Forest cover trend analysis using MODIS time series and its climatic responses in the Mari El Republic of Russia

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Abstract. This study assesses whether MODIS NDVI satellite data time series can be used to detect changes in forest phenology over the different forest types of the Mari El Republic of Russia. Due to the severe climatic conditions, coniferous and deciduous forests of this region are especially vulnerable to climate change, which can lead to stresses from droughts and increase the frequency of wild fires in the long term. Time series analysis was applied to 16-day composite MODIS (MOD13Q1) (250 m) satellite data records (2000–2020) for the investigated territory, based on understanding that the NDVI trend vectors would enable detection of phenological changes in forest cover. There was also the determination of land cover/land use change for the area and examination of meteorological data for the investigated period. For the study, we utilized four phenological metrics: start of season (SOS), end of season (EOS), length of season (LOS), and Maximum vegetation index (MVI). The NDVI MODIS data series were smoothed in the TimeSAT software using the Savitsky-Golay filter. The results of the study show that over the 20-years period variations in phenological metrics do not have a significant impact on the productivity and growth of forest ecosystems in the Mari El Republic.

1. Introduction
Numerous research reports are showing an increase in NDVI (Normalized Difference Vegetation Index) amplitude and growing season in ecosystems since 2000 in different countries of the world [1-4]. It is also believed that temperate and boreal forest ecosystems can respond to temperature anomalies with more significant biogeophysical consequences than tropical forests [5]. It is observed that at the northern latitudes the length of vegetation growing seasons is largely associated with snow cover seasonality [6-8], and that in turn may have implications for forest management.

An enhanced understanding of the interactions between climate and vegetation is a key issue in modelling the impact of climate change on ecosystems. Particularly, ongoing changes can drive shifts in the tree phenology with potential impacts on ecosystem services and species ranges [9]. However, fewer studies have considered changes in the phenology of boreal trees phenology, which is essential for a better understanding of the current state of forests and their role in future response to climate change [10-11].

Remotely sensed phenological metrics provide valuable information on land–atmosphere interactions, physiological processes, nutrient cycling, and land-use classification [12-15]. In particular, start of season (SOS) and end of season (EOS) dates are well estimated from time series images using a variety of different methods [16-18]. Nowadays, a sensor that is well suited for monitoring the seasonal patterns in regional-to-global phenology is Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the platforms Aqua and Terra, which acquires high-temporal resolution data to obtain accurate
time series seasonality parameters [19-22]. The MODIS data provide an excellent basis for global and regional studies of land surface phenology and anomalies based on the NDVI measurements [23-26]. Using TIMESAT package [27] to process MODIS NDVI time series, we can retrieve several phenological metrics and analyse them both seasonally and long term inter-annually. The TIMESAT software allows to modify the algorithm parameters to specific locations and applications for different phenological conditions and vegetation patterns [28, 29].

Due to severe climatic conditions, coniferous-deciduous forests of the Middle Volga region of the Russian Federation are especially vulnerable to climate change, which can lead to stresses from droughts and increase the frequency of wild fires in the long term [30]. The influence of ongoing changes on the sustainability of forest ecosystems, the relationship between the seasonal changes with their and the disturbances as well as the use of satellite data when carrying out such research remain understudied in this region [31, 32]. The development of comprehensive methodologies to assess phenology and vegetation succession in boreal and temperate forests of the Russian Federation will help to predict the impact of wildfires on these ecosystems.

As a follow-up effort, the current study aims to develop and test an algorithm to characterise and evaluate interannual variability of phenological metrics in the forest cover phenology of the Mari El Republic of the Russian Federation based on the analysis of MODIS time series (2001-2020) in the TIMESAT software package.

2. Study area
The study focuses on forest cover on the territory of the Mari El Republic (figure 1), which is part of the broadleaved forest region in the European part of Russia. The region is of particular interest because it represents wide areas of natural forests in western Russia that are reported to be a large terrestrial carbon sink [33, 34]. The landscape ranges from hills to plains, the height variations being almost unnoticeable (from 45 m to 275 m above sea level), and transitions from the lower to the higher parts being quite gradual.

The climate of the region is considered to be temperate–continental with stable weather in winter and summer, but considerably changing conditions in spring and autumn. The average precipitation is 450–500 mm, of which 250–300 mm falls during the vegetation period (spring and summer). Rainfall is seasonal, with a dry season from May–June until August, which is associated with wildfires, and a wet season from September to November. The mean annual temperatures vary from +2.28°C in the north-eastern part of the region, up to +3.18°C in the south-western part.

Dominant species are pine (Pinus sylvestris L.), birch (Betula pendula Roth.), spruce (Picea abies Karst.), and aspen (Populus tremula L.). Although pine stands are the predominant forest type of the landscape, especially in the Mari El Republic, regeneration of the birch–aspen species after wildfires is common over the study area. The forests of the region were severely affected by wildfires in 1921, 1972 and 2010 [31].

3. Data and methodology

3.1. MODIS images
In this study, for the estimation of NDVI time series we used a MODIS reflectance data set originally produced by the Land Processes Distributed Active Archive Center (LP DAAC), which is located at the US Geological Survey Earth Resources Observation and Science Center (USGS-EROS, http://LPDAAC.usgs.gov). The 16-day composites (MOD13Q1) with a ground (spatial) resolution of 250 m in a sinusoidal projection were further processed and released by the Atmosphere Archive and Distribution System (http://ladsweb.nascom.nasa.gov/). Compared with the daily data, these MODIS composites reduced the spectral variability introduced by atmospheric and view angle effects. For the research area, a set of 273 NDVI MODIS time series for 2000-2020 (from April 15 to November 15) was prepared. This time period makes it possible to exclude the influence of such factors as snow cover
and areas of terrain not covered with vegetation. The main work was carried out for the ground territory of the Mari El Republic, consisting of MODIS 4,157 rows and 12,008 columns.

![Figure 1. The study area on the NDVI MODIS image of the Mari El Republic of the Russian Federation.](image)

### 3.2. Data processing

In the study, we developed the algorithm for the analysis of vegetation indices (VI) in the TIMESAT-3.3 software package, designed for processing time series of satellite images and determining phenological indicators based on these data [27]. To analyse and visualize the spatial variability of phenological metrics obtained from the NDVI data the following indicators were calculated: start of season (SOS), end of season (EOS), length of season (LOS), seasonal amplitude (SA) and maximum VI (MVI) (biomass of the forest stand) for each group pixels of the studied area. The procedure for grouping and analysing time series data consisted of the following steps:

1. Transforming the original MODIS data from HDR (High Dynamic Range) to BIN (Binary) format.
2. Compiling the received binary data into a single “txt file”, named Forest.txt.
3. Visualizing the spatial distribution of VI phenological metrics to determine the boundaries of the study area.
4. Processing Forest.txt in the GUI submodule (Versatile Graphical User Interface) of the TIMESAT package.
5. Visualizing the spatial variability of the VI phenological metrics for 2000 to 2020 (figure 2).

A series of multi-temporal NDVI from MOD13Q1 data was processed in TIMESAT TSF (Temporal Spatial Filter) module to extract the images (figure 2). The obtained data went through additional processing to smooth the NDVI time series by filtering from its random component. The general approximation of the NDVI series was carried out using the Savitsky-Golay filter \[35\] in the TIMESAT-3.3 package. The second-order polynomial provides a good local approximation of the phenological (seasonal) dynamics of the forest cover’s reflectance characteristics. The studied phenological metrics were allocated for each pixel of the MODIS image without dividing into the main forest-forming species, since seasonal changes in biomass occur only in deciduous stands.

![Figure 2](image-url)  
**Figure 2.** Dynamics of NDVI annual trends for 2000-2020 based on the data of the MODIS images pixel group. The blue line represents the original NDVI data, the brown line represents smoothed values using the Savitsky-Golay function.

4. Results and discussion

Processing and visualization of the MODIS NDVI data in the TIMESAT package made it possible to obtain the average phenological metrics (characteristics) for the vegetation cover area in the forestry district of the Mari El Republic. For the comprehensive analysis, we used the spatial distribution of all the tree species growing in the area under study, including coniferous, deciduous and mixed forest stands. The phenological period of each observation during the 20 years was from mid-April to mid-November of the corresponding year, which averaged 210 days in total. The smoothed NDVI data, for
which all phenological metrics were obtained, are shown in figure 3. The NDVI of forest cover reaches its maximum during the main vegetation season from May to August and has the minimum values during the autumn season from September to November.

Figure 3. Time series of MODIS NDVI forest cover in Mari El for 2000-2020. The first and the last segments are duplicated in the TimeSAT-3.3 software package for an accurate data fit.

Analysis of the 20-year dynamics of the NDVI shows a slight decrease in the biomass of the forest stand in the study area during 2010, which confirms the accuracy of the selected area disturbed by a forest fire (figure 3). After 2010, a stable dynamics of biomass accumulation was observed in the study area of the Mari El Republic.

The obtained averages for SOS (start of season) and EOS (end of season) show relatively stable dynamics over the study period (figure 3) (table 1). Some shift in the days of the start of the vegetation season was observed in 2001, 2010, 2011, 2014 and 2018, when SOS reached more than 170 days from the beginning of the calendar year. The same years have the maximum days of the EOS, exceeding 300
days from the beginning of the calendar year. The length of the vegetation season (LOS) in the Mari El Republic on average ranges from 96 to 162 days (table 1, figure 4). The maximum LOS periods were in 2004 (162 days), in 2008 (135 days), 2012 (147 days), 2016 (138 days), and 2017 (126 days), respectively.

Figure 4. Spatial-temporal distribution of phenological indicators in the Mari El Republic: a) SOS, b) EOS, c) SA, d) MV, and e) LOS.

Table 1. Phenological metrics of forest cover in the study area based on the MODIS NDVI data.

| Years | SOS | LOS | EOS | MV, NDVI % *100 | Day of MV | SA |
|-------|-----|-----|-----|----------------|-----------|----|
| 2000  | 174 | 114 | 288 | 8,274          | 238       | 3,745 |
| 2001  | 182 | 119 | 301 | 9,454          | 230       | 7,234 |
| 2002  | 186 | 110 | 296 | 8,607          | 245       | 7,470 |
| 2003  | 157 | 110 | 267 | 7,683          | 194       | 4,802 |
For the forest cover of the study area, represented mainly by flat terrain, the SOS indicators have a persistent time interval from the beginning of April to the end of May of the current year. On average, the growing season ends on the 20th of May (figure 4a). The exception is the areas of vegetation in the central and north-eastern part of the Mari El Republic, where the growing season begins later. The distribution of EOS (figure 4b) is also fairly uniform throughout the study area, although there are some small areas with a longer period of the End of Season, which is associated with the types of forests and forest growing conditions. SA (seasonal amplitude) and MVI (max VI) also have a stable spatial distribution (figure 4 c, d). The LOS indicator tends to increase its duration (figure 4 e). In the Central and Eastern part of the Mari El Republic, a shorter growing season is observed, which also indicates the influence of the horizontal and vertical structure of the forest stand on this indicator, including the terrain of the area.

5. Conclusions
The algorithm was developed and applied in the TIMESAT software package to determine the phenological metrics (characteristics) of forest cover in the Mari El Republic for estimation its long-term dynamics based on the analysis of the MODIS NDVI time-series data. The availability of a series of satellite data on vegetation indices for the estimated period is a necessary prerequisite for applying the proposed algorithm to describe the seasonal dynamics of forest cover. The results prove the potential of the MODIS NDVI time series data analysis for monitoring the temporal forest ecosystems, as well providing additional useful information for traditional classifications of the images and algorithms of detecting changes. Although the use of the NDVI to monitor phenological metrics in mixed coniferous and deciduous forests has some limitations, our research has shown that this vegetation index can be very useful in assessing the effects of climate change on the growth of forest ecosystems. For compound research of the phenological patterns in forest ecosystems, many other climate parameters need to be taken into account in the consequent studies. The authors are planning to upgrade the proposed algorithm to improve the accuracy of identifying phenological metrics, taking into account forest types, as well as
the spatial and temporal distribution of NDVI over a larger area and in connection with meteorological parameters. The outcomes of the present study can be used as an effective tool to manage and predict the spatial and temporal dynamics of the forest stands for biodiversity conservation and climate change mitigation programmes.

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