SEASONAL DEVELOPMENT OF TREE SPECIES IN URBAN AND PERI-URBAN FORESTS IN DROUGHT

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Abstract. Our study aimed to analyze the impact of extreme drought on the phenological development of *Pinus sylvestris* L. and *Quercus robur* L. forests in Ufa city (Bashkortostan Republic, Russia) and outside it. The study area is located in the northern part of the forest-steppe subzone of the temperate climate zone. The vegetation indices NDVI, GNDVI, and CVI were calculated from cloudless Landsat images for the growing season in the dry year of 2010 and time series of 2008-2017, and they were used to analyze the phenological development of forest vegetation. To plot phenology, we used the Bayesian LSP script which uses Landsat time series data and a Bayesian hierarchical model. Higher temperatures in the city led to the higher pace at the beginning of seasonal development of pine and oak forests. The tendency for the seasonal development of forests outside the city to delay continued in the dry year. At the same time, in the dry year in pine forests both in the city and outside the city the delay of phenological development began earlier than in oak forests. Pine forests respond to a long period of water scarcity more noticeably than oak forests, which is substantially due to the features of root systems of *Quercus robur* that allow them to use deeper moisture reserves.
Keywords: *Pinus sylvestris, Quercus robur, temporal dynamics of vegetation indices, NDVI, GNDVI, CVI, Landsat TM, ETM+, OLI/TIRS*

Introduction

Currently, humanity observes significant climatic changes, which are indicated not only in changes in the temperature regime and redistribution of the summer and winter precipitation, but also in an increase in the frequency of extreme weather events (Karl et al., 1995; Beniston, 2004; Walsh et al., 2020; Cheng et al., 2021; Matkala et al., 2021). Forest communities strongly respond to climate variability (Barber et al., 2000; Lloyd and Fastie, 2002; Hirota et al., 2011), including such extreme weather events as droughts (Martínez-Vilalta and Piñol, 2002; Bigler et al., 2006; Pasho et al., 2011). Droughts can cause deterioration of trees, outbreaks of insect pests and infectious diseases of forest trees, increase in the frequency of forest fires, and other types of stress (Singatullin, 2017; Gulácsi and Kovács, 2018; Hais et al., 2019; Vanhellemont et al., 2019; Avetisyan et al., 2021; Moreno-Fernández et al., 2021; Rohner et al., 2021). Many studies show various cases of forest stand death due to severe drought stress (Pedersen, 1998; Allen et al., 2010; Williams et al., 2010, 2013; Liu et al., 2013; Moreno-Fernández et al., 2021). The vegetation seasonality reflects the reaction of species to inter-annual climate variability, including air temperature variability, daylight hours, and the soil moisture content

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(Kramer et al., 2000; Zhang et al., 2005). The influence of drought is primarily manifested in the change in the rhythm of the seasonal development of plants and in the decrease in their productivity (Ahl et al., 2006; Gaertner et al., 2019). Therefore, vegetation phenology is an effective bioindicator of the extreme weather events and a key parameter for understanding and modeling vegetation-climate interactions (Menzel, 2002; Crucifix et al., 2005). Few studies have addressed the relationship between forest dieback and phenological indicators derived from satellite imagery, despite phenology being the main indicator of the interactions between climate and vegetation. A good tool for studying the influence of stress factors on vegetation phenology is the use of various vegetation indices (NDVI, GNDVI, EVI, CVI, PRI, etc.) calculated from the spectral channels of satellite images (Soudani et al., 2008; Fedorov et al., 2019a,b). For example, vegetation indices were used to study the response of trees to drought in temperate deciduous forests (Hwang et al., 2017), to detect forest stress from outbreaks of European spruce bark beetle (Huo et al., 2021), to study inter-annual changes in the productivity of Mediterranean forests in Italy depending on the start of the dry season (Maselli et al., 2014), to assess the drought impact on the productivity of Mediterranean forests in central Chile (Miranda et al., 2020), to study drought resilience of rangelands in southern Cyprus (von Keyserlingk et al., 2021), etc. Most studies used medium- and high-resolution satellite images (MODIS, Landsat, Sentinel).

Urban environment is a specific type of vegetation habitat, and its influence on the temperature regime (the urban heat island) has been well studied (Xian and Crane, 2006; Imhoff et al., 2010; Li et al., 2011; Weng, 2012). This effect is caused by the high proportion of impervious surfaces in cities (asphalt and concrete pavements, building roofs), the low ventilation capacity of urban canyons formed by high-rise buildings, and the heat generated by urban transport (Akbari et al., 2016). The difference in temperature between the city and the suburban areas averages 1-3 °C, however sometimes it can reach 7-15 °C (Tzavali et al., 2015; Aleksashina and Le, 2018). The urban heat island effect decreases with an increase of green areas in the cities (Yuan and Bauer, 2007; Hu and Brunsell, 2013; Anniballe et al., 2014; Zhang et al., 2020). Higher air and ground temperatures in the city affect the rhythm of seasonal vegetation development (Li et al., 2017; Zhigunova et al., 2018). For different tree species the influence of the urban heat island effect on the seasonal development can appear in varying degrees and it depends, among other things, on climate variability. This issue is poorly covered in the literature because of the complexity of the selection sites. They have to include urban and peri-urban forests with tree stands similar in composition and age which would be of sufficient size to study using medium and high resolution satellite images. Otherwise, the pixel size of the satellite raster tile is larger than the studied vegetation sites (Weng et al., 2014). A good option would be to use ultra-high resolution satellite images. However, their use is limited by the low availability in the necessary quantities for the studies of phenological development of the vegetation (Yuan and Bauer, 2007; Zhan et al., 2013; Weng et al., 2014).

Extreme droughts occur in the Southern Urals periodically, and the last one happened in 2010 (Kucherov et al., 2016; Singatullin, 2017). Our previous research has shown that the seasonal development of oak and pine forests in the city and outside it differs significantly (Zhigunova et al., 2018). However, it was not clear how urban heat island-influenced forest ecosystems in the city and forest ecosystems outside the city would respond to extreme drought. The aim of our study was to analyze the impact of the extreme drought of 2010 on the features of the phenological development of pine and oak

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forests in the city and outside it, based on the analysis of vegetation indices calculated from the Landsat TM, ETM +, OLI/TIRS.

Materials and Methods

Study area

The Ufa city (Bashkortostan Republic, Russia) is located in the northern part of the forest-steppe subzone of the temperate zone. The climate is moderately continental, relatively humid. The average temperature in January is -12.3 °C and in July is 19.7 °C. The average annual air temperature is 3.8 °C. The average annual precipitation is 589 mm (www.pogodaiklimat.ru). The climate contributed to the spread of oak-linden forests (*Quercus robur* L. and *Tilia cordata* Mill.) which were the main vegetation type in the interfluve of Ufa and Belaya rivers, currently occupied by the Ufa city. The remains of these forests have been preserved in the park areas of the city. *Pinus sylvestris* L. is often used for landscaping in the city, and is also used for reforestation outside it. In this regard, we selected for our study the forest sites in the city and in the peri-urban area that are homogeneous in composition and age with the dominance of *Q. robur* and *P. sylvestris* (*Fig. 1*). The average age of *Q. robur* in different sites in 2010 ranged from 80 to 85 years. The age of *P. sylvestris* in 2010 was 65 and 70 years. No silvicultural activities have been carried out in the sites in the period between the years under consideration. The main factor of the pollution in the area of sites is urban transportation. However, the sites in the urban area were located within the forests at a distance of more than 100 meters from the forest border.

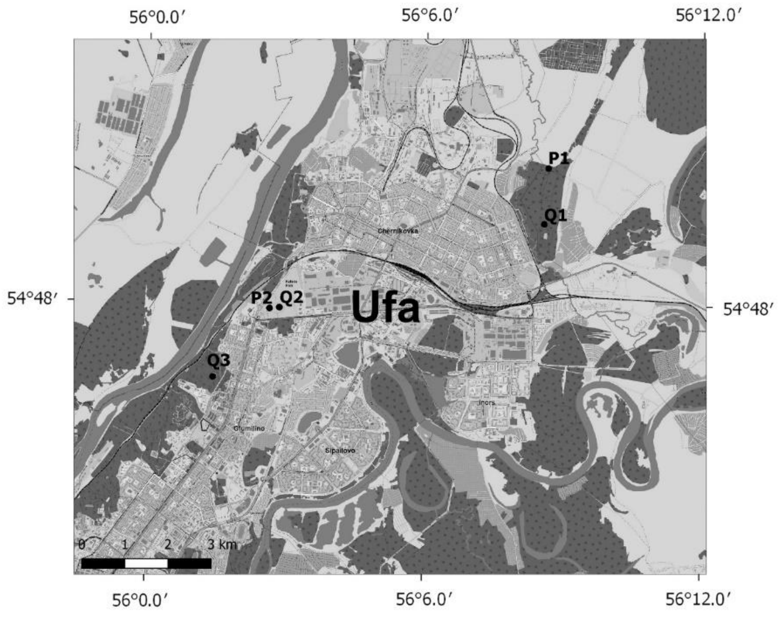

Figure 1. *Location of sites dominated by Quercus robur L. (Q1, Q2, Q3) and Pinus sylvestris L. (P1, P2) in the Ufa city and outside it*

Three oak forest sites and two pine forest sites were selected:

Q1 – an oak forest site with an area of 2.45 hectares outside the city. The coordinates of the center of the site are: 54 ° 49'0 "N, 56 ° 8'34" E. The exposure of the site is South-

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Southwest with a 3 ° slope. The forest stand is dominated by *Quercus robur*. The tree layer consists of *Q. robur* (80%), *Acer platanoides* L. (10%), and *Ulmus glabra* Huds. (10%). Tree ground cover is 35%, undergrowth ground cover is 60%. The undergrowth mainly consists of *Acer platanoides*, *Quercus robur*, *Ulmus glabra*, *Padus avium* Mill., *Sorbus aucuparia* L.

Q2 – an oak forest site with an area of 0.73 hectares in the city park. The coordinates of the center of the site are: 54°47'56" N, 56°2'52" E. The exposure is South-Southwest with a 2 ° slope. The tree layer consists of *Quercus robur* (80%) and *Tilia cordata* (20%). Tree ground cover is 45%, undergrowth ground cover is 40%. The undergrowth mainly consists of *Ulmus glabra*, *Acer platanoides*, *Sorbus aucuparia*, and *Corylus avellana* L.

Q3 – an oak forest site with an area of 0.68 hectares in the city park. The coordinates of the center of the site are: 54°47'8" N, 56°1'19" E. The exposure is South with a 26 ° slope. The tree layer consists of *Quercus robur* (80%) and *Acer platanoides* (20%). Tree ground cover is 40%, undergrowth ground cover is 60%. The undergrowth mainly consists of *A. platanoides*, *Euonymus verrucosa* Scop.

P1 – a pine forest site with an area of 1.23 hectares outside the city. The coordinates of the center of the site are: 54°49'44" N, 56°8'39" E. The exposure of the site is West-Northwest with a 3 ° slope. The tree layer consists of *Pinus sylvestris* with the addition of *Tilia cordata*. Tree ground cover is 50%, undergrowth ground cover is 25%. The undergrowth mainly consists of *Sorbus aucuparia*, *Acer platanoides*, *Tilia cordata*, *Padus avium*, *Euonymus verrucosa*, and *Corylus avellana*.

P2 – a pine forest site with an area of 0.70 hectares in the city park. The coordinates of the center of the site are: 54°47'55" N, 56°2'39" E. The exposure of the site is Southeast with a 1 ° slope. The tree layer consists of *Pinus sylvestris*. Tree ground cover is 50%, undergrowth ground cover is 50%. The undergrowth mainly consists of *Acer platanoides*, *Sorbus aucuparia*, *Ulmus glabra*, *Acer negundo* L., *Corylus avellana*, *Euonymus verrucosa*.

The analysis of the seasonal development of tree species

To analyze the seasonal development of oak and pine forests, we selected vegetation indices which, according to literature data, are often used to analyze inter-annual differences in the phenology of tree species. Five vegetation indices are often used in these studies (NDVI, GNDVI, EVI, CVI, PRI) and they are calculated from high and medium resolution satellite images (Li et al., 2019; Ochtyra et al., 2020; Dixon et al., 2021). Thus, in the study of the forests in central Indiana, USA, the vegetation indices NDVI and EVI were used to identify the trees with isohydric and anisohydric behavior in response to drought (Hwang et al., 2017). The authors calculated vegetation indices based on MODIS satellite images, which had sufficient quantity due to the high frequency of the passages of this satellite. We used Landsat satellite images of different generations (TM, ETM+, OLI/TIRS) due to the small size of the sites. These satellites have a temporal resolution of 16 days and some of the images were discarded due to the presence of clouds. Between Landsat satellites of different generations, there are between-sensor differences in the reflectance of individual channels used to calculate vegetation indices (Chen et al., 2021). The studies by Chen et al. show, that the between-sensor differences are more significant when calculating EVI than when calculating NDVI. Therefore, the direct application of the EVI is questionable when analyzing time series based on Landsat data of different generations (Chen et al., 2021). We could not calculate the PRI, which captures the response of woody species to drought well (Hwang et al., 2017; Wong et al.,

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2019), since the spectral ranges used in PRI calculation (0.53 and 0.57 mkm) are within the same spectral channel in the Landsat imagery. Therefore, in this study we used three vegetation indices: NDVI, GNDVI, and CVI.

NDVI (Normalized Difference Vegetation Index) is most often used to study the phenology of forest and herbaceous vegetation (Berra et al., 2019; Fedorov et al., 2019a,b; Dixon et al., 2021). The index is based on the ability of vegetation to absorb electromagnetic waves in the visible red light (RED) and reflect them in the near-infrared light (NIR). It is calculated using the formula:

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad \text{(Eq.1)}$$

Chlorophyll strongly absorbs visible red light while the cell structure of the leaves strongly reflects near-infrared light. NDVI can become oversaturated in dense vegetation conditions when the leaf area index (LAI) becomes high.

GNDVI (Green Normalized Difference Vegetation Index) is widely used to study the phenology of vegetation and its response to various stress factors (Gitelson and Merzlyak, 1998; Ahamed et al., 2011; Liu and Treitz, 2016; Zarei et al., 2020). It is an indicator of the photosynthetic activity of the vegetation cover used in assessing the moisture content and nitrogen concentration in plant leaves. GNDVI is similar to NDVI except that green light (GREEN) is used instead of red light. Compared to the NDVI, GNDVI is more sensitive to chlorophyll concentration (Ochtyra et al., 2020). GNDVI is recommended to identify plants under stress and at the stage of seasonal wilting (Ahamed et al., 2011):

$$GNDVI = \frac{NIR - GREEN}{NIR + GREEN} \qquad \text{(Eq.2)}$$

CVI (Chlorophyll Vegetation Index) has an increased sensitivity to the chlorophyll content of the foliage. The index was developed to assess the chlorophyll content of crops (Datt et al., 2003; Vincini et al., 2008), but it had also been used for studying tree species (Li et al., 2019):

$$CVI = \frac{NIR}{GREEN} * \frac{RED}{GREEN} \qquad \text{(Eq.3)}$$

Vegetation indices were calculated from cloudless images of Landsat TM, ETM +, and OLI / TIRS for the period from 2008 to 2017 with preliminary radiometric and atmospheric correction (Neteler and Mitasova, 2008). We did not use the images from 2018-2020 because of the appearance of the insect pest *Acrocercops brongniardella* (Fabricius, 1798) (Lepidoptera, Gracillariidae) in the peri-urban *Quercus robur* sites.

All calculations were carried out in SAGA GIS v. 7.7.0 and QGIS 3.18.1 with GRASS 7.8.5 support. The average values of the indices for each site were calculated using the Zonal Statistics plugin.

The mean plot of the temporal dynamics of vegetation indices was calculated using a double-logistic function with a “greendown” parameter (Elmore et al., 2012; Melaas et al., 2013; Gao et al., 2021; Zhang et al., 2021). This function combines the spring and autumn seasons into a single equation and allows the gradual reduction of the vegetation

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indices values in the middle of summer which is usually observed during the remote sensing of forest canopy greenness. We used a Bayesian method that uses Landsat time series data, and a Bayesian hierarchical model to plot phenology. This method is implemented in the Bayesian_LSP script, developed in the R programming language (Gao et al., 2021). One of the advantages of Bayesian methods is the ability to quantify uncertainty for the estimated parameter by the posterior distribution (Babcock et al., 2021; Gao et al., 2021). This is done by using Markov Chain Monte Carlo (MCMC) sampling (Geyer, 1992). The uncertainties of the estimated parameters are summarized by calculating the 95% credible interval of the estimated posterior distribution. The 95% credible interval of the posterior distribution can be interpreted as a range of values with a 95% probability that contains the true mean of the parameter (Gao et al., 2021).

We analyzed the seasonal dynamics of forests using the temporal dynamics of vegetation indices for the following parameters:

- the SOS and EOS parameters defined as the inflection points on the phenology plot which are used to represent the start of season (SOS) and the end of season (EOS);
- the growing season defined as the time between SOS and EOS (in the plots of NDVI temporal dynamics) which were calculated for each year separately, as well as for the generalized mean phenology plot based on Landsat time series data for 2008-2017;
- the mean value of the vegetation index during the growing season;
- the maximum value of the vegetation index during the growing season;
- the difference between the average value of the vegetation index for the whole growing season of 2010 and the mean value of the vegetation index of the growing season for 10 years (as a percentage);
- the maximum difference between the value of vegetation index in 2010 and the mean value of the vegetation index for 10 years on exact dates (as a percentage).

To characterize the weather conditions in 2008-2017 (mean daily air temperature, precipitation, snow depth), we used the data from meteorological station № 28722 of the Ufa city (aisori-m.meteo.ru).

Results

Features of weather conditions in dry 2010

In the South Ural region, the year 2010 was anomalous in terms of the precipitation and also had a higher temperature during the growing season (*Fig. 2*). The precipitation during the growing season (April-September) in 2010 was only 155.3 mm, which is almost two times lower than the mean values for the last 70 years (311.0 mm). In 2010, in addition to the summer-spring precipitation deficit, there was also less precipitation during the winter which resulted in a significantly lower snow depth. The mean monthly temperatures during the growing season in 2010 exceeded the monthly average from 2 to 5 ° C.

The analysis of the seasonal development of tree species

Abnormal weather conditions in 2010 led to the change in the phenological development of tree species (*Table 1*). The temporal dynamics of vegetation indices (NDVI, GNDVI and CVI) of oak and pine forests in 2010 and the mean temporal dynamics of the vegetation indices of 2008-2017 are shown in *Figures 3-8*.

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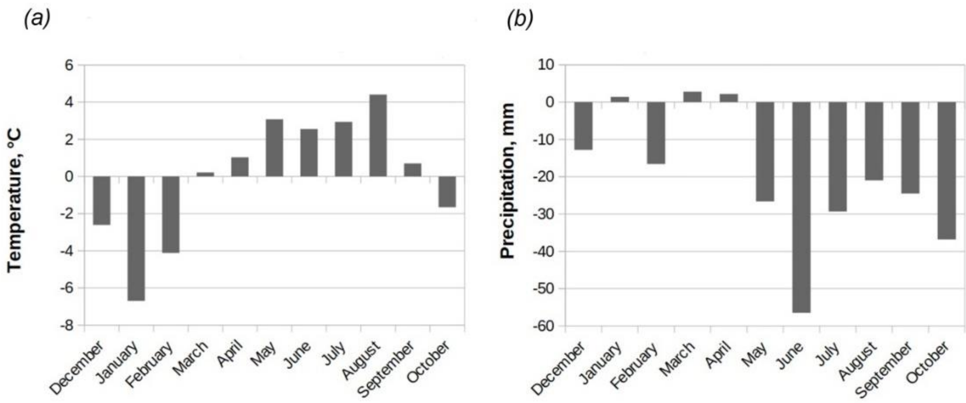

***Figure 2.** Deviation from the average values: a) monthly average temperature (from December of the previous year to October of the year under review) in the dry year 2010 from the average values for the last 70 years (1950-2019); b) average monthly precipitation (from December of the previous year to October of the year under review) in the dry year 2010 from the average values for the last 70 years (1950-2019)*

***Table 1.** Dates of the start of the growing season (SOS) (the inflection points on the temporal dynamics plots of NDVI) on the sites dominated by Quercus robur L. and Pinus sylvestris L. in the Ufa city and outside it*

Years	**Sites**[1]				
	Q1	**Q2**	**Q3**	**P1**	**P2**
2010	May 8	May 5	April 30	April 30	April 25
mean	May 10	May 4	May 2	April 30	April 24

[1]Sites dominated by *Quercus robur* L.: **Q1** – outside the city, **Q2** – in the city on a flat area, **Q3** – in the city on a steep southern slope; sites dominated by *Pinus sylvestris* L.: **P1** – outside the city, **P2** – in the city on a flat area

As seen in *Table 1*, the dates of the start of the growing season (SOS) in 2010 in the oak forest sites in the city (Q2 and Q3) and outside the city (Q1) differed slightly from the 10-years average. At the same time, in the oak forests outside the city (Q1), the pace of the NDVI increase during the crown formation (from the early April to the first ten days of May) in 2010 was higher than the average, and in the city the values did not differ (*Fig. 3*, *Table 1*). The average NDVI values of the whole growing season in 2010 in the oak forests in the city and outside the city in a dry year in all cases were lower than the 10-years average values (*Table 2*). In the second half of July of the dry year there was a sharp NDVI decrease in all sites followed by recovery caused by the rains by the end of summer. Moreover, after the recovery the NDVI values exceeded the average for 10 years.

The analysis of the NDVI temporal dynamics in the pine forests showed that in the city (P2) and outside the city (P1) the dates of the start of the growing season (SOS) in the dry year almost did not differ from the average of 10 years (*Table 1*).

However, the NDVI values during the period from the moment of snow melt to the first ten days of May in the dry year were lower than the average values for 2008-2017. In the pine forests outside the city (P1) at the beginning of June (during the completion of the formation of new needles) the NDVI values were slightly higher than average, and they almost did not differ in the city (*Fig. 4*). The mean NDVI values for the whole

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growing season in 2010 in pine forests both in the city and outside it in a dry year were lower than the mean values for 2008-2017 (*Table 2*). In the second half of July of the dry year, in both pine forest sites, as well as in oak forests, there was a sharp decrease in NDVI, followed by their recovery after rains by the end of summer, exceeding the 10-year average.

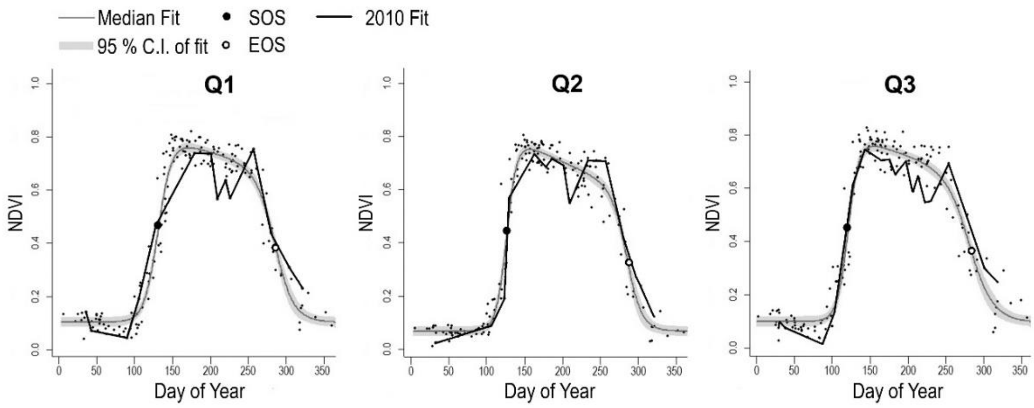

Figure 3. *The temporal dynamics of NDVI on the sites dominated by Quercus robur L. in the Ufa city and outside it.* ***Q1*** *– outside the city,* ***Q2*** *– in the city on a flat area,* ***Q3*** *– in the city on a steep southern slope;* ***Median Fit*** *– average plot of 2008-2017;* ***95% C.I. of fit*** *– 95% credible interval of median fit;* ***SOS*** *– start of season;* ***EOS*** *– end of season;* ***2010 Fit*** *– plot of 2010*

Table 2. *Average (maximum) values of NDVI, GNDVI and CVI during the vegetation period of full crown development on the sites dominated by Quercus robur L. and Pinus sylvestris L. in the Ufa city and outside it*

Sites	2010	Mean $^{2008\text{-}2017}$	$\Delta^{2010\text{-mean}}$, %	Max $\Delta^{2010\text{-mean}}$, %	Date of max $\Delta^{2010\text{-mean}}$
			NDVI		
Q1	0.6 (0.75)	0.68 (0.82)	12	22.3	2010-07-29
Q2	0.64 (0.73)	0.66 (0.8)	3.5	20.4	2010-07-29
Q3	0.65 (0.74)	0.68 (0.83)	4.7	20.6	2010-08-14
P1	0.48 (0.63)	0.56 (0.71)	15.8	42.3	2010-08-14
P2	0.53 (0.62)	0.59 (0.71)	9	27.3	2010-07-29
			GNDVI		
Q1	0.49 (0.64)	0.56 (0.7)	13.7	31.1	2010-08-14
Q2	0.54 (0.64)	0.55 (0.68)	2.5	18.4	2010-07-29
Q3	0.56 (0.63)	0.57 (0.7)	1.9	18.3	2010-08-14
P1	0.37 (0.5)	0.44 (0.58)	16.6	42	2010-08-05
P2	0.42 (0.51)	0.46 (0.58)	8.9	27.5	2010-07-29
			CVI		
Q1	2.3 (3.11)	2.52 (3.16)	8.7	32.5	2010-08-14
Q2	2.57 (3.2)	2.45 (3.34)	-4.8	18.4	2010-07-29
Q3	2.53 (3.14)	2.6 (3.21)	2.7	20.8	2010-07-29
P1	1.68 (2.21)	1.86 (2.42)	9.7	28.3	2010-07-29
P2	1.88 (2.24)	1.92 (2.37)	2.4	17.6	2010-08-06

[1] Sites dominated by *Quercus robur* L.: **Q1** – outside the city, **Q2** – in the city on a flat area, **Q3** – in the city on a steep southern slope; sites dominated by *Pinus sylvestris* L.: **P1** – outside the city, **P2** – in the city on a flat area; **Δ 2010-mean** – the difference between the average value of the vegetation indices during the growing season of 2010 and the average value of the vegetation indices during the growing season for 10 years; **Max Δ 2010-mean** – the maximum difference of vegetation indices from the average value of vegetation indices for this date for 10 years

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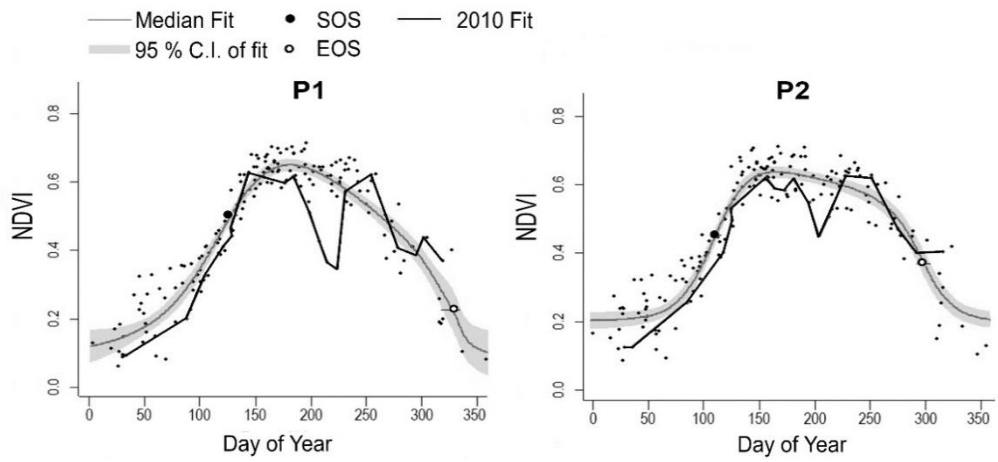

***Figure 4.** The temporal dynamics of NDVI on the sites dominated by Pinus sylvestris L. in the Ufa city and outside it. **P1** – outside the city, **P2** – in the city; **Median Fit** – average plot of 2008-2017; **95% C.I. of fit** – 95% credible interval of median fit; **SOS** – start of season; **EOS** – end of season; **2010 Fit** – plot of 2010*

The analysis of the GNDVI temporal dynamics showed the similar patterns to the NDVI temporal dynamics during the growing season of both studied tree species (*Fig. 5, 6*). However, in the second half of July of the dry year (during the maximum drought), the oak forests outside the city (Q1) showed a stronger decline in the GNDVI values compared to NDVI. The average GNDVI values for the whole growing season in the oak forests outside the city (Q1) in a dry year were significantly lower than the 10-year average. In the oak forests in the city (Q2 and Q3), the average values of GNDVI in 2010 almost coincided with the 10-years average (*Table 2*). By the end of August, the GNDVI values in all oak forest sites exceeded the 10-years average values.

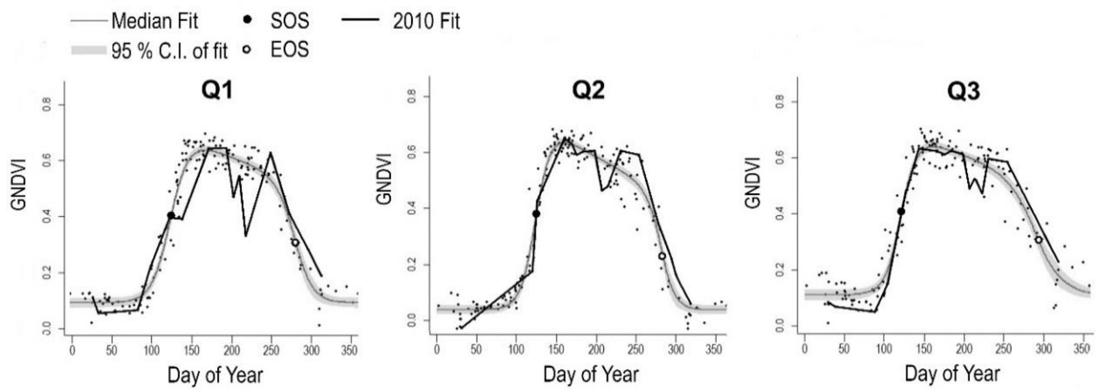

***Figure 5.** The temporal dynamics of GNDVI on the sites dominated by Quercus robur L. in the Ufa city and outside it. **Q1** – outside the city, **Q2** – in the city on a flat area, **Q3** – in the city on a steep southern slope; **Median Fit** – average plot of 2008-2017; **95% C.I. of fit** – 95% credible interval of median fit; **SOS** – start of season; **EOS** – end of season; **2010 Fit** – plot of 2010*

The GNDVI temporal dynamics in the pine forests both in the city and outside it also had a similar character to the NDVI temporal dynamics (*Fig. 6*). The GNDVI values during the period from the moment of snow melt to the first ten days of May in the dry

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year were below the 10-year average. The average GNDVI values for the whole growing season in the dry year were significantly lower than the average for 10 years (*Table 2*). In late summer, after the onset of regular rains, the GNDVI values exceeded the 10-year average.

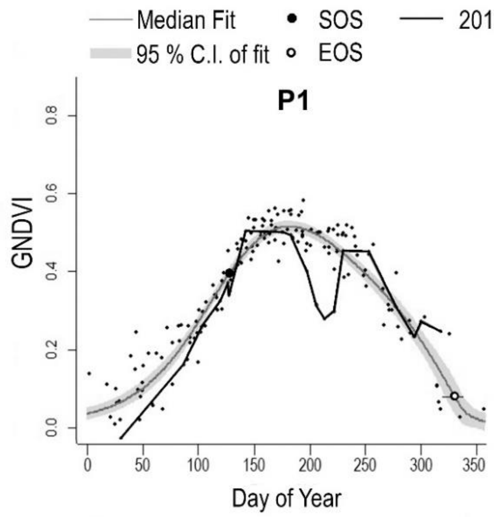

Figure 6. *The temporal dynamics of GNDVI on the sites dominated by Pinus sylvestris L. in the Ufa city and outside it.* ***P1*** *– outside the city,* ***P2*** *– in the city.* ***Median Fit*** *– average plot of 2008-2017;* ***95% C.I. of fit*** *– 95% credible interval of median fit;* ***SOS*** *– start of season;* ***EOS*** *– end of season;* ***2010 Fit*** *– plot of 2010*

The CVI temporal dynamics of oak and pine forests differ significantly from the temporal dynamics of GNDVI and NDVI. *Figures 7* and *8* show that CVI was higher than the average in the first half of summer at the beginning of the drought in 2010 in all studied sites, and during the period of severe drought the CVI dropped. After the rains in the second half of August, the CVI values increased up to the average or higher.

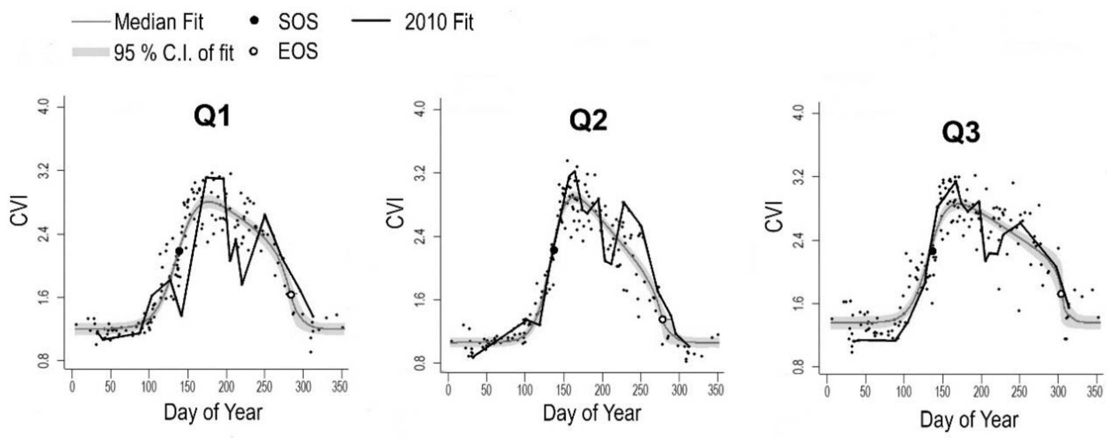

Figure 7. *The temporal dynamics of CVI (****c****) on the sites dominated by Quercus robur L. in the Ufa city and outside it.* ***Q1*** *– outside the city,* ***Q2*** *– in the city on a flat area,* ***Q3*** *– in the city on a steep southern slope;* ***Median Fit*** *– average plot of 2008-2017;* ***95% C.I. of fit*** *– 95% credible interval of median fit;* ***SOS*** *– start of season;* ***EOS*** *– end of season;* ***2010 Fit*** *– plot of 2010*

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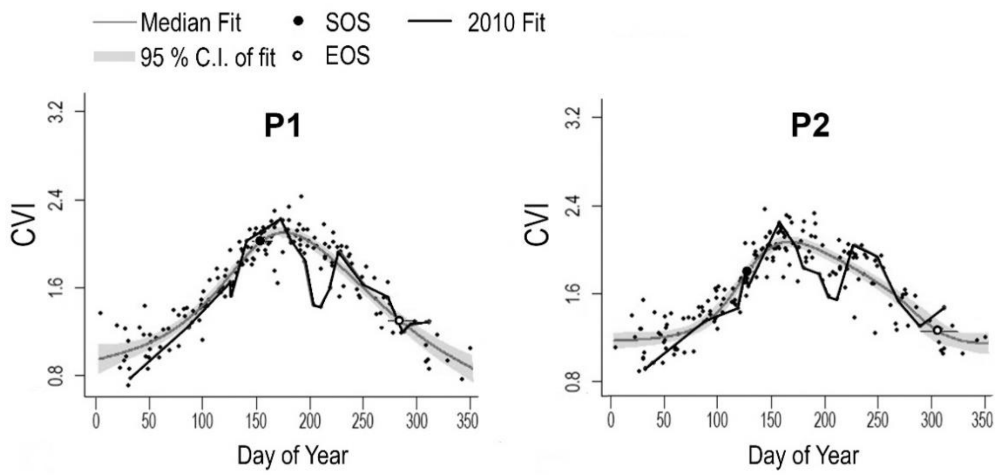

Figure 8. *The temporal dynamics of CVI on the sites dominated by Pinus sylvestris L. in the Ufa city and outside it.* ***P1*** *– outside the city,* ***P2*** *– in the city;* ***Median Fit*** *– average plot of 2008-2017;* ***95% C.I. of fit*** *– 95% credible interval of median fit;* ***SOS*** *– start of season;* ***EOS*** *– end of season;* ***2010 Fit*** *– plot of 2010*

Discussion

The basic strategy of plant adaptation to drought is aimed at maintaining water balance through more efficient water use using morphological and physiological mechanisms (Querejeta et al., 2007; McDowell et al., 2008; Hwang et al., 2017; Rohner et al., 2021). There are changes in transpiration level and a decrease in photosynthesis at the initial drought stages. Further, chlorophyll content in leaves and the total surface area evaporating moisture decrease due to inhibition of the young shoots growth and even partial shedding of the leaves (Kozina et al., 2011; Vanhellemont et al., 2019). Due to this, the vegetation indices also change (Joiner et al., 2018; Miranda et al., 2020; Yang et al., 2020; Avetisyan et al., 2021).

The average annual temperature excess was observed as soon as the second half of April of 2010 (*Fig. 2*), which led to an earlier snow melt-off. This also facilitated the lower amount of winter precipitation (from December to March), which was 19% less than the average precipitation according to the long-term observations. Earlier snow melt-off and higher temperatures during the beginning of crown formation (April-mid-May) led to the acceleration of the phenological development of the oak forests outside the city compared to the 10-year average. At the same time, during this period in the urban oak forests (Q2, Q3) there was no increase in the phenological development pace which was apparently due to the lower moisture supply caused by the earlier convergence of the snow cover in comparison with the peri-urban forest (*Fig. 3*). However, by mid-May, a significant decline in soil moisture began to occur and the phenological development of the oak forests both in the city and outside it slows down.

In general, the development of oak forests in the city and outside the city happened differently. Urban heat island effect lead to an earlier start of the growing season and to the higher pace of the crown development at the beginning of seasonal development (Zhigunova et al., 2018). According to the average data for 2008-2017, there was a lag in phenological development of oak forests outside the city (Q1) from early spring until the complete formation of the crowns (*Fig. 9*). The date of the start of the growing season (SOS) in the oak forest outside the city (Q1) comes on average 6 days later than in the

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oak forests in the city park (Q2) and 8 days later than in the oak forests on the southern slope (Q3) (*Table 1, Fig. 9*). The tendency for the development of the peri-urban oak forests to lag behind the development of the urban oak forests continued in the dry year. At the same time, due to drought in 2010 in the peri-urban oak forests the lag in phenological development began during the leaf unfolding. At the same time, the crown development was already underway in the city and the average size of leaves on the flat area of oak forests (Q2) did not yet reach 50%, and on the southern slope (Q3), it was more than 50% of the size of fully developed leaves.

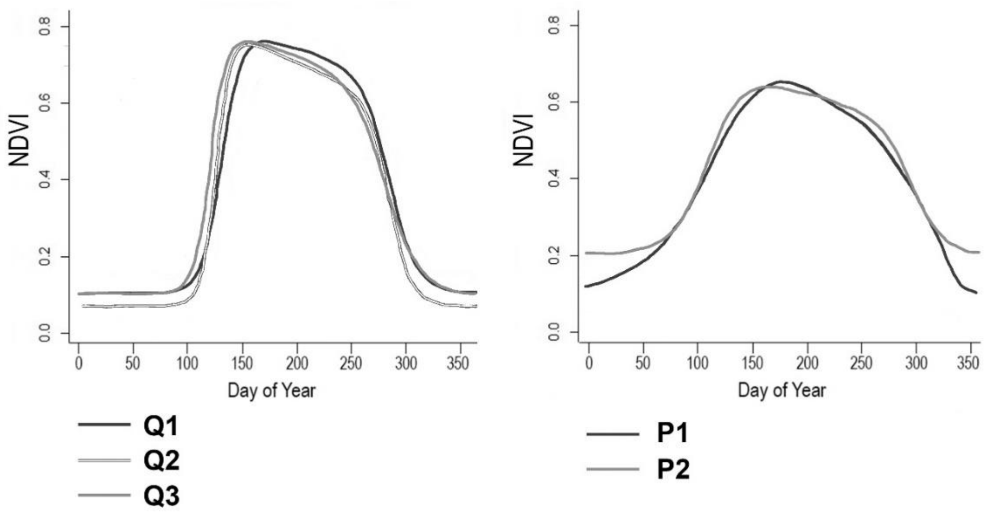

Figure 9. *The averages temporal dynamics of NDVI (average plot of 2008-2017) on the sites dominated by Quercus robur L. and Pinus sylvestris L. in the Ufa city and outside it.* ***Q1, P1*** *– outside the city,* ***Q2, Q3, P2*** *– in the city*

The average NDVI values for the whole growing season in 2010 in the oak forests both outside the city (Q1) and in the city (Q2 and Q3) were lower than the average values for 2008-2017. Lower NDVI values indicate a pronounced suppression of the tree layer with a photosynthetic activity decrease and a slowdown of the new leafy shoots formation (Joiner et al., 2018; Miranda et al., 2020; Avetisyan et al., 2021).

Small intermittent rains in July led to local increases in NDVI, however up to mid-August a downward trend in the NDVI was observed. The maximum decline in NDVI in the oak forests compared to the 10-year average was 20.4% to 22.3% (*Table 2*). In mid-August, regular light rains led to a gradual increase in NDVI and lowering the differences between the values of the dry year and the average values of 2008-2017.

The plots of the NDVI temporal dynamics in the pine forests show that the lag in the phenological development of the urban (P2) and peri-urban (P1) pine forests in contrast to the oak forests in the dry year began from the snow melt-off (*Fig. 4*). This happened because the seasonal development of pine is more dependent on the spring precipitation (Elmore et al., 2012; Kucherov et al., 2016). The suppression of the pine forest in the city from the seasonal development beginning was observed and NDVI did not reach the values of 2017, before regular precipitation at the end of August 2010, which is explained by the intensification of drought in the urban environment (Zhigunova et al., 2018).

Comparison of the prolonged drought response in oak and pine forests is of considerable interest. Comparing the temporal dynamics of the NDVI of the oak and pine

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forests in 2010 (*Figs. 3, 4*, *Table 2*) showed that the pine forests react more strongly to a long period of water deficit in the middle of summer. The maximum decrease in NDVI compared to the 10-years average in the pine forests is 1.5-2 times greater than in the oak forests (*Table 2*). Different responses to prolonged drought can be explained by the difference in the root systems structure of these species. The drought tolerance of plants as a function of root length has been well studied in crops, but this is also true for tree species (Lynch, 2013). Under relatively favorable edaphic conditions, such as study area, *Q. robur* forms a deeper root system. Oak taproots are two to three times longer than the pine roots (Praciak et al., 2013; Prutskoy, 2017). After the prolonged drought in the study area, the groundwater level has changed by 0.84-3.27 m (Abdrakhmanov et al., 2018). The deeper root system allows *Q. robur* to use deeper moisture reserves. Besides, broad-leaved trees can use the water stored in the heartwood during prolonged dry periods while conifers keep their water reserves mainly by real-time absorption (Querejeta et al., 2007; Goldsmith, 2013). The results are also confirmed by the fact that oak is more resistant to summer drought conditions than pine (Merlin et al., 2015; Toïgo et al., 2015; Vanhellemont et al., 2019; Steckel et al., 2020).

Changes of GNDVI and NDVI were similar in both oak and pine forests during the growing season. However, in the absence of precipitation during the period of the most severe drought from the second half of July to mid-August, in oak forests outside the city (Q1) the GNDVI decrease was much more significant than NDVI decrease (*Table 2*). The maximum decline in GNDVI in oak forests compared to the 10-year average is ranged from 18.3% to 31.1% (*Table 2*). At the same time, in the oak forests outside the city a stronger decrease in GNDVI was observed. Perhaps this was due to the fact that the lag in phenology outside the city began at an earlier stage of crown development than in the city. Thus, when assessing the stress caused by drought the informative value of GNDVI in some cases may be higher than NDVI. Literature data confirm that GNDVI has a higher sensitivity to moisture and chlorophyll content in plant leaves as well as to a greater extent reflects the level of plant stress (Ahamed et al., 2011).

The temporal dynamic of CVI (*Figs. 4, 5*) is significantly different from the temporal dynamics of NDVI and GNDVI. In a year with the average precipitation, the plots of temporal dynamics of the CVI in the pine and oak forests show fluctuations in values which are not explained by objective reasons. The CVI values in oak and pine forests in the early summer of 2010 were significantly higher than the average for 2008-2017. The highest CVI values were recorded in the second half of June when the NDVI reached a plateau or had already begun to decline. Thus, no positive correlation was observed between the CVI values and the chlorophyll concentration reflected by the NDVI and GNDVI. This result does not contradict the literature data. Initially, Vincini et al. (2008) found a positive correlation between CVI and chlorophyll content in leaves of crops; however, Ortiz et al. (2011) found a negative correlation of CVI with chlorophyll content of crops and control plots of crops showed lower CVI values than the plots with inhibited herbicide treatment. Also, a negative correlation between CVI and chlorophyll content was shown using the example of mangrove forest (Heenkenda et al., 2015). However, with the prolonged drought in the second half of the summer the CVI values decrease, similarly to NDVI and GNDVI. Thus, NDVI and GNDVI seem to be more informative when analyzing the impact of drought on the phenology of forest vegetation.

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Conclusions

Abnormal weather events, the frequency of which increases with the climate change, have a significant impact on the phenological development and condition of urban forests. We have shown that NDVI and GNDVI were most informative and CVI was uninformative when using high-resolution satellite images to study the impact of drought on forest vegetation. Higher temperatures in the city lead to the earlier start of the growing season and to the higher pace at the beginning of seasonal development of pine and oak forests. This tendency for the seasonal development of the peri-urban forests to delay continued in the dry year. Thus, at the beginning of the growing season, the effect of the location on the development of plants were much more intense than the impact of the weather conditions. At the same time, in both urban and peri-urban pine forests in the dry year the delay of the phenological development began earlier than in the oak forests. Pine forests respond to the long period of water scarcity to a greater extent than the oak forests. This is largely explained by the features of *Q. robur* root systems which allow the plants to use deeper moisture reserves.

After the rains at the end of summer, there was an increase in the NDVI and GNDVI values in the urban and peri-urban forests to a level exceeding the 10-year average values. This happened due to the combination of sufficient precipitation and higher air temperature which led to the increase in photosynthetic activity.

Q. robur along with *P. sylvestris* should be used more widely when landscaping the cities located in the forest-steppe subzone of the temperate zone. We especially recommend using oak in places where it has become extinct as a result of the abnormally low winter temperatures of the 20th century, since the oak forests have not been observed in the study area for more than 40 years due to the climate change.

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Conflicts of Interests. The authors declare no conflict of interests.

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