REMOTE SENSING-BASED QUANTIFICATION OF SPATIAL AND TEMPORAL VARIATION IN CANOPY PHENOLOGY OF FOUR DOMINANT TREE SPECIES

QIFEI HAN February, 2012

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ABSTRACT

The spatio-temporal development of the vegetated land surface as revealed by satellite sensors is allowing measurement and monitoring of vegetation phenology at multi spatial scales. The overall objective of this study is to characterize the spatial and temporal patterns of satellite-derived phenology metrics for four dominant tree species (i.e., beech, birch, pine and spruce) across Europe. The specific objectives are thus 1) to identify the key phenology metrics significantly distinguished among the four tree species; 2) to investigate the spatial variation of phenology metrics for different tree species along the geographical (latitude/longitude/altitude) gradients; 3) to examine the relationships between phenology metrics and climate factors (i.e. temperature and precipitation).

In this study, a threshold method is used to estimate the start of season (SOS), length of season (LOS), Maximum NDVI (MaxNDVI) and Integral NDVI (I-NDVI) for the selected species from SPOT VGT NDVI data. At the European continental scale, the deciduous forest can be distinguished from the evergreen forest by their distinct SOS, and the four species can be distinguished by using the combination of SOS and I-NDVI.

The dependence of phenology metrics on latitude are well characterized except for beech, which is more rely on altitude. The beginning of the growing season starts 1.6 days later per 1° latitude from south to north for birch, 2.3 days for spruce and 2.9 days for pine. The average length of season exhibits a similar trend as SOS, i.e. 2.7 days shorter per 1° latitude for birch, 2.8 days for pine and 3 days for spruce. The Max-NDVI remains stable while the integral NDVI is slightly varied along latitude. The 1° latitude northward induces I-NDVI smaller by 1.8, 0.8 and 1.3 for birch, pine and spruce respectively. The relationship between SOS and the longitude is significant only for birch (R² range from 0.45 to 0.68 for four phenology metrics): SOS starts later from west to east by 0.7 d per 1° longitude, LOS is 0.7 days shorter per 1° latitude.

The rate of change in SOS as a function of mean annual temperature is highest for pine species (5.6 days per 1°C), followed by spruces. The LOS and SOS, are well-correlated with the mean annual air temperature ($1^{\circ}C = 4.5$ days SOS, 7 days LOS) but not with precipitation. However, the significant relationships have been found between the SOS/LOS and the precipitation in winter (December to February) in Mediterranean area. The phenological response to climatic variability (1999-2005) varied with species. The SOS is the most sensitive phenology metrics and the birch the most sensitive species.

We get the conclusion that remote sensing phenology is able to estimates the phenological metrics over large areas. This makes our research the first one to characterize the spatial and temporal variation of phenology for different tree species across Europe using remote sensing.

Keywords: Remote sensing phenology, tree species, spatial variation, climate

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1. INTRODUCTION

1.1. Background

1) Phenology

Phenology studies the annual rhythm of biological phenomena mainly in relation to climate parameters (Maignan et al., 2008). When applied to plants, phenology refers to the remarkable events such as the beginning of season, end of season, or start of major growth phases like budding or flowering. The research on plant phenology has improved the understanding of the variation in life cycle events in the past centuries (Ahlgren, 1957; Arroyo, 1990; Bianco & Pitelli, 1986; Slade, 1975; Williams, 1971). Recently, phenology has been widely applied in research on terrestrial ecosystem and ecological models.

Firstly, causes and consequences of plant phenology response to climate change have received increasing attention recently (Ehrlen et al., 2007). Convincing evidences demonstrate that species are altering their phenology (Menzel & Fabian, 1999; Visser & Holleman, 2001) due to climate change. Numerous recent phenological studies have been reported in this context (Chmielewski & Rötzer, 2001; Wang et al., 2010).Secondly, quantifying the effect of phenological variability is necessary for understanding the uncertainty of the terrestrial carbon cycle. White et al. (1999)suggested that failure to incorporate realistic phenological subroutines will induce serious errors in simulated carbon fluxes. In addition, phenology also related to ecological assessment, agriculture monitoring and biome classification (Gu et al., 2010; Haralick et al., 1980; Schiller et al., 2005; Xin et al., 2002). Site and species-specific phenological measurements are now broadly used for those purposes (Ivizi & Araujo, 1997; Valdez-Hernandez et al., 2010).

2) Phenology derived from remote sensing

Phenological data are comparatively scarce in many parts of the world. Moreover, ecological models relating to climate change studies require phenology information at large spatial scales, other than the inventory data which focus mostly on specific plant species and are mostly point observations. As a result, remote sensing data for inferring phenological characteristics of vegetation is increasingly regarded as key to understanding large area seasonal phenomena (Prasad et al., 2007) . The vegetation phenology derived using remote sensing is defined as land surface phenology (LSP) by de Beurs and Henebry(2004). It refers to the spatio-temporal development of the vegetated land surface as revealed by satellite sensors. Remote sensing technology has been used for monitoring the seasonal dynamics of vegetation at large spatial scales in recent decades (Asner et al., 2000; Hill & Donald, 2003; Roberts et al., 1997). As illustrated by Bin et al. (2008), remote sensing provides a key means of measuring and monitoring phenology at continental to global scales. Vegetation indices derived from satellite data as a proxy for phenology are now commonly used for this purpose.

Among the several vegetation indices derived from remote sensing, the Normalized Difference Vegetation Index (NDVI) is the mostly used one for reflecting the seasonal variation of growing vegetation and the shift between the vegetation covers. The NDVI is derived from the red and near-infrared reflectance ratio: NDVI = (NIR-RED)/(NIR+RED), where NIR and RED represent the amounts of near-infrared and red light reflected by the vegetation and captured by the sensor of the satellite, respectively. The value of NDVI values range from -1 to +1. Agrawal et al. (2003)have illustrated that NDVI can reduce influence of topographic factors. NDVI is usually assumed broadly indicative of, and associated with, plant photosynthetic activity and aboveground primary production. At the same time, remote sensing is the possibility to gather information at regular time intervals over large areas. These time series data can be

utilized for monitoring phenological dynamics. In term of this, NDVI time series have been extensively used for monitoring vegetation phenology (Li et al., 2008; Lv & Sun, 2009; Zhang et al., 2006). Chen and Pan (2002) suggested that phenology can be an effective means to monitor inter-annual vegetation dynamics and to estimate growing season parameters using meteorological and satellite data at regional scales.

The use of daily data at medium spatial resolution provided by satellite sensors such as AVHRR, MODIS or SPOT VEGETATION to investigate the timing of canopy phenology (Beck et al., 2006; Delbart et al., 2005; Fisher et al., 2006; Guyon et al., 2011; Maignan, et al., 2008; Soudani et al., 2008). At the same time inter-annual changes or its long-term trends of phenology on large extents has been widely developed during the last decade (Delbart et al., 2006; Myneni et al., 1997; Stöckli & Vidale, 2004; Zhou et al., 2001). These various studies benefited from substantial advances in the renovation of land surface reflectance time-series data, in particular due to the recent improvements in filtering of cloudy or snowy pixels, correction of atmospheric disturbances and normalisation of directional effects (Bacour et al., 2006; Hagolle et al., 2005).

Each satellite-based sensor provides certain advantages and disadvantages. the VEGETATION instrument on-board SPOT 4 can offer a valuable tool for vegetation mapping at regional scale (Agrawal, et al., 2003). The high temporal resolution of 10m day compare to 16 days of MODIS allows the capability for image selection according to best quality, least cloud cover and the optimal phenological stage of vegetation cover, which plays a significant role in monitoring the phenology variation.

The derivation of phenology of forest ecosystems from remote sensing is commonly based on the analysis of the seasonal trajectory of NDVI indices pixel-by-pixel. The start and the end of the growing season are identified from the increase of vegetation index in spring and its decrease in autumn with time (Guyon, et al., 2011). Several approaches can be used for phenology derivation. The range of methods can be divided into four main categories: threshold, derivative, smoothing algorithms, and model fit. The simplest and most frequently applied method determines SOS and EOS based on threshold values. Some researches (Alberte, 1994; Lloyd, 1990; Zhou et al., 2003) arbitrarily use a threshold value at a certain level or amplitude, like 0.09, 0.099 to define the specific NDVI value for timing of season. The SOS is then determined as the day of the year (DOY) that the NDVI crosses the threshold in upward direction; likewise, the EOS is determined as the DOY that the NDVI crosses the same threshold in downward direction. The conceptual of derivation is defined the maximal increase and decrease in NDVI as the SOS and the EOS (Balzter et al., 2007; Tateishi & Ebata, 2004a; White et al., 1997). They assumed that the SOS is characterized by the greatest leaf expansion or the fastest green-up during the growing season. Smoothing algorithm determined the SOS and the EOS as the dates that a smoothed time series crosses a curve established from moving average models. The moving average has an introduced time lag which is arbitrarily chosen (Reed et al., 1994). The last category for vegetation phenology derivation based on satellite imagery is model fitting. Several models have been developed to allow the variability of natural environment, like logistic models (Badhwar, 1984; Jönsson & Eklundh, 2002), Gaussian local functions (Jönsson & Eklundh, 2002).

3) Application of remote sensing phenology

Over the past two decades, remote sensing phenology has provided tools for many purposes including monitoring biospheric activity, developing prognostic phenology models, and deriving land cover maps (Reed et al., 2003). Satellite based phenology measures have also been utilized to study trends in growing season length and vegetation production. Myneni et al. (1997) presented evidence from satellite data that the photosynthetic activity of terrestrial vegetation increased in plant growth associated with a lengthening of the active growing season. (Tucker et al., 2001) using NDVI data from NOAA satellites from 1982 to 1999 estimate variations in photosynthetic activity and growing season length at latitudes above 35°N,

and get the same results as (Myneni, et al., 1997). Their study showed that the NDVI increases were associated with earlier starts of the g rowing season and with increases in the surface temperature at these latitudes. Phenology variation detected by remote sensing helps in the classification process to accurately discriminate vegetation types based on their growing characteristics. In the study of (Agrawal, et al., 2003), SPOT VEGETATION data has been used to prepare a land use/land cover map of south central Asia. Their project aims to explore the possibilities of SPOT VEGETATION data sets for vegetation analysis. The differences between evergreen and deciduous trees can be highlighted by the fact that the former may appear quite uniform throughout the year, whereas the latter varies widely between leaf-on and leaf-off periods. The discriminant power of multi-temporal observations is based on their characterization of seasonal dynamics of vegetation growth. With the use of multi-temporal satellite images people can detect and monitor phenological variations and timings over large areas, at a lower cost, and frequently several times each week. The use of multi-temporal images not only results in higher classification accuracy but also gives consistent accuracy in all classes being mapped.

Phenology has emerged as an important emphasis for ecological research since it is sensitive in identifying how plant species respond to climate conditions and to climatic changes. In mid-latitudes the seasonal timing of spring events of plants depends highly on air temperature. Several phenological studies were reported on earlier spring events in recent decades (Ahas et al., 2002; Menzel, 2000; Stöckli & Vidale, 2004), and the results vary among different species (Kramer et al., 2000). In climates with a distinct seasonality, the vegetation adapts to this seasonality by its phenology. If a significant climate change occurs, forest tree species will be not well adapted to this new climate. It is important to understand the climatic factors driving the phenology of the vegetation in the context of assessing the possible impact of climate change on growth of different forest ecosystems in Europe.

4) Phenological analysis on European forest

Forest ecosystems have competing importance regarding to their economical, ecological and social functions. Forests cover 44% of Europe's land area and they continue to expand. The trees that grow in the forests of Europe can be placed into two major categories: coniferous and broad-leaves. The oak, beech and birch trees are all examples of broad-leaved trees. The Cork oak and Holm oak are the only two evergreen broad-leaved trees. The fir, pine and spruce are well-known coniferous trees. In colder climates, boreal forests made of conifers are dominant, while in temperate regions, varieties of tree species are distributed. There are also mountain forest and dry Mediterranean forest presence in Europe (CEJA, 2002). The results from (Köble & Seufert, 2001b) showed that Scots pine, Norway Spruce, Common Beech, Birch cover 68.7% of the forest area in the 30 countries considered.

However, as illustrated by Alley et al. (2003) Forest ecosystems seem to be especially prone to climate change and European forests are among the most intensively used forests of the world. Against this background, analysing forest ecosystems status and their dynamic builds a substantial basis for future conservation practice and strategies. Several research and review papers concern the phenology of forest trees and ecosystems in Europe. Wang et al. (2005)evaluate the seasonal variation of MODIS derived leaf area index at two European deciduous broadleaf forest sites. Menzel et al. (2009) got the conclusion that European phenological response to climate change matches the warming pattern after they captured the spatial variation in onset dates and trends in phenology across Europe. Rötzer & Chmielewski (2001) map the phenological pattern of Europe using observatory data of IGPs.

1.2. Problem statement

1) Remote sensing employed as a way of examining phenology variation for different tree species at continental scale is scarce.

Why the phenological variation of different tree species is important? Recently, with the Kyoto protocol, the interest has been focused on tree species 'potential for mitigation of greenhouse gases

and for carbon sequestration (Jandl et al., 2007). In addition, it is becoming increasingly important that agencies working with forests fully understand the seasonal behaviour of different tree species. Vegetative and reproductive responses of different tree species vary considerably(Ahlgren, 1957). An understanding of how these variations occur for different tree species is important to the tree breeder, entomologist, physiologist, ecologists and so on. Moreover, fully comprehensions of tree species phenology provide guidance on carbon and species distribution modelling.

Although A number of phenology researches for different tree species are carried out, the data being used are inventory data(Bhat, 1992; Dahiya, 2003; Ivizi & Araujo, 1997; Reich et al., 2004; Valdez-Hernandez, et al., 2010). And considerable researchers investigated the forest phenology using remote sensing data, they did not investigate the species level(Duchemin et al., 1999; Guyon, et al., 2011; Wang, et al., 2005; Wang et al., 2004; Yu et al., 2005). All in all, research examining the phenology variation for different tree species using remote sensing at the continental scale is scarce.

2) Analysis of phenological response as a function of geographical gradient is uncommon.

Responses of phonological events in plants to climate change may vary with latitude/longitude and altitude gradient. The spatial variation maps showing the phenological response as a function of geographical gradient are important in several aspects: they form the bases of maps displaying the climatological suitability for growing trees, the risk of frost damage for fruit trees and the climatic risks of plant diseases and pests affecting forest.

Nevertheless, the status is most studies conducted for different tree species with similar geographical zones, or for several forest types along a geographical gradient, few of them have been made for different tree species along geographical zones. Data analysis of phenological response as a function of geographical gradient at continental scale is still uncommon (Doi & Takahashi, 2008). (Rötzer, 2001) analysed the spatial pattern of phenology in Europe with inventory data from IGPs; however the advantages of using remote sensing data will be revealed in this research.

3) Which phenological metrics can better explain the variation of tree species and geographical gradient are unidentified.

The interrelationship among phenological, climatic, and satellite-derived variables can be well explained by using satellite-derived variables as proxy. Chen and Pan (2002) demonstrated that generally speaking, estimating the beginning date of the growing season is more reliable than estimating the end date. Also, Chen (2001) recommended that the beginning of season and the length of the phenological growing season are principle variables to assess the impact of seasonal and interannual climate change on terrestrial vegetation and to evaluate the role of vegetation in the seasonal carbon cycle. These phenology metrics reflect the amplitude and timing of variations in carbon estimation. However, when involving the geographical gradient and tree species, which metrics can better explain different variations are still unidentified.

4) It is important to understand the climatic factors driving the phenology of the vegetation in the context of assessing the possible impact of climate change on growth of different tree species in Europe. Climatic seasonality may be caused by temperature or precipitation and the influences vary among different areas and different species. To exam which one is the dominant factor, relationship between phenology and temperature/precipitation should be constructed.

Overall, research investigating the spatial phenology variation for different tree species using remote sensing at continental scale has not been illuminated. Therefore, for the first time, we will propose our objective according to these problems and accomplish them progressively.

1.3. Research objectives

The overall objective of this study is using remotely sensed phenology data derived from SPOT VGT time-series NDVI profile to characterize the spatial pattern of phenology for four dominant tree species across Europe. In specific,

- 1) To calculate average phenology metrics (SOS, LOS, Max-NDVI, integral-NDVI as specified in our research) for different tree species using NDVI profile,
- 2) To identify the key metrics significantly distinguish among the four tree species
- 3) To investigate the spatial variation of phenology metrics for different tree species along the geographical (latitude/longitude/altitude) gradients,
- 4) To examine the relationships between phenology metrics and climate factors (i.e. temperature and precipitation).

1.4. Research questions

- 1) What is the corresponding phenology metrics for four dominant tree species in Europe?
- 2) Is the phenology for different tree species significantly different? What the key metrics distinguish among different tree species respectively?
- 3) What are the relationships for tree phenology along geographical gradients?
- 4) What kind of relationships can be fitted for phenological metrics and climate factors?
- 5) Is the reaction to climate variation same for four tree species from 1999 to 2005?

2. MATERIALS AND METHODS

2.1. Study area

The forest of our research scattered over 34 European countries (Macedonia, Yugoslavia, Bosnia and Herzegowina and Albania are not included) ranging across 38° latitude (from South Greece to North Sweden) and across56° longitude (from Ireland to Finland in the north and from Portugal to Moldova in the south). The continent of Europe, extending from the Arctic Circle in the north to the Mediterranean Sea in the south, is a land of varied topography. Forest area sums to 1.02 billion ha in Europe, i.e. 45% of Europe's land area. Europe is the most forest-rich region in the world (FOREST EUROPE, 2011). The four dominant tree species i.e. beech, birch, pine and spruce amount for 70% of the all the forest areas in Europe (Köble & Seufert, 2001a). The study area is shown in Figure 2-1.



Figure 2-1 tree species map across Europe



Figure 2-2 Pictures of four tree species, pictures a-d indicate beech, birch, pine and spruce

1) Common Beech (*Fagus sylvatica*)

It is a deciduous tree species typically 25–35 m (80–115 ft) tall and up to 1.5 m (5 ft) trunk diameter. The appearance varies according to its habitat. Climate and temperatures vary for beech habitat, though the European Beech has several significant requirements: a humid atmosphere (precipitation well distributed throughout the year and frequent fogs) and well-drained soil (Figure 2-2a).

- Birch (*Betula pubescens*)
 Birch species are deciduous tree or shrub, generally small to medium-size. Birch is in the family Betulaceae, closely related to the beech/oak family (Figure 2-2b).
- Scots Pine (*Pinus sylvestris*)
 Pine is an evergreen coniferous tree species. It occurs from sea level to 1,000 m, while in the south of its range it is a high altitude mountain tree (Figure 2-2c).
- 4) Norway spruce (*Picea abies*)

It is a large evergreen coniferous tree species growing to 35-55 m (115–180 ft) tall and with a trunk diameter of up to 1-1.5 m. The Norway spruce grows throughout Europe from Norway in the northwest and Poland eastward, and also in the mountains of central Europe, southwest to the western end of the Alps, and southeast in the Carpathians and Balkans to the extreme north of Greece. The northern limit is in the arctic, just north of 70°N in Norway (Figure 2-2d).

2.2. Data

For the study, following data are acquired:

1) SPOT VGT 10-day composite NDVI

The VEGETATION instrument can offer a valuable tool for vegetation mapping at regional scale. The first satellite component (VEGETATION 1) of the programme was launched on 24th March 1998 on board SPOT 4, while the second instrument was launched on board SPOT 5 on 4th May 2002. They deliver measurements specifically tailored to monitor land surfaces parameters with a frequency of about once a day on a global basis and a medium spatial resolution of one kilometre. The entire system complements the existing high spatial resolution capabilities of the SPOT series, providing similar and simultaneous spectral measurements in the visible and short wave infrared domain. The SPOT VGT S10 products provided surface reflectance in the blue ($0.43 - 0.47 \mu$ m), red ($0.61 - 0.68 \mu$ m), near infrared (NIR, $0.78-0.8 9 \mu$ m), and shortwave-infrared (SWIR, $1.58 - 1.75 \mu$ m) spectral regions using maximum value syntheses (SAINT, 1994). The high temporal resolution of 10 days allows the capability for image selection according to best quality, least cloud cover and the optimal phenological stage of vegetation cover. The data are available free of charge at the Vlaamse instelling voor technologisch onderzoek (VITO) Image Processing center(Belgium) (http://www.vgt.vito.be).Atmospheric corrections are routinely done using the SMAC model (Rahman & Dedieu, 1994) for evaporation, ozone and aerosols effects. Status maps are provided for each S10 product including per-pixel cloud-cover information.

In this study, the SPOT-Vegetation S10 NDVI data from 1999 to 2005 acquired over the study area were used. The reason we choose this time range is firstly because the tree species map we used is derived from year 2000, accordingly, choosing corresponding time range may exclude the influence of land cover change. Secondly, in order to eliminate the bias introduced by the inter-annual variation and extreme case, 7 years data was chosen. Therefore, the average spatial distribution result we got is much more convincible. The S10 NDVI was delivered in the undefined projection formation. Each decadal VGT-synthesis is delivered in the form of HDF-files (Hierarchical Data Format).Mixed and deciduous forests found in intermediate and high latitudes have a large seasonal variability, with low NDVI values in winter and high values in summer.

2) Tree species maps of Europe



Figure 2-3 tree species distribution maps. From Figure a-d, indicate beech, birch, pine and spruce

An up-to-date tree species inventory data is vital to analysing the phenology for different tree species. Novel maps for forest tree species in Europe with resolution of 1km are used in this research (Figure 2-3). The basis of this map is CORINE on the one hand, and the level I plot data from ICP forest(ICPForest, 2011). With implying interpolation procedures, a forest tree species map including 115 species are mapped in Europe, the overall accuracy of classification amount to 86.6% on a European level (Köble & Seufert, 2001a). The International Co-operative Programme (ICP) monitors the forest condition in Europe, in

cooperation with the European Union using two different monitoring intensity levels. The Level I inventory is based on around 6000 observation plots on a systematic transnational grid of 16 x 16 km throughout Europe. The field data including timing of the annual development stages of forest trees, species richness and abundance. We selected four tree species widely used in the timber industry with a wide range of natural distribution over Europe but contrasting ecological requirements as shown in Figure 2-3.

3) CORINE data

CORINE (Co-ordination of Information on the Environment programme) data are the only pan-European land cover maps based on RS data with a spatial resolution finer than 100 m. CORINE Land Cover for 2000 named as "CLC2000"isderived using Landsat TM and ETM+ imagery and visual interpretation. CORINE land cover maps 2000 are adopted in this research for refreshing tree species map. The majority of the training data was derived via overlaying of co-registered coarse-resolution novel tree species maps and interpreted high-resolution data sets CORINE.

4) Climate data

A set of global climate layers (climate grids) with a spatial resolution of about 1 kilometre were acquired from a daily gridded observational dataset for precipitation and temperature in Europe (E-OBS) based on European Climate Assessment and Dataset (ECA&D) information for the period 1999-2005 (Haylock et al., 2008). The resolution of E-OBS data is about 0.25 degree which covers the area of 25N-75N x 40W-75E. The data files contain gridded data for 5 elements (daily mean temperature TG, daily minimum temperature TN, daily maximum temperature TX, daily precipitation sum RR and daily averaged sea level pressure PP). The data files are in compressed NetCDF format (Figure 2-4).



Figure 2-4 Annual Temperature (a) and precipitation (b) in Europe between 1999 and 2005

5) DEM data



Figure 2-5 Elevation map of Europe

The elevation map is downloaded from Worldclim which is a set of global climate layers (climate grids) with a spatial resolution of about 1 square kilometre. The data layers were generated through interpolation of the SRTM elevation database to 30 arc-seconds (1 km) (Hijmans et al., 2005). The altitude of Europe ranges from -188 to 4498 meter as indicated by the elevation map (Figure 2-5).

2.3. Data pre-processing

1) Refining the tree species

In order to reduce the influence of mixed pixel for single tree species because of the 1km resolution, we use 100m CORINE data to refresh the tree species map. The CORINE data divided the forest area into 3 categories including Broad-leaved forest, Coniferous forest and Mixed forest. We firstly select the broadleaved area and intersect with common beech and birch, and only those tree species pixels located totally inside the forest area in CORINE are identified as consisting of 100% of the cover type of interest (Figure 2-6). Figure 2-6a shows the original map of scots pine, the blue points in Figure 2-6b indicate pixel of 100% pine and the red points are sample point left after intersecting with CORINE coniferous data. The same procedures are carried out for Scots pine and Norway spruce. After this, we got now tree samples used for further analysis (Figure 2-7).



Figure 2-6 Process of refining tree species map.



Figure 2-7 Samples of different tree species across Europe after refine

The results were double check using GoogleEarth and it is proved to rational (Figure 2-8). Blue points in picture Figure 2-8b indicates all the 100% pines pixels and red points indicate the points left after refining by CORINE data.



Figure 2-8 Cross check tree species map in GoogleEarth before and after refine

2) Quality mask

Maximum value composite method for compositing of NDVI minimize cloud contamination, nevertheless the data are often still influenced by clouds and atmospheric variability. This affects the extraction of phenology metrics. Therefore, we apply cloud masking using the 8 bits status map provide by SPOT VGT website (Table 2-1).

The algorithm proposed by (Kempeneers et al., 2000) has been implemented by SPOT VEGETATION. They identify the threshold of reflectance for cloud, shadow, snow/ice and uncertain. In addition to these, the red and NIR band are sensitive to vegetation and can improve the discrimination of vegetation and other land cover types (Boles et al., 2004). So we choose "bits of interests" as: red, NIR, ice/snow, land, shadow and cloud. Only those pixels with good quality in blue, red, NIR, with indicator of land and cloud free are chosen. These processing are carried out in IDL-ENVI.

Bit	seque	nces						Meaning
х	х	х	х	х	х	0	0	Clear(cloud free)pixel
x	х	х	х	х	х	0	1	Shadow detected
x	х	х	х	х	х	1	0	Shadow/cloud detection is uncertain
x	X	х	х	х	х	1	1	Cloud detection
x	X	х	х	х	0	х	х	No ice/snow
x	X	х	х	х	1	х	х	Ice/snow detected
x	X	х	х	0	х	х	х	Sea/water pixel
x	X	х	х	1	х	х	х	Land pixel
x	X	х	0	х	х	х	х	Bad radiometric quality of SWIR band
x	X	х	1	х	х	х	х	Good radiometric quality of SWIR band
x	X	0	х	х	х	х	х	Bad radiometric quality of NIR band
x	X	1	х	х	х	х	х	Good radiometric quality of NIR band
x	0	х	х	х	х	х	х	Bad radiometric quality of red band
x	1	х	х	х	х	х	х	Good radiometric quality of red band
0	х	х	х	х	х	х	х	Bad radiometric quality of blue band
1	х	х	х	х	х	х	х	Good radiometric quality of blue band

Table 2-1 Bits of status map

3) Winter NDVI calculation

In boreal regions, the presence of snow and the polar night during winter complicates the use of NDVI time series for modelling vegetation activity at high latitudes. As snow has a negative effect on the NDVI, the disappearance of snow at the end of winter causes the NDVI to rise. In addition, NDVI values are missing due to the polar night in northern Europe. As shown in Figure 2-9, we take a image from 01th, January 2004 as an example, large area in northern Europe are missing. Hence, the NDVI values out of the growing season need to be calculated to cover the shortage of these two matters (Beck, et al., 2006). We use Pan-European Map of Biogeographical Regions from EEA to mask the NDVI data (http://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-2001/bio-geographicregions-coverage/biogeo01.zip/?searchterm=None). Depending on the climate characters, the ecoregions are separated into three categories; one is Mediterranean areas including Mediterranean, Pannonia, Macaronesian, and black sea. These regions usually identified by hot summers and mild winters. And the other climate type including alpine (Certain highland climates can also fit under hemi-boreal climate or Semi-arid climate groups of climate classification, moving up 100 meters on a mountain is roughly equivalent to moving 80 kilometres (45 miles or 0.75° of latitude) towards the pole, so we divide alpine into boreal area), arctic, boreal which was defined as boreal regions. These regions are exceptional for its high latitude, long, usually very cold winters, and short, cool to mild summers. The last one named as continental regions consist of continental, Atlantic, steppic.

Using the method proposed by Beck (Beck, et al., 2006) For boreal areas, the Ground observations indicate that leaf fall in northern Norway starts no later than mid-October. Therefore we consider the time period from 11th October to 21th November (totally 5 images are included) as suitable for calculating the WinterNDVI. Firstly the two maximum values are chosen from the 5 images as M1 and M2, and then the WinterNDVI is calculated by:

WinterNDVI = Sqrt (M1*M2)

In the function, if only one value is found among five images, the results will be zero, which means that only those pixels displaying a long term of greenness are given the value of non-zero.

After this step, all winter NDVI values lower than 0.4 were set to 0.4. This value is comparable to thresholds set by other authors defining NDVI values below which changes in NDVI are not related to major changes in vegetation dynamics. Suzuki et al. (2003) chose 0.2 using an AVHRR-NDVI dataset, and

Delbart et al. (2005) chose 0.4 with SPOT-VGT. On account of the difference of sensors, we choose to use 0.4 as reference.

After the calculation of WinterNDVI, all the winter period are replaced by WinterNDVI. And after that, we replace all the values lower than WinterNDVI with WinterNDVI. Values missing because of polar night are directly replaced by WinterNDVI. The comparison of NDVI profiles are shown in Figure 2-10 before and after winterNDVI calculation.



Figure 2-9 Original data of SPOT NDVI showing the data missing for high latitude



Figure 2-10 Spectral profile of NDVI before (a) and after (b) WinterNDVI calculation

2.4. Calculation of phenology index

1) Phenology differed when using different function fitting

Phenology metrics derived from NDVI time series are mainly corresponding phases in vegetation growth. A number of seasonality parameters such as time of the start/end/mid of season, and length of the season are the basic metrics. Based on these basic metrics, several secondary metrics can be derived. TIMESAT can produce eleven metrics including start and end of the season, 80 % levels largest value, seasonal amplitude, the seasonal length, small and large integrals during the season and rate of increase at the beginning and end of season.

A widely used time-series analysis program, TIMESAT, was employed to calculate LSP metrics from the SPOT-VGT data (Eklundh & Jönsson, 2009; Jönsson & Eklundh, 2002; Jönsson & Eklundh, 2004).TIMESAT is free download on internet, and at the same time, the user interface embedded in the software is easy to operate under windows environment compare to the other algorithm written in script.White et al. Compares 10 ways of retrieving phenology data from AVHRR NDVI time series data, and get a conclusion that TIMESAT has the least start of season variability anomalies. At the same time, they produce an ensemble estimate of trends in start of season based on ground data, and TIMESAT mostly consistent with this estimation (White et al., 2009). TIMESAT has been used in a number of applications. (Eklundh & Olsson, 2003) characterized phenology for African Sahel to study recent trends in vegetation greenness and for mapping environmental and phenological changes in Africa from 1982 till today; (Tottrup et al., 2007) mapped fractional forest cover across the highlands of mainland Southeast Asia using MODIS data and regression tree modelling for improving data in ecosystem classification; (Beck et al., 2007) mapping high-latitude forest phenology using a ground-validated NDVI dataset. So we choose TIMESAT to derive phenology metrics.

At larger scales, different vegetation types exhibit multiple modes of growth and senescence within a single annual cycle, because of the complex in community composition, micro- and regional climate regimes, soils, and land management. Therefore, remote sensing based methods need to be sufficiently flexible to allow for this type of variability.

TIMESAT implements three processing methods based on least-squares fits to the upper envelope of the vegetation index data. The first method uses local polynomial functions in the fitting, and the method can be classified as an adaptive Savitzky-Golay filter. The other two methods are least-squares methods, where data are fitted to non-linear model functions of different complexity (Gaussian and double logistic). All three processing methods use a preliminary definition of the seasonality (uni-modal or bi-modal) along with approximate timings of the growing seasons.

Our overall approach was to compare ways of phenology derivation, principally at the level of whole ecoregions for all of Europe. Therefore, three different smoothing ways are tested for 3 different ecoregions mentioned before. Different fitting functions result in different phenology metrics for same ecoregion, as shown in Figure 2-11.



Figure 2-11 phenology metrics derived after smoothing using different function fitting

2) Which function should be chosen?

As illustrated by (Beck, et al., 2006), many of the algorithms used for vegetation monitoring are ill-suited for boreal regions. Fitted Fourier series tends to overestimate the duration of growing season, and other algorithms have not yet been applied in high latitude environments. Therefore they tested for several algorithms in their research and suggested that double logistic functions or asymmetric Gaussian function are the most suitable for describing vegetation dynamics at high latitudes. And the double logistic is slightly better than Gaussian function. On the other hand, results shown by White et al. (2009) revealed that The Gaussian method, which relies on a range of absolute thresholds, had similarly large failure rates for much of North America. So double logistic are chosen as a smoothing function for phenology derivation. We eliminated NDVI spikes larger than two times the standard deviation of the median values of the closest neighbours in the time series and fitted the remaining upper envelope. SOS is defined from the global model as the interpolated composite period when the NDVI has increased 20% of the seasonal amplitude from the growing season minimum level. Although the threshold level can be adjusted, the 20% threshold has been used effectively (Jonsson & Eklundh, 2002). We estimated SOS DOY values by the interpolated composite period multi-plied by 10 days.

It should be noted that the term onset is intentionally vague, as it reflects behavior at the ecosystem level, rather than any ground-based phenological events (e.g., budburst, first flowering, etc.) that cannot be discerned from satellite images. Furthermore, the purpose of this research is to tries to analyze the spatial variation of phenology for four different tree species over Europe. We are not necessarily attempting to create the most 'accurate' phenology estimation; so much as we want to see how much variability in the onset of the growing season can be tied to each tree species. So, no validation is carried out.

2.5. Selection of phenology metrics

Phenology parameters are exported by TIMESAT and preliminarily calculated using EXCEL to eliminate the missing pixel if season is not found or other reasons. The seasonality metrics printed are shown in Figure 2-12 and Table 2-2. In Figure 2-12, points (a) and (b) represent, respectively, start and end of the season. Points (c) and (d) give the 80% level. Point e gives the largest value. Point (f) mark the seasonal amplitude and (g) give the seasonal length. Finally, (h) and (i) are integrals showing the cumulative effect of vegetation during the season



Figure 2-12 phenological metrics captured by NDVI profile

Table 2-2 phenology metrics derived by TIMESAT

Phenology	explanation
metrics	
Start of season	time for which the left edge has increased to a certain of the seasonal amplitude measured
	from the left minimum level
End of season	Time for which the right edge has decreased to the certain level measured from the right
	minimum level.
Length of season	time from the start to the end of the season
Base value	average of the left and right minimum values
Middle of season	Computed as the mean value of the times for which, respectively, the left edge has increased to
	the 80 % level and the right edge has decreased to the 80 % level.
MaximumNDVI	largest data value for the fitted function during the season
Amplitude	difference between the maximum value and the base level
Left derivative	the ratio of the difference between the left 20 $\%$ and 80 $\%$ levels and the corresponding time
	difference
Right derivative	absolute value of the ratio of the difference between the right 20 $\%$ and 80 $\%$ levels and the
	corresponding time difference
Large integral	integral of the function describing the season from the season start to the season end
Small integral	integral of the difference between the function describing the season and the base level from
	season start to season end
To assess the spat	ial variability in phenology metrics for different tree species, we computed the date of

To assess the spatial variability in phenology metrics for different tree species, we computed the date of start of season (SOS) the annual maximum NDVI (M-NDVI), length of season (LOS) and time integrated NDVI (I-NDVI) for different tree species.

2.6. Statistical analyses

2.6.1. Phenological characteristics for different tree species

1) The general difference for different tree species aggregated in Europe

We used analysis of variance (ANOVA) to test the significance of the differentiation among tree species. Before the ANOVA was performed, phenological metrics were examined to confirm their homogeneity of variance and normal distribution. All analyses were performed using EXCEL and SPSS.

2) Inspect the significant of latitude and tree species

If the means of different tree species are different. Then the next step is to investigate, are the differences introduced by the variability of spatial regions or by the genic difference of species? Which is main influence factor is tested by two-way-ANOVA in SPSS.

2.6.2. Analysis of phenological variation along geographical gradient

For preliminary analyses, the region was divided into tabulation areas with even-numbered parallels of latitude/longitude of 1 degree. And elevation gradients are classified depending on the UNEP-WCMC (http://www.unep-wcmc.org/habitats/mountains/eur.htm) by every 100m. Curves showing the four estimated phenological dates were plotted for spatial factor for all the species. For each species and in each spatial region, naturally established populations were sampled using the 100% pixel indicated by the tree species map.

The relationships between the annual timing of a phenological phase and altitude, latitude and longitude could be determined using the way proposed by (Rötzer, 2001). By means of the resulting equation, the phenological phases can be calculated for any given location of the map.

 $P = c + a_x *_X$

 $P = c + a_y * y$

 $P = c + a_z * z$

Where pp(x, y, z) is the starting date of the phenological phase at altitude z, longitude x and latitude y, c is a constant and a_x , a_y and a_z are regression coefficients. Those equations compute the date of phenological phase depending on the regressors altitude, longitude and latitude.

2.6.3. Analysis of response of tree phenology to climate factors

Vegetation phenology is controlled by temperature, photoperiod, precipitation, vegetation type, and human activity. In temperate and boreal regions, temperature is the dominant climatic variable related to vegetation phenology (Cannell & Smith, 1986; White, et al., 1997). By using zonal averages, the spatial uncertainty in both phenology and temperature is reduced. Zonal averages for phenological transition dates across 1 degree latitude intervals were then computed for all of the four tree species. Using the same procedure, we also computed the corresponding mean month temperature and precipitation for each one-degree zone because phenological events are strongly associated with mean annual temperature at continental scale (White, et al., 1999; White, et al., 1997).

The relationship of phenology metrics with climate was analysed with climate layers for the period 1999-2005. The data were aggregated by month for analysis. Statistical analysis of trends over time was demonstrated by linear regression of response variables against year, and relationships with temperature and precipitation by correlation and regression analyses.

Annual mean SOS dates were correlated by Pearson's product moment correlation with the average temperature of the month of SOS and the two preceding months. The slopes of linear regressions of the annual mean dates against the mean temperature of the month before the event provided a measure for the temperature sensitivity. These regression coefficients were analysed for selected species.

3. RESULTS

3.1. Phenology metrics

To examine the spatial variability of the phenology metrics, four different NDVI metrics were mapped in Figure 3-1. These metrics were averaged over seven years after calculation in order to show the general trend.



Figure 3-1 Spatial distributions of four phenology metrics across Europe: dates of the start of season (a), length of season (b), the maximum NDVI (c), and finally integral of NDVI (d)

We notice a general spatial variation of dates, which suggests the variation of environmental factors at the corresponding scale. Changes are generally continuous and variations are gradual. Phenology metrics maps show that phenological behaviors vary from east to west and from north to south. Pixels that correspond

to water surfaces, rock, deserts or other surface features with insufficient NDVI dynamics cannot be detected (which are shown in the color of white). The spring green wave comes from March to June over the whole northern Europe.

Figure 3-1a presents maps showing the dates for SOS estimated from SPOT-VGT data between 35N and 70N in averaged over the years 1999–2005. As expected, the patterns depend strongly on latitude in the mid- to high latitudes, and reveal how the date of SOS pushes northward from March to early June, and how the data of SOS pushes eastward from March to early May. The growing season starts in most regions of central-Europe between 20th march and 15thApril. Note that a late date of SOS after June was calculated for southern France, northern Portugal and Spain and for most of the coastal regions of the Mediterranean Sea because of heat stress and seasonal precipitation patterns. In mountainous regions such as the Alps Mountains, great differences in the phenology metrics can be seen: the growing season starts much later than nearby area where altitude was lower. The latest data of SOS after 01 June is observed in the Alps area, which is same as Norway and north of the Arctic Circle.

As the length of the growing season (Figure 3-1b) mainly depends on the beginning {Rötzer, 2001 #909, almost the same trend was found for LOS as SOS. The longest growing seasons, with over 220 d, can be found in the southern part of France and in the coastal regions of southern Europe. In large parts of central Europe, except for the mountainous regions, the growing season lasts between 180 and 220 d. Shorter growing seasons, with less than 170 d, are calculated for high altitudes as well as for nearly all of Scandinavia. High altitudes in Scandinavia as well as the regions north of the Arctic Circle show growing seasons as short as 120d.

The mean Max-NDVI is lower in the northern hemisphere (boreal area) and in Mediterranean area than in the continental region, while over the whole continental area the value of Max-NDVI is much more consistent (Figure 3-1c). The pattern of mean integral-NDVI is the combined function of MaxNDVI and LOS (Vrieling et al., 2011), the largest integral NDVI was found in Eastern Europe. The integral NDVI increases from Mediterranean area to continental area and decrease again to boreal area and generally increase from western to Eastern Europe (Figure 3-1d).

3.2. Phenological characteristics of different tree species

3.2.1. Overall difference of the phenological metrics for four tree species

To examine the difference of growth for different tree species, four different NDVI metrics aggregated across Europe were analyzed (Table 3-1). These metrics were calculated using the 7-year mean NDVI data. Results suggested strong difference of phenology metrics occur among four species.

Forest	SOS (DOY)		LOS(days)		M-NDVI		I-NDVI	
	Mean	STDEV	Mean	STDEV	Mean	STDEV	Mean	STDEV
Beech	93.1	3.0	220.9	5.4	0.82	0.02	7.13	0.5
Birch	150.0	7.5	136.2	6.0	0.74	0.01	3.55	0.2
Pine	106.9	4.4	195.1	8.9	0.74	0.02	4.91	0.3
Spruce	106.6	4.0	193.3	5.4	0.78	0.02	5.84	0.5
ANOVA	*		*		*		*	

Table 3-1 Phenology metrics averaged over seven year time period

Note: * indicate that the means are significantly different at the level of 0.05

Among the four tree species, the date of start of season and length of growing season for different tree species is given in Table 3-1. It is interesting to note that the two evergreen species had a distinct I-NDVI while with same growing season length of 190 days, and the same date of SOS. The varying maximum NDVI and I-NDVI for these two species make the difference. The two broadleaf species exhibit distinct

phenology performance: SOS for beech start earliest among the four species while birch is the latest, and beech has the longest start of season while birch is the shortest one. As a consequence, the integral of NDVI for beech is the largest one and birch is the smallest one.

Further among the different evergreen forest types, MNDVI, INDVI were higher for spruce than pine. The date of SOS is theorized to differentiate between these four species; thus, the date of SOS can be used to distinguish these tree species. The above differences in NDVI metrics for these forest types were mainly attributed to the differential response of species environmental conditions.

3.2.2. Inspect the significant of latitude and tree species

As shown from result 3.2.1, the means of different tree species are significantly different. As shown in Figure 2-7, the four tree species are located in different geographical regions. So, the difference of the phenological metrics can be introduced by two factors: the genic difference of the trees and the geographical difference of their location. In order to investigate this problem, samples located in the same region for these tree species are chosen, and tested by one-way-ANOVA in SPSS. Since beech and birch are not intersect in their location so, two analyses are carried out, one for beech, pine and spruce; the other one for birch, pine and spruce. The results indicate that the variability introduced by species are not significant for beech/pine /spruce, they exhibit the same phenology at the same region. For birch, the data of SOS and LOS are significantly different from pine/spruce even at the same latitude (Table 3-2).

		Beec	h/Pine/Spruc	e	Birch/Pine/Spruce				
	DF	F value	Prob>F	significant	DF	F value	Prob>F	Significant	
SOS	41	1.81	0.18		23	5.3037	0.01366	*	
LOS	41	0.30	0.74		23	9.10145	0.00142	*	
Max-NDVI	41	11.2345	1.4027E-4	*	23	2.29	0.13		
I-NDVI	41	0.76833	0.47068		23	1.88599	0.17649		

Table 3-2 ANOVA analysis for beech/Pine/Spruce and Birch/Pine/Spruce

Note: * indicate that at the level 0.05, the means are significantly different.

3.3. Spatial variations for four tree species along geographical gradient

In Table 3-2 the results of the regression analysis for different phenological phases are listed. They are sorted according to different tree species. The Mediterranean area are excluded considering the vegetation cycle begins at end of year(Moulin et al., 1997). The dependences of the start of season, length of season, maximum NDVI and integral NDVI on altitude, longitude and latitude, averaged over the years 1999–2005 can be derived from the regression coefficients averaged over the indicator phases.

The dependence of phenology metrics on latitude are well characterized except for beech, which is more rely on altitude. The beginning of the growing season starts 1.6 days later per 1° latitude from south to north for birch, 2.3 days for spruce and 2.9 days for pine. length of season averaged exhibit the same trend as SOS, a 2.7 days shorter per 1° latitude for birch, 2.8 days for pine and 3 days for spruce. Maximum NDVI stays all most the same while the integral NDVI was slightly varied. For birch, pine and spruce, the 1° latitude northward induced1.8, 0.8 and 1.3 smaller for integral NDVI respectively.

The relationship of SOS with longitude was significant only for birch: SOS start later from west to east by 0.7 d per 1 $^{\circ}$ longitude, LOS was 0.7 days shorter per 1 $^{\circ}$ latitude, maximum NDVI show a steady trend and integral NDVI smaller by 0.8.

Metrics	species	a _x	R ²	a _y	R ²	az	R ²
Beech	SOS	0.7	0.16	-0.05	0.005	1.0	0.7
	LOS	0.7	0.06	-0.05	0	-1.3	0.45
	Max-NDVI	-0.03	0.15	0.01	0.3	0.02	0.2
	Integral-NDVI	-2.1	0.54	-0.3	0.002	0.7	0.06
Birch	SOS	1.6	0.35	0.7	0.45	0.7	0.36
	LOS	-2.7	0.45	0.7	0.45	-0.6	0.24
	Max-NDVI	-0.08	0.72	-0.04	0.48	0.1	0.61
	Integral-NDVI	-1.8	0.69	-0.8	0.68	0.8	0.60
Pine	SOS	2.9	0.79	0.4	0.07	0.3	0.02
	LOS	-2.8	0.56	-1.2	0.34	-0.6	0.03
	Max-NDVI	-0.02 0.34 -0.003		-0.003	0.006	0.01	0.003
	Integral-NDVI	-0.8	0.2	0.03	0.002	-0.2	0.05
Spruce	SOS 2.3		0.60	0.4	0.13	1.8	0.54
	LOS	-3	0.55	-1.9	0.53	-2	0.43
	Max-NDVI	-0.02	0.48	0.01	0.004	-0.03	0.57
	Integral-NDVI	-1.3	0.30	0.4	0.08	-1.3	0.29

Table 3-3 The results of the multi-regression analysis are derived from the means of the period 1999–2005

In addition, altitude is a significant regressor for all the tree species except for pine. The dependence of phenology metrics on altitude was also significant especially for beech. The SOS starts 1 day later per 100 m altitude except for beech, 0.7 day for birch and 1.8 days for spruce. LOS was 1.3 days shorter per 100m altitude for beech, 0.6 days for birch and 2 days for spruce. For maximum NDVI and integral NDVI, the trend was not significant, no single later or earlier trend was observed. From the analysis we conclude that the variations of vegetation phenology metrics with latitude is the most striking trend, so extensive analysis are carried out (Figure 3-2).



Figure 3-2 Zonal average of SOS obtained from average of 1999-2005 NDVI data. For given latitude, the average over longitudinal values was performed

Form 55° N to 72° N, Over the Northern Hemisphere, the length of the vegetation cycles regularly decreases when latitude increases from continental to boreal regions (Moulin, et al., 1997). The SOS increases with a rate of about 4.7 days per degree latitude. From 49-55° N, an earlier spring was found between latitude 49-55° N, the mean SOS was 27 days earlier compare to the average date of SOS across the whole area. SOS derived from 39-49° N is 12 day later in general compared to 49-55° N, because

SOS for Mediterranean area, an ecoregion with a pronounced and regular wet and dry season, was inconsistently estimated (Figure 3-2).

3.4. Relationship between satellite derived phenology and climate factors

The annual timing of phenology is to a great extent a temperature response (Chmielewski & Rötzer, 2001). To assess the relationship between the climatic parameters, we first assessed the linear correlations between SOS/LOS/M-NDVI/I-NDVI and temperature (Figure 3-3a-d) for different tree species. Figure 3-3 show that all species had a negative slope between SOS and Tmean and a positive correlation between LOS and Tmean, meaning that higher temperatures promote earlier SOS. The good correlations suggest that temperature is a major control of NDVI response. Compare to SOS and LOS, the maxNDVI and integral are less correlated to Tmean. The regression between SOS and Tmean indicates that 1°C increase in mean air temperature is associated with an earlier start of season by about 4.5 days. Similarly, 1°C increase in mean air temperature and phenology in a more detailed way, a regression analysis of air temperature for all tree species was done (Figure 3-3).



Figure 3-3 Relationship between mean annual air temperature (Tmean) and SOS, LOS, maximum NDVI and integral NDVI for different tree species of Europe

Chmielewski and Rotzer (2001) indicated that the most phases correlated significantly with mean monthly temperatures of the month of onset and the two preceding months. (Tryjanowski et al., 2006) also illustrated that SOS mainly depend on the temperature from February to May. Here we carried out regression analysis using phenology metrics with the main temperature of mean monthly temperatures of the month of onset (T0), the following two months (T1, T2), mean temperature of onset and the following two months (T012) and the preceding two months (T-1, T-2) and the mean temperature of onset and the two preceding months (T0-1-2) (Table 3-4).

		T0	T1	T2	T(012)	T-1	T-2	T0-1-2
SOS	Beech	0.72	0.05	0.05	0.12	0.41	0.16	0.45
	Birch	0.22	0.03	0.1	0	0.26	0.4	0.3
	Pine	0.87	0.81	0.71	0.79	0.8	0.8	0.8
	Spruce	0.8	0.8	0.67	0.76	0.65	0.61	0.63
LOS	Beech	0.02	0	0	0	0.02	0.01	0.02
	Birch	0.45	0	0.03	0.1	0.45	0.5	0.5
	Pine	0.8	0.8	0.67	0.76	0.65	0.61	0.63
	Spruce	0.76	0.89	0.83	0.89	0.81	0.71	0.83
MaxNDVI	Beech	0	0.33	0.32-	0.22	0.32	0.5	0.37
	Birch	0.5	0	0.2	0.03	0.5	0.4	0.5
	Pine	0.45	0.4	0.3	0.31	0.41	0.44	0.43
	Spruce	0.47	0.57	0.5	0.55	0.47	0.46	0.5
Integral	Beech	0.01	0.52	0.48	0.38	0.31	0.55	0.35
	Birch	0.5	0	0.2	0.01	0.5	0.6	0.55
	Pine	0.42	0.40	0.38	0.39	0.33	0.29	0.30
	Spruce	0.21	0.46	0.50	0.49	0.26	0.17	0.31

Table 3-4 Correlations between phenology metrics and mean monthly temperatures (p < 0.05)

Table 3-4 shows that the phenology metrics are mainly influenced by the air temperature in the month of season start. Also in the two preceding months, significant correlation coefficients between temperature and phenology metrics were found. As it can be seen, in the first column of Table 3-4 all correlation coefficients between the average air temperature of the month season start and phenology metrics are significant (p < 0.05) except for beech, which means that the temperature in this period is decisive for the annual timing of phenology in Europe.

(Potter & Brooks, 1998) suggest that three climate indexes: degree days (growing/chilling), annual precipitation total, and an annual moisture index together can account to $70\pm 80\%$ of the geographical variation in the NDVI seasonal extremes. For different climatic zones, (Justice et al., 1985) drew the result that a similar pattern between rainfall and NDVI with a phase shifts appeared after they plotted mean-monthly rainfall against NDVI. (Davenport & Nicholson, 1993) investigated the spatial and temporal relations of monthly NDVI with rainfall in East Africa for 3 yr. They observed a clear lagged response of the vegetation to rainfall. Therefore, besides temperature, we also assessed the linear correlation between the phenology metrics and the annual rainfall over the same period. The correlations were poor suggesting that precipitation is not a major control of NDVI response (Figure 3-4). Similar results were obtained from northern latitudes where surface temperature has been identified as a major limiting factor of phenological events (Myneni, et al., 1997; Tateishi & Ebata, 2004b). However, sensitivity of NDVI to rainfall is in general obvious depending on several other studies conducted in some of the tropical areas (Prasad, et al., 2007).



Figure 3-4 Relationship between annual precipitation (precipitation) and SOS, LOS, maxNDVI and integral NDVI for different tree species of Europe

In fact, the phenological responses of vegetation is sensitive to summer drought, which tend to limit growth and to drastically reduce water loss through transpiring surfaces by reducing the leaf surface devoted to gas exchange or by increasing leaf xeromorphism (Lillis & Fontanella, 1992) in Mediterranean area. Vegetation in Mediterranean area experienced maximum water stress in the months of July and August , and the rainiest month occurs mostly in the winter period (between December to February) (Kutiel et al., 2000), so we plot the phenology metrics against the mean precipitation between December to February (Figure 3-5). Significant relationships were found between SOS/LOS and the precipitation in winter. But the linear relationship of MaxNDVI and I-NDVI cannot be detected. However the relationship between these two metrics with precipitation in summer dry period (July and August) were obvious as shown in Figure 3-6.



Figure 3-5 Relationship of phenological metrics with the mean precipitation between December to February



Figure 3-6 Relationships of phenological metrics with mean precipitation between July and August

3.5. Interannual variability of phenology metrics in Europe (1999-2005)

From year 1999 to 2005, the beginning of growing season in Europe has slightly fluctuation, but the overall trend is steady (Figure 3-8). As shown in Figure 3-7, region between 50-56 ° N are the most variable region from 1999 to 2005. Temporal variability of the aggregated SOS values ranges from 4 days to more than 2 weeks, and the LOS variability range from 4 days to 21 days. Shown in Figure 3-8, in 2002, the start of season was extremely early. Compared to mean SOS, the date of SOS in 2002 in Europe started 7 days earlier, because of the warmer climate in 2002-2003.

One of the warmest years in Europe in the period1999–2005 was the year 2003. Averaged over all of Europe, a lengthening of the growing season by 12 d compared to the long-term mean was found for 1990, whereas a shortening of the growing season by 10 d was found for the cool year 1970.



Figure 3-7 Spatial variations of phenol-phases along latitude in the 7 years (1999-2005), the boxplot shown the values of phenology metrics in the five years

Compared to the SOS, the length of growing season shows smaller annual variations except for birch Figure 3-8 b). The Maximum NDVI and integral-NDVI shows the same trend, they both rise to extreme values because of the warm trend in 2002-2003 (Figure 3-8c and Figure 3-8d). Different tree species did not show various reactions to climate variability.

- 1) In 2000, the temperature reaches its climax but the phenology metrics did not react so sensitively, with the continuous warm trend until 2002 and 2003, the obvious trend can be detected. In 2002, SOS starts a week earlier than the 7-year mean. In detail, birch starts 2 weeks earlier than the average, and the other 3 species starts 4 days earlier. The can be concluded that, birch is much more sensitive the climate change.
- 2) The reaction to LOS, MaxNDVI and Integral NDVI to climate variation is not as sensitive as SOS, the length of season start to extend in 2002, but the longest seasons were observed in 2003 and 2004. LOS in 2004 was 6 days longer than the average length. The MaxNDVI keep increasing since 2002 and the integral reach to peak value in 2003.



Figure 3-8 Interannual variability of phenology metrics for four tree species from 1999 to 2005

The phenology metrics depends highly on the mean annual air temperature from 1999 to 2005, the regression equation indicates that 1°C increase in mean air temperature is associated with an extension of growing season by about 7 days (Figure 3-9).



Figure 3-9 Relationship between mean annual air temperature and SOS for different tree species of Europe from 1999-2005

4. DISCUSSION

Remote sensing data were used to monitor the phenological variation for four tree species at the global scale. With the assumption that NDVI profile of natural vegetation can be characterized by a main growing cycle, the evolution of vegetation phenology (SOS, LOS, MaxNDVI and Integral NDVI) was detected from SPOT VGT NDVI data. To obtain continental-scale NDVI data, eliminating the influence of additional factors like snow or polar light, WinterNDVI was calculated for boreal regions. A double logistic algorithm was chosen to estimation the phenology metrics for the whole area. Then the spatial variation of four dominant tree species (beech, birch, pine and spruce)was evaluated and climate factors are introduced as explanatory data for those variations.

Results showed a large-scale spatial variation in phenology metrics across the Europe. Clear latitudinal variations were observed that correspond to climatic regimes (temperature and rainfall). Results also show longitudinal gradient (birch).

4.1. Phenology metrics derived form SPOT VGT time series data

(1) On the use of the different methods for smoothing NDVI time series data.

In TIMESAT the user can choose between adaptive Savitzky-Golay filtering and fits to asymmetric Gaussians and double logistic functions. The different processing methods in TIMESAT have different strengths and weaknesses. Hird and McDermid (2009) evaluated the performance of different processing methods in a recent study. They demonstrated the strong influence of noise level, strength, and bias, and the extraction of phenological variables on technique performance. So they recommended users should be cautioned to consider both their ultimate objectives and the nature of the noise present in an NDVI data set when selecting an approach to noise reduction, particularly when deriving phenological variables. They also get the conclusion that the methods in TIMESAT are highly competitive and that they to a great extent preserve the signal integrity.

For comparatively smooth time-series the three different processing methods often give very similar results, and which one to use should be carefully tested using the graphical interface in TIMESAT (Figure 2-11). If the time-series is smooth, but with a plateau indicating that the underlying signal is composed of two vegetation signals, then the more local Savitzky-Golay filter is the preferred method (Jönsson & Eklundh, 2003). For noisy time-series the Savitzky-Golay method sometimes yields undesirable results. In these cases fits to the asymmetric Gaussians or double logistic functions may be the better choice. The final choice of methods depends on the character of the input data and has to be decided by inspecting how well the fitted functions math the original data.

Beck et al. (2006) have tested whether a method using a double logistic function is more suitable for modelling the yearly NDVI time series of boreal vegetation than approaches based on asymmetric Gaussian functions in high-latitude environments using yearly NDVI time series acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS). They get the conclusion that use of a double logistic function or asymmetric Gaussian function is appropriate for describing vegetation dynamics at high latitudes, and the double logistic function describes the NDVI data slightly better than the asymmetric Gaussian functions.

It is more convincible that we should use different smoothing functions across the Europe, in order to better fit the NDVI profile. However, since our main objective in this research is to characterize the spatial variation for different tree species in the continental level, and they bias introduced by using different smoothing functions my hamper our analysis. Therefore, we choose a unique function- double logistic for the whole area.

(2) On the phenological characteristics

The maps of the long-term time series (Figure 3-1) of the mean onset dates and mean trends of other 3 key metrics in the 1990s are reliable since we use 7 years average instead of using one year. This may exclude the influence of external bias like extreme abnormal year with high temperature or the unexpected NDVI data error when obtained from remote sensing. Note that the main period of growth for vegetation in Mediterranean regions is in the winter and spring because of heat stress and seasonal precipitation patterns. These interpretation coincide with discover of several publications (White, et al., 1999; Zhang et al., 2004). The average length of growing season in Europe lasts 186 days (Figure 3-1b)and coincide with the discovery of 188 days modeled by Chmielewski and Rotzer(2001). The shortest duration was observed in North Scandinavia with only 136 days (4.5 months). A long duration of growing season of about 6.5 months was calculated for the northern Europe regions. The longest period, with an average of 220 days, occurred in southern France, northern Portugal and Spain and for most of the coastal regions of the Mediterranean. The pattern of mean integral-NDVI is the combined function of Maximum NDVI and LOS (Vrieling, et al., 2011), the largest integral NDVI was found in Eastern Europe. The integral NDVI increases from Mediterranean area to continental area and decrease again to boreal area and generally increase from western to Eastern Europe.

We confirmed the "south to north" variation of the mean onset of the seven years (1999-2005) as detected visually for most of the phenophases with a linear regression. The variations of vegetation phenology metrics with latitude is the most striking trend. The beginning of the growing season starts 1.8 days later per 1° latitude from south to north, length of season averaged of 2.8 days per 1° latitude, and maximum NDVI stays almost the same while the integral NDVI was 1.5 smaller per 1° latitude. At the same time, we also acquire the same trend as reported by (Menzel et al., 2005) that a west to east gradual change for the spread of spring phenophases across Europe in warmer years. However, among four species only birch contained a clear west to east gradient (Figure 3-1 and Table 3-3).

4.2. Phenological characteristics of different tree species

The timing of the phenological events of different species across a large scale is an interesting phenomenon. Which factor is the dominant factor influence the phenology metrics is still uncovered. This study revealed large differences of phenology metrics between different tree species, in common with other studies (Sparks & Carey, 1995; Tryjanowski, et al., 2006). Besides climate and geographic factors, genetic background may have a crucial impact on phenology. In the present study, inherent phenological variability causes similar uncertainties as in conventional studies with other statistical methods. After aggregated across the whole area, the Phenology metrics can be used as a way of tree species differentiate. Deciduous forest types can clearly be distinguished from evergreen forest which is mostly found in the boreal zone and in alpine areas. As shown in table 3, SOS can be used to distinguish evergreen and broadleaf and even further, classify beech and birch (both of them are broadleaf). Afterwards, combining the I-NDVI, pine and spruce can also be differentiated.

The results from Table 3-2 suggest that Site-specific factors and genetic background may have a modifying impact on phenology interactively. Species may be locally adapted to their own environment, but the gene difference still account for part of its variation especially in large scale, i.e. birch/pine and spruce exhibit totally different phenology even at the same area.

4.3. Spatial variation for four tree species

The dependences of phenology metrics on spatial factors are different for different tree species. The dependence of phenology metrics on latitude are well characterized for birch, pine and spruce. The beginning of the growing season starts 2.3 days later per 1° latitude from south to north (R^2 = 0.6 with p

< 0.05). Length of season averaged of 2.8 days per 1° latitude, and maximum NDVI stays all most the same ($R^2=0.51$ with p<0.5) while the integral NDVI was 1.5 smaller per 1° latitude.

The dependence of phenology metrics on altitude was also significant especially for beech. The SOS starts 1 day later per 100 m altitude except for pine (R^2 = 0.46 with p < 0.05). And length of season was 1.1d shorter per 100m altitude. For maximum NDVI and integral NDVI, the trend was not significant, no single later or earlier trend was observed.

The relationship of SOS with longitude was not significant only for birch: SOS start later from west to east by 0.7 d per 1° longitude, LOS was 0.7 days shorter per 1° latitude, maximum NDVI show a steady trend and integral NDVI smaller by 0.8. In addition, altitude is a significant regressor for all the tree species except for pine. (König & Mayer, 1988) computed a beginning of spring phenophases that was 1 to 3 d later per 100 m greater altitude for different regions of Europe corresponds well with our results.

Form 55° N to 72° N, the SOS increases with a rate of about 4.7 days per degree latitude (Figure 3-2). Rotzer illustrated in their publication that the growing season starts- averaged over the years-after April 25 in Scandinavia and in the Baltic Sea region. This was proved by our research. an earlier spring was found between latitude 49-55° N, this was coincidence with the research of (Rötzer, 2001), they illustrated that the British Isles with the exception of Scotland, Belgium, The Netherlands, the northern part of France as well as Hungary, Croatia and the former Republic of Yugoslavia show an earlier beginning of growing season. SOS derived from 39-49 ° N is 12 day later in general compared to 49-55° N, because Apart from effects on plant growth related to topography, the southern and eastern ridge of the Alps are known to be strongly influenced by Mediterranean climate, which can lead to a significant difference in the plant phenology to the one observed in the northern ridge (Defila & Clot, 2001). SOS for Mediterranean area, an ecoregion with a pronounced and regular wet and dry season, was inconsistently estimated (Figure 3-1). The switch from dry to wet occurs around the end of December to early January, and the SOS methods' variable treatment of calendar years vs. a continual time series likely influenced these results (White, et al., 2009). Also in their research, they recommend the extraction of SOS estimates from continual time series. In our research, only the main growths were observed in spring, which makes the SOS much later than other areas.

4.4. Relationship between phenology and climate factors

Several authors have established some relationships between phenology and climatic conditions, at continental or regional scale (Chmielewski & Rötzer, 2001; Cook et al., 2005; Stöckli & Vidale, 2004). The results suggest that the phenology correspond well with changes in in air temperature of the early spring, especially temperature of the month season start. These results are in coincidence of discoveries of other authors, concerning the influence of air temperature on the phenology metrics. In several researches, an advanced timing of spring events such as budding, leafing and flowering between 2 and 4 days per degree was found (Beaubien & Freeland, 2000; Kramer, et al., 2000; Sparks et al., 2000). The result that an increase in mean annual air temperature of 1°C is associated with an extension of growing season by 7 days in Europe is larger than the findings of (White, et al., 1999) for US.

In Figure 3-3, phenological metrics are correlated with temperature variables, Similar results were obtained by (Chmielewski & Rotzer, 2001). They concluded that the length of season depends highly on the mean annual air temperature. For Europe, temperatures are negatively correlated with the timing of SOS (Figure 3-3a) and positively related to LOS. However the relationships between temperature and MaxNDVI /Integral NDVI are not as significant.

No significant correlation with precipitation is found (Figure 3-4). In elevated terrain and at high latitudes plant growth in spring is known to be temperature limited and—because of the high soil moisture availability—not highly dependent on precipitation. Spring events such as needle flush and leaf unfolding are found in biometeorology to be very sensitive to spring and winter temperatures (Stöckli & Vidale, 2004).

(Köble & Seufert, 2001a)In fact, it has been noted that plant growth is a function not only of annual precipitation but also of the availability of nutrients (Montenegro et al., 1979; Rundel, 1982) Carbon also plays a major role in plant growth (Mooney et al., 1981).

4.5. Interannual varibility of phenology metrics in Europe for different tree species (1999-2005)

Chuine et al. (Chmielewski & Rotzer, 2001; Chuine et al., 1999) showed that the phenological response of trees to an increase in temperature depends on the plant species. An extension as well as non-extension or a reduced length of growing season is possible (Kramer, et al., 2000). In this research, we can also conclude from our analysis that species' pheno-phases often react in specific ways. Differences can be found between species and/or pheno-phases; some adapt quickly, and others do not seem to have reacted very quickly to climate variability. Generally, all the species has the same reaction to climate variability but birch is much more sensitive, this was firstly because birch is deciduous forest and secondly birch distributed mostly in boreal area. Several studies have drawn the conclusion that high latitude areas are more prior to climate change (Beck, et al., 2006; de Beurs & Henebry, 2005).

As shown in the research of (Schleip et al., 2009), an earlier occurrence of spring pheno-phases as a likely consequence of climate warming and the dominance of the change point model clearly underlines that these changes did not occur gradually, but more or less abruptly. In this sense, a warmer spring temperatures in 2000 and in 2002/2003 are a possible indication of the continental scale climate influence on the observed greening pattern. The increased positive temperature in 2000/2002 led to milder temperatures in late winter and early spring which resulted in an extension of growing season by 11 days in 2000 than the seven years average. This was in coincidence with the research of (Karlsen et al., 2009), they point out that the year 2000 was generally the most extreme in terms of late NDVI-defined SOS of birch flowering: 48% of Norway showed a more than one week later onset of birch flowering than the 2000-2007 average. In the year 2002, early SOS of birch flowering in 47% of Norway were also detected by them.

The reaction to MaxNDVI and Integral NDVI to climate variation is not as sensitive as SOS, furthermore a time lag was found between the reaction of these three phenology metrics and climate variation. (Schleip, et al., 2009) indicated that plants showed different sensitivities to temperature changes according to the time of year of their onset. They found that we can distinguish between pheno-phases which show a prompt temperature response pattern and those pheno-phases with a delayed response pattern.

Although we did not conduct long term analysis of phenological trend across Europe, conclusion can also be drawn from our research that there is no doubt that a global warming will lead to changes in the phenology characteristics within certain limits. The extension of growing season was mainly influenced by an earlier beginning.

5. CONCLUSION

Remote sensing phenology is able to consistently generate estimates of the phenological metrics over large areas. In general the phenology estimated from remote sensing are necessarily coarser than direct observations of individual plant phenology, such as bud burst or first leaf, but can summaries of the constituents of pixels and normally represent vegetation variation. A variety of approaches can be used to derive phenology from remote sensing, with different performance. Therefore, which method is appropriate for particular application should be carefully considered. It is apparent there are uncertainties in estimating phenology using remote sensing, for example, we need to understand what factors, both vegetative and non-vegetative are influencing the vegetation index values. Furthermore, ground truth data of phenology that are monitored specially to validate the remote sensing phenology are required, this would involve designing an approach for making large area estimates of phenology over heterogeneous study areas, rather than plant specific measures (Reed, et al., 2003).

The fact that the input data are 10 maximum value composites means that only one NDVI value is retained for every period of 10 days. However, the date of acquisition of the NDVI value selected to represent the 16-day period is not known, introducing a significant amount of uncertainty in the MVC dataset. Nevertheless, this was much better than using 16 day composite data like MODIS. Beck et al using 16 day composite MODIS NDVI data for deriving phenology metrics and the validation of the results comparing with ground data indicated good agreement in both cases. So, we can confident that the 10 day composite data should not a problem for analysing phenology metrics.

The NDVI dataset were smoothed by a double logistic smoothing function, and for northern Europe we calculated WinterNDVI. These allow us to remove both the influence of snow and the polar night and low-quality data. Furthermore, missing values have been replaced. The use of double logistic was validated by Beck et al that it describes the NDV I data better than the Fourier series and slightly better than the asymmetric Gaussian functions, both outside and during the growing season for describing vegetation dynamics at high latitudes (Beck, et al., 2006).

When taken in the context of phenology metrics derivation, white et al. identified the strengths and weaknesses of particular methods and SOS approaches based on thresholds. They suggest that absolute thresholds may be appropriate for geographically limited application in specific ecosystem but maybe not appropriate for continental area.

Those methods for deriving phenology metrics especially for deriving SOS were frequently incapable of retrieving estimates for desert and tropical ecoregions or ecoregions in which the initiation of growth spans the start of the calendar year. White et al. found in their research that SOS for Mediterranean California, an ecoregion with a pronounced and regular wet and dry season, was inconsistently estimated. The main reason for this is the switch from dry to wet occurs around the end of December to early January, and the SOS methods' variable treatment of calendar years vs. a continual time series likely influenced these results.

This paper has explored spatial and temporal patterns of vegetation phenology and their relationships with both tree species and climate data across Europe from 1999 to 2005. Using SPOT VGT NDVI data. The results show that phenological variations correlate strongly with both temperature and latitude for all tree species. On average, SOS moves northward at a rate of about 1.8 days per degree of latitude. The rate of change in SOS as a function of mean annual temperature is highest for pine species (5.6 days per 1° C), followed by spruces.

Although we have only looked at 4 species, there is strong evidence that identical species have a different response to temperature. This may point to local adaptation to climate and suggest that response to future climate warming will also vary for different tree species at the same latitude. This may further suggest that

not all of the phenological response so far reported is attributable to global warming. Tryjanowski et al. analysed phenological observations of first flowering of early dog violet *Viola reichenbachiana* and horse chestnut *Aesculus hippocastanum* at similar latitudes (and hence photo-period) in the UK and Poland during the years 1970–1995, they conclude that locally adapted species may differ in their projected change under future climate (Tryjanowski, et al., 2006).

Our results highlight both the challenge and potential for using remote sensing as a way of phenology analysis. No other technology besides remote sensing offers consistent long-term monitoring, yet the validation is a big problem because of limitations in using existing historical datasets. Establishing consistent plant phenology monitoring networks is therefore essential. Similar analyses and study selections could be replicated on other continents to produce a network of phenological monitoring tree species. In all, we get the conclusion that remote sensing phenology is able to estimates the phenological metrics over large areas. This makes our research the first one to characterize the spatial and temporal variation of phenology for different tree species across Europe using remote sensing

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