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The Response of Vegetation Cover in the West Siberian Plain to Climate Changes in 1982–2015

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Abstract—This paper is devoted to studying the response of different types of vegetation cover in the West Siberian Plain to temperature changes observed in recent decades. The paper analyzes trends in the series of the normalized difference vegetation index (NDVI) and air temperature in the vicinities of meteorological stations of the West Siberian Plain, which are characterized by different types of vegetation. Phases of growth (1982–1997) and stabilization (1997–2015) of NDVI values have been revealed against the background of the observed effects of global-warming slowdown, decrease of solar activity, and transition from the positive phase of the ocean-surface temperature to the negative phase in the El Niño region (ONI). It is shown that the spring months make the main contribution to variations in the seasonal NDVI value. A correlation analysis of spring NDVI and air-temperature values during the periods of NDVI growth and stabilization has been carried out. It is shown that the pattern of response of vegetation to the observed increase in temperature depends on its type and location. Thus, the relationship between the NDVI and air temperature increases in the tundra zone, decreases in very swampy areas of forest tundra and northern taiga, generally decreases in the Ob–Yenisei interfluvium from forest tundra to subtaiga, and increases on the left bank of the Ob River.

Keywords: vegetation cover, normalized difference vegetation index, air temperature, climate changes, Western Siberia

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INTRODUCTION

At the present time, many studies are devoted to global and regional changes in vegetation cover due to the currently observed climate changes. Data of the normalized difference vegetation index (NDVI) indicate changes in the vegetation productivity in northern regions of Eurasia and America, which are most sensitive to the growing air temperature (Seidl et al., 2017; Seddon et al., 2016). In recent decades, a widespread “greening” has been recorded in tundra, which is indicated by the increasing NDVI maxima during the growing season (Walker et al., 2009; Epstein et al., 2012; Bhatt et al., 2017); at the same time, the NDVI has tended to change from “greening” to “browning” in some areas of the boreal forest zone (Beck and Goetz, 2011; Elsakov and Telyatnikov, 2013; Buermann et al., 2014). However, the observed trends are highly sensitive to temporal and spatial sampling and have a large spatial heterogeneity (Miles and Esau, 2016).

The area of the West Siberian Plain has been poorly studied in terms of climatically determined changes in

vegetation productivity. The few currently available studies of the state of the vegetation cover in the taiga zone of the region are incomplete and deal mainly with anthropogenic impact on landscapes due to the active development of oil and gas fields (Sharikalov and Yakutin, 2012; Alekseeva and Yashchenko, 2013; Korkina and Talyneva, 2015; Kobzar’ et al., 2016). The available estimates of changes in tundra vegetation indicate that there has been an increase in its productivity in recent decades (Elsakov and Telyatnikov, 2013; Titkova and Vinogradova, 2015; Belonovskaya et al., 2011). Miles et al. (2019) attempted to assess changes in the productivity of different types of vegetation in the northern part of the West Siberian Plain in 2000–2016; their research also revealed a predominant increase in vegetation productivity in tundra and its decrease in taiga. In turn, the NDVI values for the period of 1982–2015 that were considered in (Zuev et al., 2019) show mainly positive trends in vegetation productivity in both the tundra and taiga zones.

Climate studies indicate that the air temperature is increasing at a more rapid rate in Siberia than in other

regions (Cohen et al., 2014), and climate models show there will be further warming (Miao et al., 2014). Therefore, the study of the response of different types of vegetation in the West Siberian Plain (one of the most significant carbon pools in the world) to the observed climate changes appears to be a particularly important task. The available NDVI data from 1982 to 2015 (Pinzon and Tucker, 2014) make it possible to assess trends of variation in the productivity of different types of vegetation in the West Siberian Plain over more than 30 years and compare them with the temperature changes over the same period.

MATERIALS AND METHODS

To assess the effect of climate changes on the vegetation of Western Siberia, we analyzed the correlation between the NDVI vegetation index and air temperature. The analysis involved areas near Roshydromet (Russian Hydrometeorological Service) meteorological stations with long series of air-temperature observations. In total, we selected 33 meteorological stations located in natural zones from tundra to subtaiga; the more southern stations were not considered in the analysis due to a high anthropogenic disturbance of the landscapes of these areas (abundant arable lands). Series of mean monthly air temperatures were obtained using the service of the All-Russia Research Institute of Hydrometeorological Information, World Data Center (Bulygina et al.). The NDVI vegetation index was used as an indicator of vegetation state; this index shows the amount of photosynthetically active biomass and is determined by the difference in spectral radiance between the red and near-infrared ranges on satellite images of the Earth's surface. This study used NDVI GIMMS data from the multichannel AVHRR radiometer installed on board the NOAA satellites; these data present the average monthly values of the NDVI index for the period of 1982–2015 at a resolution of $1/12^\circ \times 1/12^\circ$ (Pinzon and Tucker, 2014). Although the data of the NDVI GIMMS set cover the period until 2015, it is the most representative long-term set of those currently available (Marshall et al., 2016; Tian et al., 2015). To calculate the NDVI in the vicinity of each meteorological station, we selected a square area ($0.5^\circ \times 0.5^\circ$) with the most homogeneous vegetation type and minimum number of infrastructure facilities; the data from this area were averaged. Vegetation types were determined according to the vegetation map of Russia developed at the Space Research Institute, Russian Academy of Sciences, based on data of satellite monitoring of the Earth's surface (Bartalev et al., 2011). All calculations were performed for a significance level of 0.05.

The list of meteorological stations included in the analysis (with indication of the natural zone, charac-

teristic type of vegetation in the square area selected for each station ($0.5^\circ \times 0.5^\circ$), and warm period for each natural zone determined from the data of the mean monthly air temperature at the stations for 1982–2015) is given in Table 1.

RESULTS

One of the main factors determining the productivity of vegetation systems is air temperature. Vegetation in northern areas is particularly sensitive to air temperature fluctuations in autumn and spring, i.e., when temperature is a limiting factor of photosynthesis and determines the beginning and end of the growing season and dates of the occurrence of phenological phenomena (Wang et al., 2011; Piao et al., 2008, 2011, 2015). To assess changes in the NDVI and air temperature over the warm period determined in Table 1, we calculated the seasonal values of the parameters for each station and their linear trends for 1982–2015. As can be seen from Fig. 1a, significant positive trends in the seasonal NDVI value are observed in the vicinities of most of the meteorological stations of the region except very swampy areas in forest tundra and northern taiga (areas near the Salekhard, Yanov Stan, Nadym, Tarko—Sale, Tolka, Berezovo, and Khalyasavei stations and midtaiga Aleksandrovskoe station), for which the trends of the seasonal NDVI value are insignificant. Air-temperature trends during the warm period are positive at most of the stations of the region; however, they are insignificant (Fig. 1b).

Analysis of the dynamics of the seasonal NDVI value revealed that the pattern of its increase is nonlinear at most of the stations in the region. Averaging of the seasonal NDVI values within the natural zones shows that the NDVI generally reaches its peak value in 1997, while its values decrease or stabilize in all natural zones from the late 1990s to the early 2000s (Fig. 2a). At the same time, the increase in the seasonal NDVI value in 1982–1997 (the trends are significant for all natural zones of the region) is accompanied by an increase in the seasonal air temperature only at stations in the southern taiga and subtaiga; in other natural zones, the trends in seasonal air temperature are close to zero or negative in 1982–1997 (Fig. 2b). Therefore, against the background of general positive trends in the NDVI and air temperature in 1982–2015 (Fig. 1), the dynamics of the parameters within this period does not have unidirectional trends, although it is known that fluctuations in the seasonal NDVI value depend on air-temperature fluctuations during the warm period—in particular, in the spring months (Zuev et al., 2019). No significant trends in seasonal air temperature in natural zones of the region were revealed in any of the two periods (1982–1997 and 1997–2015).

Table 1. Characteristics of meteorological stations selected for the analysis

Natural zone	Station	Type of vegetation in the vicinity of the meteorological station	Warm period
Tundra	Antipayuta	Sparse vegetation (mosses, lichens, and low-growing shrubs)	June–September
	Novyi Port	Shrub, herbaceous, and dwarf-shrub vegetation	
	Tazovskiy	Shrub vegetation	
	Nyda	Shrub and bog vegetation	
Forest tundra	Forest tundra	Bank vegetation and bog vegetation	May–September
	Yanov Stan	Bog vegetation and dark coniferous evergreen forests along river valleys	
	Nadym	Bog vegetation and dark coniferous evergreen forests along river valleys	
	Tarko-Sale	Larch forests	
Northern taiga	Saranpaul	Bog vegetation and mixed forests	May–September
	Tolka	Bog vegetation and deciduous forests	
	Berezovo	Dark coniferous, light coniferous, and mixed forests	
	Khalyasavei	Bog vegetation	
Midtaiga	Oktyabrskoe	Mixed dark coniferous forests	May–September
	Nyaksimvol	Light coniferous forests with deciduous and mixed forests and bog vegetation	
	Laryak	Bog vegetation and deciduous forests	
	Khanty-Mansiysk	Bog vegetation and light coniferous forests	
	Ugut	Bog vegetation and mixed forests	
	Aleksandrovskoe	Floodplain vegetation, bog vegetation, and deciduous forests	
	Vanzhil-Kynak	Dark coniferous and mixed forests and bog vegetation	
	Napas	Bog vegetation and mixed forests	
	Leushi	Deciduous forests with mixed forests and bog vegetation	
Middle Vasyugan	Bog vegetation and mixed forests		
Southern taiga	Ust-Ozernoe	Bog vegetation and light coniferous forests	April–October
	Kolpashevo	Bog vegetation and mixed forests	
	Tobolsk	Deciduous forests, meadow vegetation, and pine forests	
	Turinsk	Mixed forests	
	Bakchar	Mixed forests and bog vegetation	
	Pudino	Bog vegetation and mixed forests	
Subtaiga	Tyumen	Deciduous forests and meadow vegetation (with arable lands)	April–October
	Pervomaiskoe	Meadow vegetation and light coniferous forests (with arable lands)	
	Tara	Deciduous forests and meadow vegetation	
	Tomsk	Mixed and light coniferous forests and meadow vegetation	
	Severnoe	Deciduous forests and meadow vegetation	

A slowdown of increase in the NDVI since 1997 has been recorded throughout the Northern Hemisphere—in particular, in Europe, North America, and Central Siberia—and is explained by a decrease in the input of solar radiation to the Earth's surface and a

decrease in soil-moisture reserves (Kong et al., 2017). An extremely strong El Niño phenomenon was observed in 1997–1998 and a low phase of the ocean-surface-temperature index in the El Niño region (ONI) against the background of a decrease in solar activity

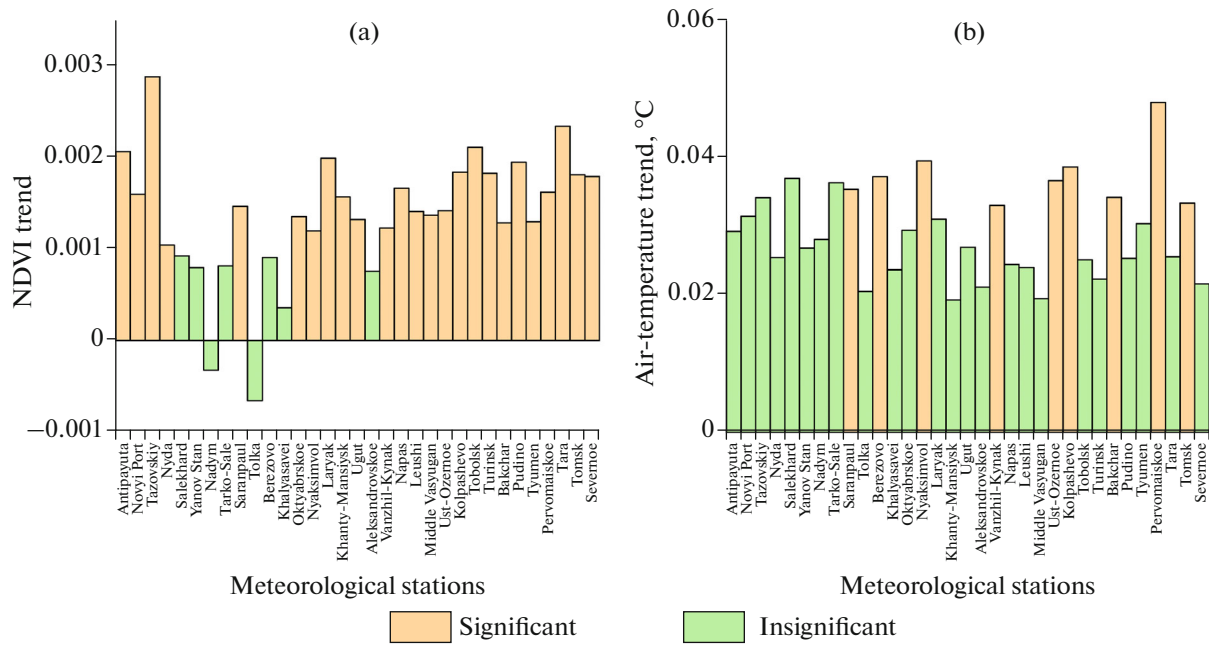


Fig. 1. Linear trends in the seasonal values of (a) NDVI and (b) air temperature at the meteorological stations in the region for 1982–2015.

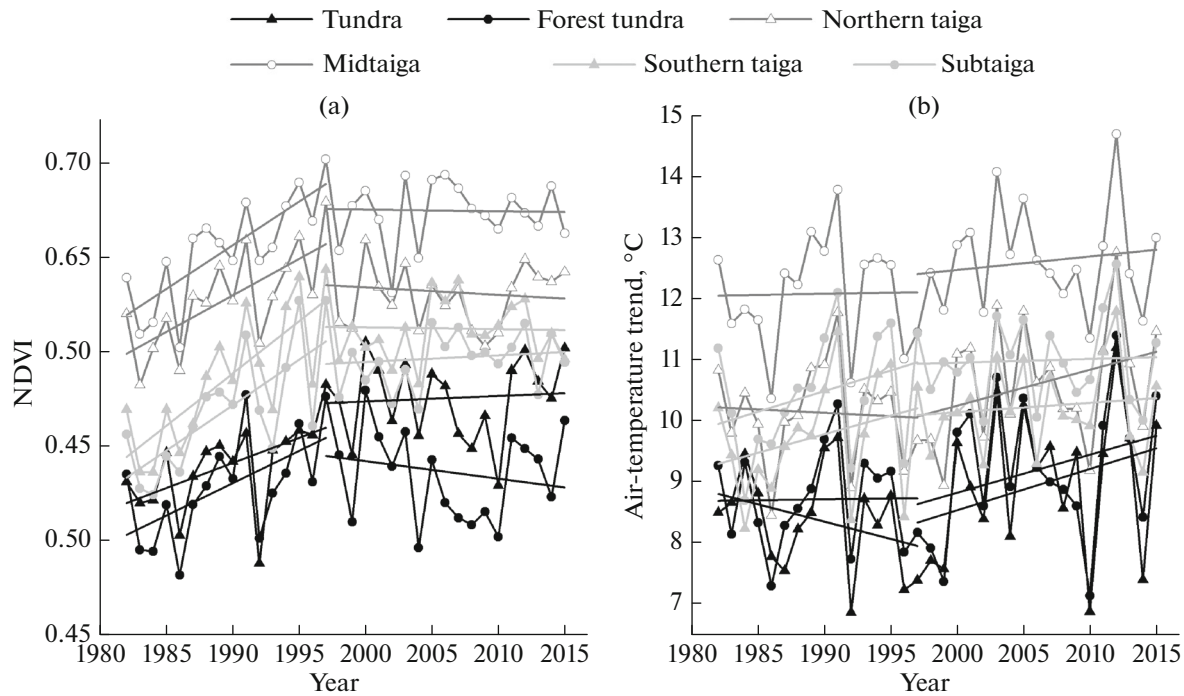


Fig. 2. Dynamics in the seasonal values of (a) NDVI and (b) air temperature within the natural zones of the region in 1982–2015.

has been recorded since the late 1990s (Climate..., 2021). Therefore, the change in the NDVI trend after 1997 may also be determined by the low ONI phase due to the decrease in solar activity. It should also be noted that the growth of NDVI values in 1982–1997

was observed during the high ONI phase. In addition, the NDVI values cease to increase against the background of the slowdown of global warming, the causes of which are currently debatable (Volodin and Gritsun, 2018).

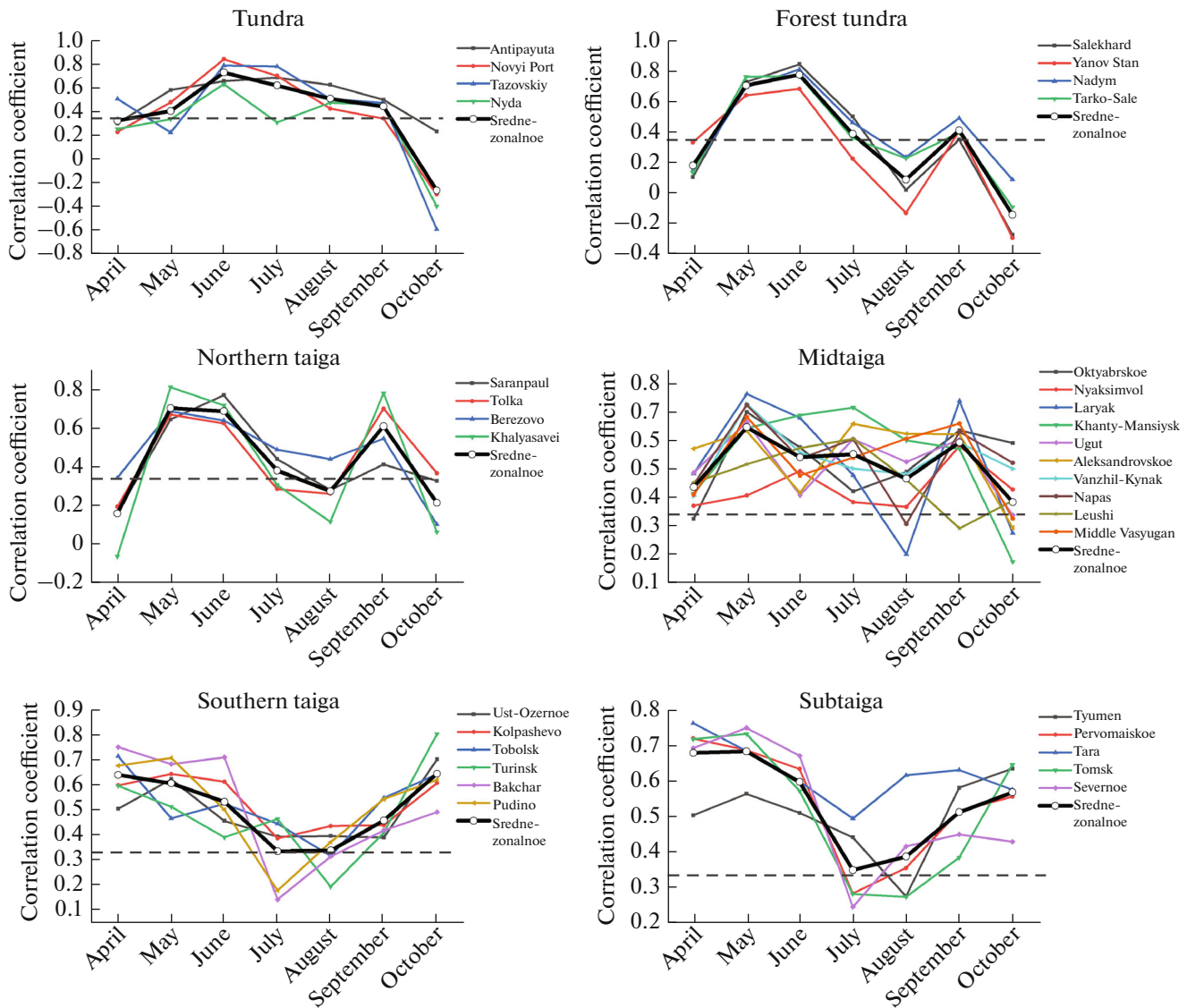


Fig. 3. Seasonal and monthly NDVI correlation coefficients for the stations in 1982–2015; dashed line indicates the critical value of the correlation coefficient at a significance level of 0.05 ($r = 0.34$).

Based on the results of the previous studies (Zuev et al., 2019), it was found that the variation in the seasonal NDVI in the taiga and tundra zones of Western Siberia is largely determined by the variation in the NDVI in the first month of the warm period. To elucidate this conclusion, let us consider the coefficients of correlation between the seasonal and monthly NDVI values for all selected stations (Fig. 3).

It can be seen that the largest contribution to the dynamics of the seasonal NDVI value is made by the spring and autumn months, i.e., the months when the air temperature is a limiting factor of photosynthesis. At tundra stations, the maximum coefficients are observed in the first month of the warm period (June) and generally show a strong correlation with the sea-

sonal NDVI value ($r > 0.7$). At forest-tundra stations, the maximum correlation coefficients are also observed in spring (May to June) and the correlation is strong during this period; at the same time, an autumn peak also begins to be observed in September and its values vary at a significance level during this period. At northern-taiga stations, the autumn peak is more pronounced; here, the correlation coefficients, indicating a strong and average correlation between the seasonal and monthly NDVI values, are typical for May, June, and September. In the midtaiga zone, the correlation coefficients behave ambiguously during the warm period. The average regional value indicates the presence of May and September peaks; however, the data significantly differ between the stations. For instance,

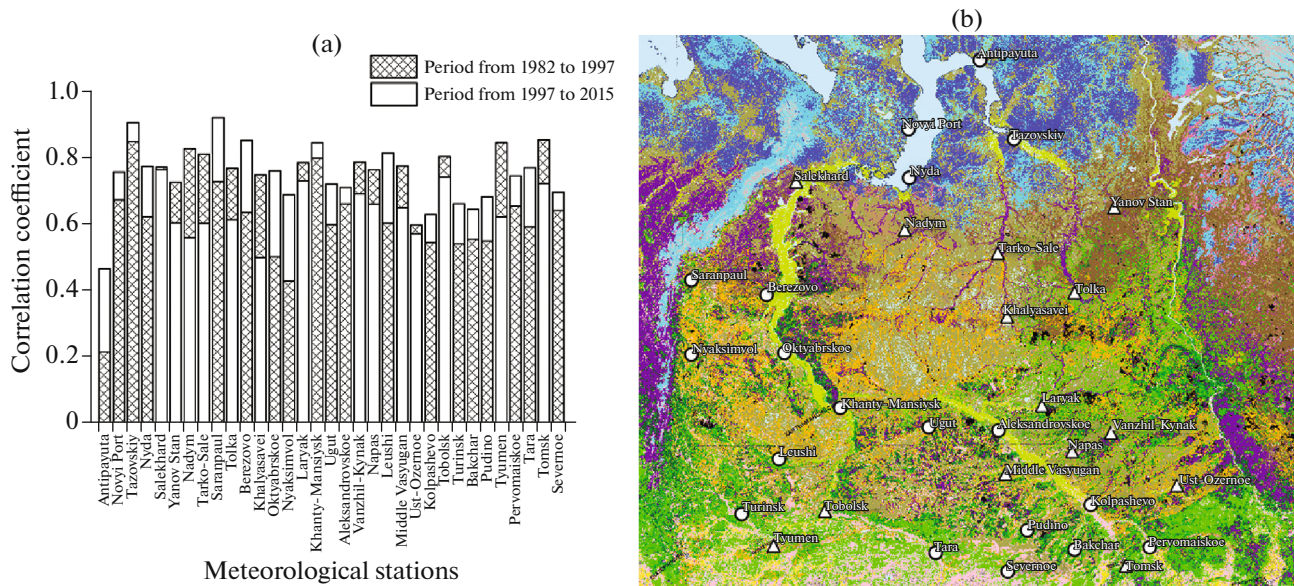


Fig. 4. Coefficients of correlation between the spring NDVI and air temperature values at the stations in the region. (a) Correlation coefficients in 1982–1997 and 1997–2015. (b) Distribution of the increasing (red) and decreasing (blue) correlation coefficients on the vegetation map (Bartalev et al., 2011).

the maximum values of the correlation coefficients for the Khanty-Mansiysk, Aleksandrovsкое, and Leushi stations are observed in July, while its peak near the Nyaksimvol station is usually observed only in autumn (September). The correlation coefficients are also less significant at the southern taiga and subtaiga stations than at the stations in the tundra, forest tundra, and northern taiga; the average maximum coefficients are observed in April–May and October. Therefore, it is clear that the greatest contribution to the variation in the seasonal NDVI value is made by the autumn and spring months, i.e., when the main factor that limits photosynthesis and, hence, influences the development of vegetation is air temperature.

Summarizing the results, we can conclude that the months that make the greatest average contribution to the dynamics of the seasonal NDVI value are June for tundra, May and September for forest tundra and northern and midtaiga, and April and October for southern taiga and subtaiga. The maximum NDVI values for the study area are observed in the summer months (Zuev et al., 2019); accordingly, the formation of vegetation in summer in current year is influenced by the meteorological conditions of the summer and preceding spring. Therefore, our further analysis involved the NDVI data for the spring months that made the greatest contribution to the variation in the seasonal NDVI value, as well as the air temperature in the spring months. To assess changes in the contribution of the temperature factor to the development of vegetation in the study area, we calculated the coeffi-

cients of correlation between the NDVI and air temperature for the area of each station for two periods (1981–1997 and 1998–2015). We used the monthly NDVI values for June for tundra, May for forest tundra and northern and midtaiga, and April for southern taiga and subtaiga. The coefficients of correlation between the monthly NDVI values and air temperature averaged over two months (May–June for tundra, April–May for forest tundra and northern and midtaiga, and March–April for southern taiga and subtaiga) proved to be most indicative.

The results of the correlation analysis are given in Fig. 4. It can be seen that the coefficients of correlation between the NDVI and air temperature at the stations of the tundra zone increase in 1997–2015 compared to the previous period, which indicates an increase in the contribution of air temperature in the spring months to the development of vegetation in these areas. The highest sensitivity to air temperature is observed for the vegetation cover of southern tundra (in the vicinities of the Novyi Port, Tazovskiy, and Nyda stations), which is characterized by shrub and dwarf-shrub vegetation. In turn, the vegetation in the vicinity of the Antipayuta station in the northern tundra zone, dominated by moss–lichen cover in the summer–spring period, is less dependent on air temperature; however, the coefficient of correlation between the NDVI and temperature became significant in 1997–2015.

Opposite trends are characteristic of the forest-tundra zone: the coefficients of correlation between

the spring NDVI values and air temperature decreased from 1997 to 2015 compared to the previous period. The areas of the stations in the forest-tundra zone are characterized mainly by bog landscapes interspersed with dark coniferous, larch, and mixed forests and by open water surfaces. In the northern taiga zone, the decrease in the correlation coefficients from 1997 to 2015 is also typical for the wetlands of the Khalyasavei and Tolka stations, located in the eastern part of the region. It should be noted that the wetlands of these stations are characterized by insignificant positive and sometimes negative NDVI trends throughout the observation period against the background of positive air-temperature trends (Fig. 1). The well-known effects of warming in the northern areas of Western Siberia are permafrost melting, the formation of thermokarst lakes, and the resulting increase in the water surface area in the wetlands (Manasypov, 2014). This process leads to a decrease in the surface area covered with vegetation, which determines a decrease in the NDVI and a decrease in its correlation with air temperature. On the contrary, vegetation in areas near the Berezovo and Saranpaul stations on the left bank of the Ob River, dominated by pine forests in 1997–2015, responds to warming by an increase in its productivity: an increase in the coefficient of correlation between the spring values of the NDVI and air temperature is observed alongside significant positive trends in seasonal air temperature at these stations (Fig. 1b).

The decrease in the contribution of spring air temperature to the development of vegetation in spring in 1997–2015 is typical for the areas of stations in the midtaiga zone on the right bank of the Ob River (Laryak, Napas, and Vanzhil-Kynak stations); the vegetation in these areas is represented by mixed forests and bog communities. The areas of midtaiga stations located in the north of the Vasyugan Plain, dominated by bog vegetation and dark coniferous forests (Ugut and Aleksandrovscoe, except the Middle Vasyugan station), and on the right bank of the Irtysh River (bog vegetation with pine forests in Khanty-Mansiysk and mixed forests in Leushi) are characterized by an increase in the coefficient of correlation between the spring values of the NDVI and air temperature in 1997–2015.

Vegetation in the southern taiga and subtaiga zones responds to warming mainly by an increase in the correlation between the productivity and air temperature, although the trends in both the seasonal NDVI value and temperature value in these zones are close to zero in 1997–2015. Thus, areas with mixed forests near the Turinsk station, as well as wetlands with mixed forests near the stations in the south of the Vasyugan and Ketsko-Tymskaya plains (Kolpashevo, Bakchar, and

Pudino), show an increase in the correlation between the spring values of the NDVI and temperature air in 1997–2015. The exceptions are the areas of the Ust-Ozernoe (wetlands with pine and cedar forests) and Tobolsk (wetlands with mixed forests) stations, although the correlation coefficients are similar for these stations in 1982–1997 and 1997–2015. The vegetation of southern taiga areas, represented mainly by deciduous forests and meadows, demonstrates an increase in the correlation between the spring NDVI values and air temperature in 1997–2015 (areas near the Tara, Severnoe, and Pervomaiskoe stations); however, the areas near the Tomsk and Tyumen stations are characterized by the decrease of this correlation.

CONCLUSIONS

The results of the analysis showed that the linear trends of the seasonal NDVI value, together with the air-temperature trends, in 1982–2015 are mainly positive for all studied regions of the West Siberian Plain. However, the growth of seasonal NDVI values within the natural zones of the studied region are no longer observed since the late 20th century. The growth of NDVI values in 1982–1997 and their stabilization in 1997–2015 are recorded against the background of the observed effects of global-warming slowdown, decrease in solar activity, and transition of the positive phase of ocean surface temperature to the negative phase in the El Niño region.

A significant contribution to the variations in the seasonal NDVI value is made by the development of vegetation in the spring–summer months in the tundra and forest-tundra zones and in the spring–autumn months in the northern, middle, and southern taiga and subtaiga zones; however, the maximum summer NDVI values are determined by the conditions of the preceding spring.

The results of the comparative analysis between the phases of growth (1982–1997) and stabilization (1997–2015) of the seasonal NDVI value showed different responses of different types of vegetation in the West Siberian Plain to warming. Thus, the relationship between the productivity of tundra vegetation, in particular, southern tundra, and air temperature increases in 1997–2015, which indicates an increasing sensitivity of tundra vegetation to warming. Opposite trends are observed in wetlands of forest tundra and northern taiga: due to warming and permafrost melting, these areas become even more boggy; this leads to an increase in water space areas, which negatively affects the productivity of vegetation and leads to a decrease of the correlation between the NDVI and air temperature. On the whole, the correlation between the NDVI and air temperature decreases in the zones from

forest tundra to subtaiga in the Ob–Yenisei interfluvium and, on the contrary, increases on the left bank of the Ob River up to the Ural Mountains in 1997–2015.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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