et al. (2009), Liang et al. (2011).

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