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LONG-TERM VEGETATION DYNAMICS OF THE URBAN VEGETATION OF ABAKAN IN SEMIARID CONDITIONS OF KHAKASSIA FOR 2001-2022 ACCORDING TO TERRA MODIS

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Abstract: The relevance of this work is that the analysis of time series of satellite data allows for the remote assessment of urban vegetation productivity, identification of its general trend, and establishment of factors influencing plants. The value of such data is obvious for an independent assessment of the effectiveness of urban greening programs, the impact of pollution, and the timely identification of disturbed areas. The objective of this work is to identify patterns of long-term dynamics of urban vegetation productivity using the example of Abakan, located in the semiarid conditions of the Republic of Khakassia, based on ground-based meteorological information and Terra MODIS satellite data. As a result of the work, it was concluded that in the semiarid conditions of Khakassia, the amount of heat received has a strong effect on urban vegetation. In the period from 2000 to 2023, based on the basic growth rate, a weak positive trend of NPP and GPP (8-15.2%) was established. The novelty of the study is that new Terra Modis data on the long-term dynamics of productivity and evapotranspiration of urban vegetation in Abakan from 2019 to 2023 were analyzed.

Keywords: gross primary productivity (GPP); net primary productivity (NPP); total evapotranspiration; total potential evapotranspiration; fraction of photosynthetically active radiation (FPAR); leaf area index (LAI); Terra MODIS; urban vegetation; analysis of variance; ecosystem carbon balance

INTRODUCTION

The necessity to coordinate the monitoring of green spaces, urban and suburban forests stems from the imperative to enhance their stability, aesthetics, sanitation-hygienic qualities, landscape-forming capabilities, and other environmental protection and environment-forming attributes of the city's green resources (Shelukho & Simonova, 2017).

The territorial development of Abakan is restrained by the presence of natural and technological restrictions around the perimeter of the residential district, which occupies the major part of the city area. In relation to the synantropization and degradation of vegetation cover in urban areas, urban vegetation can be categorized into cultivated (garden and park complexes, lawns) and natural (steppes, forests and meadows) (Vasilyeva, 2016). The main types of green spaces in Abakan are parks, squares, street stands and public lands that occupy 1/3 of the territory. The natural vegetation in the city is very fragmented and only slightly represented in the residential zone. In the precincts of the city, significant areas are occupied by natural plant complexes.

Abakan is the capital city of the Republic of Khakassia. It is located in the central region of the Minusinsk Depression, which occupies the lowest part at 250 m above sea level at the confluence of the Abakan River into the Yenisey River and covers an area of 112.87 km². The city is located in a zone with an increased natural potential for atmospheric pollution, which is characterized by frequent repeatability of calm and ground inversions. This complicates the scattering of chemical pollutants (Department of Environmental Protection, Ministry of Natural Resources and Ecology of the Republic of Khakassia, 2022).

According to geobotanical subdivision, Abakan is located in the Abakan steppe district, on the territory of the Uybat plane hilly solonized district. In the northern part of the district, low-mountain hilly steppes are sculptural forms, which are facetted by denudation and almost deprived of a cloak of overburden. More aligned spaces along the interfluve area and the ancient river valleys are unevenly covered with a cloak of quaternary deluvial, river and lake deposits of various capacities.

The climate in Abakan is sharply continental, with a dry hot summer and a cold dry winter. Atmospheric moisture is unstable and uneven, since most of the territory is in the precipitation shadow of the Kuznetsk upland. The mean air temperature in July is +17.9 ° C, in January: -18.9 ° C (Kuminova & Maskaev, 1976; Alisov, 1956). The climatic parameters correspond to the semiarid climate (Khromov & Mamontova, 1974; Alisov, 1956).

The hydrology of Abakan has a significant impact on the vegetation, owing to its close proximity to rivers such as the Yenisey, Abakan, and Tasheba, as well as the drainage canals located within the city limits.

Abakan is located in the zone of chestnut soils formed under steppe vegetation.

Chestnut soils are widespread on the high terraces of the Abakan River valley and its tributaries. In the river floodplain, the soil-forming material are deluvial and eluvial-deluvial red coloured loams and clays, as well as ancient alluvial deposits underlain by gravel-cobble and bouldery-cobble overburden (Tanzybayev, 1993; Tanzybayev & Kallas, 1993). On the lower ground features there are common and southern chernozems, as well as alkaline chernozems, alcali soils, chernozemic meadow, meadow-alkaline soils,

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swampy alkali soils, alluvial laminated soils and saline soils.

The zonal vegetation type is a bunchgrass steppes (Kuminova & Maskaev, 1976). The city's vegetation is formed under the influence of natural steppes surrounding Abakan and synanthropic species (including ruderal). The city's soils are degradated and unfavourable for plant development, and require agromeliorative practices.

Consequently, urban areas necessitate continuous surveillance, and utilizing ground-based techniques to study the productivity of plant communities in the urban setting proves to be challenging. From this standpoint, the use of remote sensing data (Maksimov, Skachkova, & Kurlovich, 2016; Vorobyev et al., 2015), for example, Terra MODIS, is of particular importance for monitoring the state of vegetation in urbanized areas. Despite their obvious importance, urban vegetation studies are often conducted in an irregular manner.

Among the remote sensing indicators, net primary productivity (NPP) is a commonly used as ecological indicator for evaluating the carbon cycle of the Earth. However, despite their widespread use, there are significant uncertainties regarding the pattern of NPP response to climate variability along the aridity gradient, especially under the influence of the human factor (Liu et al., 2019). The literature contains data on productivity in the Tuva Republic, neighboring Khakassia, such as through NPP, which was gathered through ground-based methods. Ecosystem exchange is often assessed using vegetation maps (Titlyanova, Bazilevich & Snytko, 2018; Sambuu, 2010).

Remote sensing is a valuable instrument for estimating gross primary production in ground-based ecosystem regions on both regional and global scales. One limitation of remote sensing-based GPP models is the mischaracterization of precipitation effects. For example, a positive relationship has been shown between monthly flux-measured GPP of grassland ecosystems and precipitation intensity (Wu & Chen, 2012).

A comparison of ground-based data with remote sensing data would allow adjustments to regional productivity models, taking into account data validation (Kurbanov et al., 2015). At the same time, there is the emergence of more contemporary satellites, such as Sentinel or the newest Terra MODIS products (ECOSTRESS), archives are replenished.

Remote sensing (RS) is important for solving urgent problems: assessing the impact of land use on the global carbon cycle, the impact of ecosystems on water balance and vice versa, the impact of climate on vegetation productivity. It is also important for identifying disturbances in vegetation cover in order to understand the causes and consequences of changes. RS will ensure sustainable development of the territory.

The purpose of the study is to identify patterns in the long-term dynamics of urban vegetation productivity using the case of Abakan, located in the semiarid conditions of the Republic of Khakassia, based on ground-based meteorological information and Terra MODIS satellite data.

MATERIALS AND METHODS

In accordance with the purpose of the work, the following research objectives were set:

1) Summarizing the ground-based data on various types of vegetation in Abakan;

2) Analysis the basic parameters of time series of Terra MODIS satellite data for the study area;

3) Revealing regression dependencies of indicators of ground-based meteorological information and satellite data;

4) Determination of the factors that influence gross primary productivity to the greatest extent.

In order to solve the first problem, we summarized the vegetation data obtained from our own long-term route studies (from 2012 to the present) and satellite data analysis (Zhukova & Lagunova, 2019, 2020), and materials from the Scientific Herbarium of Khakassia State University (Tupitsyna, Shaulo & Gureeva, 2017). The names of plant communities are given according to the dominant classification of A.V. Kuminova et al. (Kuminova, Zvereva & Lamanova, 1976; Kuminova, Neufeld & Pavlova, 1976). The material was collected during different biotic seasons: spring (May), summer (June-August), and autumn (early September). Thus, all flowering times of plants from different systematic groups are covered. The traditional method was used for collecting and herbarization of plants (Ankipovich & Lagunova, 2015). In laboratory conditions, the collected plants were determined according to the "Plant determinant of the south of the Krasnoyarsk Krai" (Krasnoborov et al., 1979). The Latin (scientific??) names of plants were specified according to the Flora of Siberia (Malysheva & Peshkova, 1987-2003) and the Plantarium website.

Time series analysis was performed using two types of data:

1) Archived meteorological data from a ground-based weather station obtained from the Weather resources website (rp5.ru);

2) Archived Terra MODIS satellite data from the Online service for satellite data processing LPDAAC website.

Abakan is dominated by deciduous trees, which make the greatest contribution to productivity. In this regard, data pertaining to the growing seasons spanning from April 30 to September 30 in the timeframe of 2000 to 2023 were utilized for the compilation of the time series.

The materials from the ground-based weather station located in Abakan included the sum of positive daily mean temperatures and precipitation amount. A model of the Selyaninov hydrothermic factor was also calculated for the period with temperatures above 0 ºC (Khromov & Mamontova, 1974).

The study employed a remote methodology to evaluate the productivity and dynamics of vegetation, which included a time series analysis:

1) Basic statistical methods (calculation of the average number, standard deviation, determination of the minimum and maximum, integration of the vegetation curve to obtain gross indicators for 5 months of vegetation, testing for normality of data distribution using the Kolmogorov-Smirnov & Lilliefors test (StatSoft, 1995);

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2) Determination of the basic growth rate (BGR), defined as the ratio of the absolute growth to the basic level (the indicator at the beginning of the time series), expressed as a percentage (Ayvazyan, 2010).

3) Regression analysis of ground-based and satellite data (a nonlinear polynomial of degree 3 was used to drawing the equation);

4) Two-way analysis of variance (ANOVA), which allowed us to estimate how two factors (FPAR in combination with ET and the sum of temperatures in combination with FPAR) affected the dependent variable (GPP). For the analysis of variance, a sample from 2005 to 2022 was taken due to the availability of meteorological data. Before applying the analysis of variance, all parameters were checked for normality using the Kolmagorov-Smirnov method with additional testing. As a result, we obtained data on the normal distribution in the sample ($p > 0.05$). Therefore, the ANOVA analysis of variance can be carried out. For each indicator, the sample consisted of 361 parameter values. Using the interval series in the available samples, 9 variants of the factor action were determined (StatSoft, 1995).

Calculations were performed in the Statistica program. Table 1 presents the types of Terra MODIS satellite products used in the work.

The characteristics of the products were taken from the LPDAAC website. Data on individual indicators was unavailable for technical reasons, and the parameter values were replaced by the median values of neighboring dates. For NPP, there are no data for 2000 and 2023. For the remaining data, there are no complete series for 2023. Pixel size is 500 meter, number of pixels is 107.

Table 1.

Product Terra MODIS Description

Product Terra MODIS	**Name**	**Transcript**	**Description**	**Units**	**Compo-site, day**	**Pixel size, meter**
MOD17A2H_061	Gpp_500m	gross primary productivity	the rate at which solar energy is captured by photosynthesis (radiation efficiency)	kg C/m²/ 8day	8	500
MOD17A3HGF	Npp_500m	net primary productivity	annual primary productivity за minus the energy expended during maintenance respiration	kgC/m²/year	365	500
MOD16A2GF_061	ET_500m	total evapotranspiration	the combined processes of water evaporation from soil and plant surfaces and water transpiration through plant tissues is based on the logic of the Penman-Monteith equation which incorporates daily meteorological analysis data and MODIS products	kg/m²/8day for gross values kg/m² ·5 month	8	500
	PET_500m	total potential evapotranspiration	the amount of water that could evaporate and transpire from a large area completely covered by vegetation, given sufficient water	kg/m²/8day kg/m²/5 month	8	500
MOD15A2H_061_Fpar_500m	Fpar_500m	fraction of photosynthetically active radiation	rate of impinging photosynthetic active radiation in 400-700nm	%	8	500
MOD15A2H_061_Lai_500m	Lai_500m	leaf area index	LAI is defined as the one-sided green leaf area per unit ground surface area	m²/m²	8	500

Source: Online service for satellite data processing.

RESULTS

According to the aridity index (the ratio of average annual precipitation to potential evapotranspiration), the territory of Khakassia is classified as a dry semiarid region. Semiarid climate is a climate with humidity, in some years insufficient for the normal development of agricultural crops, and with natural vegetation of a steppe or forest-steppe nature. Droughts are typical for this type of climate (Khromov & Mamontova, 1974).

In order to gain a deeper understanding of the ongoing dynamic processes and the decoding of satellite data, it is necessary to generalize the results of long-term ground-based studies of urban vegetation in Abakan.

In the precincts of the city under study, small areas of poplar forests were noted, confined to the floodplain of the Abakan River, which is periodically flooded. The main part of the forest stand consists of *Populus laurifolia* Ledeb. In some places, groups of *Salix viminalis* L., *S. caprea* L., *S. rosmarinifolia* L. are noted. The dominant mixed fodder plants are *Equisetum pratense* Ehrh., *Veronica longifolia* L., *Aster alpinus* L., *Thalictrum minus* L. To a lesser extent, the presence of cereals such as *Bromopsis inermis* (Leyss.) Holub, *Festuca pratensis* Huds., *Poa pratensis* L., *Phleum pratense* L. was noted.

In accordance with our own observations and the classification of steppes proposed by A. V. Kuminova,

G. A. Zvereva and T. G. Lamanova (1976), in the study area, small turf and large turf steppes are widespread. Small turf steppes are widely represented in the vicinity of the city in the driest ecotopes. Their edificators are *Festuca pseudovina* Hack. ex Wiesb., *F. valesiaca* Gaudin, *Koeleria macrantha* (Ledeb.) Schult., *Agropyron pectinatum* (M. Bieb.) P. Beauv., *Poa transbaicalica* Roshev. In addition to the listed cereals, *Carex duriuscula* C. A. Mey., *C. pediformis* C.A. Mey., *Galium verum* L., *Veronica incana* L., *Artemisia frigida* Willd., *Dianthus versicolor* Fisch. ex Link, *Goniolimon speciosum* (L.) Boiss., *Cleistogenes squarrosa* (Trin.) Keng. are often found. On the northern slopes covered with crushed stone, there are areas of flinty Hedysarum steppes with *Hedysarum gmelinii* Ledeb. The shrub *Caragana pygmaea* (L.) DC is found.

In contrast to small turf steppes, large turf steppes are significantly less prevalent. These steppes are characterized by more humid ecotopes, compared to the previous one. Large turf grasses are represented by feather-grasses – *Stipa capillata* L. and fatuoid grass – *Helictotrichon altaicum* Tzvelev. Along with large turf grasses, there are also small sod forming grasses *Festuca pseudovina, Poa transbaicalica*. Of the mixed fodder plants, *Artemisia commutata* Besser, *Thermopsis lanceolata* R. Br., *Galium verum*, *Bupleurum scorzonerifolium* Willd. and others are typical.

In Abakan, valley meadows are represented by fragments of natural vegetation of the coastal part of the Abakan and Tasheba rivers and along drainage canals. True floodplain meadows occupy significant areas and include formations of cereal polydominant floodplain meadows (*Agrostis gigantea* Roth, *Poa pratensis*, *Festuca pratensis*, *Alopecurus pratensis* L. with *Lathyrus pratensis* L., *Vicia cracca* L., *Trifolium pratense* L., *T. repens* L., *Carum carvi* L. etc.), grass-forb floodplain meadows (*Sanguisorba officinalis* L., *Bistorta officinalis* Delarbre, *Geranium pratense* L., *Carum carvi*, *Phlomoides tuberosa* (L.) Moench., among the cereals there are *Poa pratensis*, *Phleum pratense*, *Bromopsis inermis*, *Dactylis glomerata* L.), quackgrass valley meadows (*Elytrigia repens* (L.) Nevski) and bluegrass valley meadows (*Poa pratensis*).

The steppificated meadows are found on elevated areas in the central part of the floodplain and on the terraces above flood-plain. In the study area, grass-forb valley meadows are widespread, with the dominant species being *Iris ruthenica* Ker Gawl., *Galium verum*, *Onobrychis arenaria* (Kit.) DC., *Geranium pratense*, *Vicia cracca*, *Poa pratensis*, etc. The wormwood-quack-grass meadows are found in small areas. The main background is represented by such species as *Elytrigia repens, Poa pratensis, Artemisia glauca* Pall. ex Willd. The forb-grass steppificated meadows are formed on elevated floodplains (*Calamagrostis epigeios* (L.) Roth, *Phleum phleoides* (L.) H. Karst., with *Medicago falcata* L., *Geranium pratense*, *Phlomoides tuberosa*, *Carum carvi* etc.).

The marshy meadows occupy large areas and are confined to low-lying areas of river valleys, in narrow strips on the terrace near flood plain, and are represented by formations of sedge-grass marshy meadows (*Carex enervis* C.A. Mey., *C. cespitosa* L., *Calamagrostis langsdorffii* (Link) Trin., *Poa palustris* L.), grass-sedge marshy meadows (*Calamagrostis langsdorffii*, *Poa palustris*, *Carex cespitosa*, *Equisetum palustre* L.).

The study area also includes saline marshy valley meadows, which are represented by bentgrass communities (*Agrostis stolonifera* L., *Alopecurus arundinaceus* Poir., *Poa pratensis*, *Festuca rubra* L.), alkaligrass salt (*Puccinellia tenuiflora* (Griseb.) Scribn. & Merr.) saline meadows. In these same meadows, among the mixed fodder plants, we can find *Halerpestes salsuginosa* (Pall. ex Georgi) Greene, *Iris biglumis* Vahl, *Potentilla anserine* L.

The intensive development of Abakan is currently underway, which is accompanied by the disturbance of the surface soil layer, its compaction, and pollution. Furthermore, the city is increasingly being artificially greened, resulting in the creation of a synanthropic plant complex, wherein synanthropic trees and shrubs play a significant role. Synanthropic dendroflora of cities is formed by artificial plantings of *Populus alba* L., *Juglans mandshurica* Maxim., *Populus balsamifera* L., *Padus avium* Mill., *Tilia cordata* Mill., *T. sibirica* Bayer, *Philadelphus coronarius* L., *Syringa vulgaris* L. and others.

The herbaceous plant are mainly represented by the families Poaceae, Asteraceae, Brassicaceae.

The city territory is represented by various types of vegetation, the predominant type is artificial tree plantations, the zonal component is represented by small areas of preserved small turf steppes. Vegetation of the semiarid zone is sensitive to seasonal weather conditions.

Based on Terra MODIS satellite data, the average parameters of time series of vegetation in Abakan for the vegetation periods from 2000 to 2022 were analyzed (Fig. 1, Table 2).

Figure 1 demonstrates that the greatest variations are observed in net primary production, ranging from 23.6 to 37.6 kgC/m²/year. The maximum for this indicator was observed in 2010, the minimums were in 2002, 2007, 2011 and 2019. During 2019-2022, an increase in NPP and potential evapotranspiration (PET) was observed. The total basic growth rate (BGR) for these indicators over the observation period was 8% and 4.5%. Therefore, the state of vegetation has improved and the productivity of vegetation in Abakan has increased.

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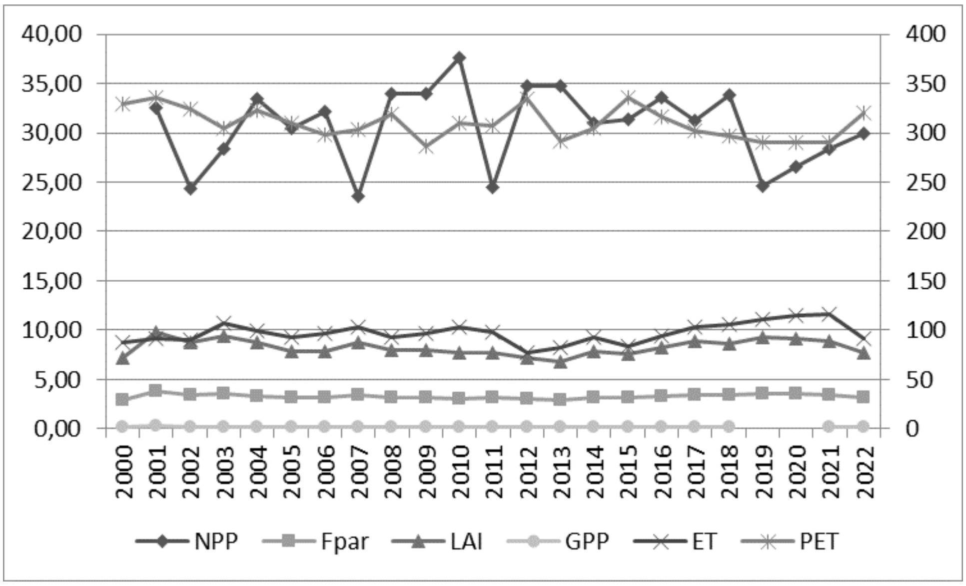

Fig. 1. The long-term dynamics of the general indicators of the vegetation of Abakan for the vegetation periods from 2000 to 2022. *Source:* Compiled by authors

Table 2.
The general indicators a long-term dynamics of the vegetation of Abakan for the vegetation periods from 2000 to 2023

Parameters	Average	Min	$Year_{min}$	Max	$Year_{max}$	BGR, %
NPP, kgC/m²/year	30.7±8.1	23.6	2007	37.6	2010	8.0
Gross Fpar, %/5 month	61.8	52.4	2000	67.6	2003	7.4
Average Fpar, %	3.3±0.9	2.9	2013	3.8	2013	17.1
Gross LAI, m²/m²/5 month	155.4	128.8	2000	178.1	2003	11.5
Average LAI, m²/m²	8.2±3.4	6.8	2013	9.8	2001	20.8
Gross ET kg/m²/5 month	1838.9	1473.2	2012	2202.7	2021	0.2
ET, kg/m²/8day	97.0±32.2	77.5	2012	115.9	2021	0.2
Gross PET kg/m²/5 month	5870.9	5451.4	2009	6380.0	2001	4.5
PET, kg/m²/8day	309.8±82.7	286.9	2009	335.8	2001	4.5
Gross GPP, kg C/m²/5 month	3.7	3.1	2013	4.7	2001	11.8
Average GPP	0.20±0.01	0.2	2013	0.25	2001	15.2

Source: Compiled by authors

The gross primary production GPP is a characteristic of biological productivity, commonly referred to as gross photosynthesis or total assimilation. During the vegetation period, there is an accumulation of 3.7 kg C / m² / 5 month, the minimum was observed in 2013, and the maximum in 2001, which does not coincide with the NPP data. BGR of GPP is also positive (11.8%). The share of average values of photosynthetic active radiation Fpar averaged 3.3 ± 0.9 %, with fluctuations from 2.9 % to 3.8 %.

The gross share growth of Fpar increased by 7.4%, average values increased by 17.1%.

The leaf area index (LAI) depicts the efficacy with which plants utilize solar radiation for photosynthesis, with an optimal value of 6-8. The average LAI index was 8.2±3.4, with the years of minimums coinciding with the GPP data. Hence, high values of LAI were associated with woody vegetation, as evidenced by ground data.

The water regime conditions can be analyzed based on evapotranspiration data – total (ET) and potential (PET). The greater the difference between these data, the less water is provided to the study area. The difference was 4032 kg/m²/5 month, which corresponded to 69%. The minimums and maximums of both indicators were observed in different periods, standard variations did not exceed 1.8%, which indicated the stability of the water regime. No significant changes in BGR were found for evapotranspiration.

It is noteworthy to investigate the regression correlations between indicators of ground-based meteorological data and satellite data within the study area (Table 3).

Based on the available meteorological data, a correlation was identified between the sum of positive temperatures and GPP (R^2 = 0.596). A significant positive correlation was detected between GPP and LAI (R^2 = 0.8222). For GPP and precipitation amount, as well as the hydrothermal coefficient, the linear dependence was weaker. GPP has a lower dependence on potential evapotranspiration than ET. This confirmed the ground-based data on the influence of rivers on the city's vegetation.

Table 3.

Regression analysis of the Terra MODIS products and meteorological indicators

Parameters for regression	Equation	Determination coefficient, R^2
GPP*-FPAR	$y = -2445.7x^3 + 83.671x^2 + 8.2756x + 0.2046$	0.6748
GPP-LAI	$y = -11883x^3 + 687.12x^2 + 21.657x + 0.2695$	0.8222
GPP-ET	$y = -329769x^3 + 28277x^2 – 387.11x + 8,9736$	0.7431
GPP-PET	$y = 147107x^3 - 26099x^2 + 1629.8x + 13.64$	0.5415
GPP-sum of temperatures	$y = -65375x^2 + 5465.3x + 38.119$	0.596
GPP-precipitation amount	$y = -289075x^3 + 27652x^2 – 430.3x + 10.044$	0.0845
GPP-hydrothermal coefficient	$y = -3154.3x^3 + 394.8x^2 – 12.23x + 0.1948$	0.0458

Source: Compiled by authors

Thus, relationships were established between satellite indicators and meteorological data (sum of positive temperatures, precipitation and hydrothermal coefficient), but the nature of these relationships differs.

A two-factor analysis of variance was conducted in order to identify significant parameters affecting gross primary productivity (Fig. 2, Table 4).

Based on Figure 2 and Table 4, it can be inferred that the dependent parameter GPP is significantly influenced by the independent factor "sum of temperatures-FPAR", and may also be influenced by the second factor "FPAR-ET".

The probability of confirming the alternative hypothesis (the factor that influences GPP) for the factor "sum of temperatures-FPAR" was p=0.77545, exceeding the threshold value of 0.5. Therefore, the null hypothesis can be rejected. Additionally, the factor "Fpar*ET" had a probability of p=0.0000, which is less than the threshold value of 0.05. Therefore, the null hypothesis cannot be rejected.

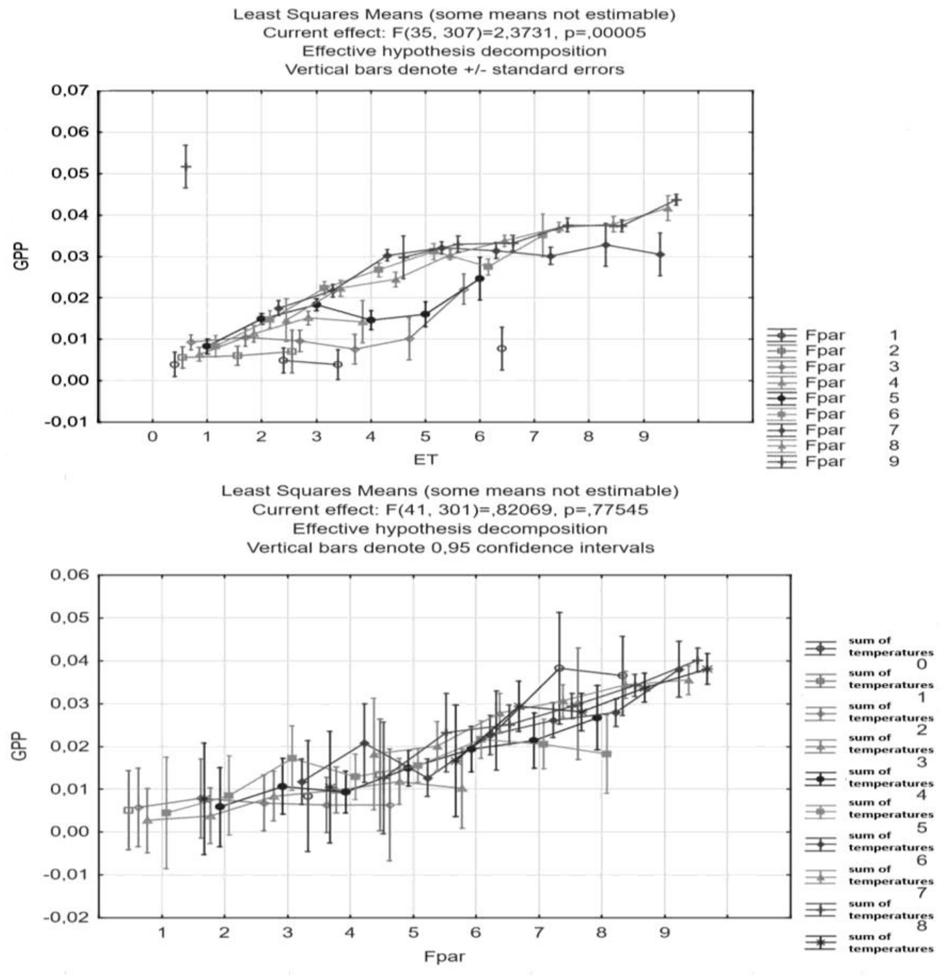

Fig. 2. The long-term dynamics of the general indicators of the vegetation of Abakan for the vegetation periods from 2000 to 2022. *Source:* Compiled by authors

Table 4.

Regression analysis of the Terra MODIS products and meteorological indicators

Variant	SS	Degree of freedom	MS	F	p	Partial eta-squared	Non-centrality	Observed power
Fpar*ET	0.0022	35	0.0001	2.3731	0.0000	0.2129	83.0597	0.9999
Error Fpar*ET	0.0081	307	0.0000					
Fpar*sum of temperatures	0.0015	41	0.0000	0.8207	0.7755	0.1005	33.6485	0.8521
Error sum of temperatures	0.0131	301	0.0000					

DISCUSSION

The primary indicator for assessing ecosystem carbon balance is net primary production. NPP varies depending on the forest ecosystem type. Forests produce high levels of foliage and needles. Urban forests have been poorly studied in this respect.

For Tuva, the following data are given on NPP of forest, forest-steppe, steppe and river valley zone ecosystems: 213.0, 124.0, 141.0 and 72.2•10^6 t/year (Sambuu, 2010). Due to the rapid growth of underground organs, grass ecosystems have a high production of 5.3 to 16.4 t/ha/year. The degree of anthropogenic load affects the species composition of plants and reduces production. The value of above-ground net production (ANP) in true steppes exceeds the ANP of dry steppes by approximately two times, and underground production by more than 2 times. NPP estimates for 2010 show rapid accumulation of plant substance (Sambuu, 2010). The NPP Terra Modis data represent a distinct indicator that is clearly underestimated.

The impact of global climate change on precipitation regimes could have significant implications for ecosystem productivity. The literature provides evidence for the influence of precipitation characteristics (level, frequency, interval, and seasonal rainfall distribution) on gross primary productivity GPP based on long-term measurements of ecosystem net CO_2 exchange and evapotranspiration using the eddy covariance method in a water bound steppe in Mongolia. Heavy precipitation events (>10 mm/day) had the greatest positive effect on GPP in the steppe. GPP was higher as precipitation intervals became longer or as the distribution shifted toward shorter but longer intervals (concentrated distribution). Compared with small events, heavy precipitation events recharged deeper soil layers in the temperate steppe, which was biologically more meaningful for plant transpiration (i.e., an increase in the ratio of transpiration to evapotranspiration), relief from drought stress (an increase in the duration of high soil water content), and thereby higher GPP (Guoa et al., 2015). The dependence of urban vegetation GPP on precipitation in the semiarid climate was modified by the influence of the hydrological regime of the territory (the influence of rivers and water bodies).

There are studies published in the literature (rice fields) that confirm the correlation between FPAR and LAI. There were varietal differences in the development of LAI, which in turn affects FPAR (crown cover absorb solar radiation). The study showed that most of the changes in GPP during the growing season can be explained by changes in daily solar radiation (Xuea, 2017).

A study conducted on the vegetation of Abakan also revealed a significant correlation between FPAR and LAI.

Prime nonlinear models are suitable for productivity models. For example, a model permits the calculation of daily and monthly values of gross (GPP) and net (NPP) primary forest production based on parameters that define the efficacy of plant utilization of photosynthetic active radiation (PAR) on GPP and NPP, as well as the integral value of PAR absorbed by vegetation, determined through measurements, including remote sensing (Olchev, 2016). The creation of such models assumes the existence of significant dependencies between the above indicators. The general patterns of regression models are similar to the data presented in the article.

CONCLUSIONS

The study examined the long-term dynamics of urban vegetation in Abakan by utilizing both ground-based and satellite methods for the timeframe of 2000 to 2023. The results revealed a modest positive trend in productivity, ranging from 8-15.2%, and a stable water regime in the region, with evapotranspiration fluctuations of up to 1.8%, low base growth rates, and the influence of two rivers. Gross NPP indicators were 30.7±8.1 kgC/m²/year. The difference between PET and ET is significant, which is consistent with the semiarid climate of the study area. The leaf area index was 8.2±3.4, which corresponds to the abundance of tree stands in Abakan. The results of the regression analysis showed that GPP had a close positive relationship with FPAR, LAI, ET and the sum of positive average daily temperatures, but no relationship was found with precipitation and the hydrological coefficient. A reliable influence of the FPAR factor in combination with the sum of temperatures on GPP was established.

The study holds practical significance due to its potential to obtain data on carbon and water exchange in urban ecosystems, as well as its potential for automated remote monitoring and forecasting of urban vegetation's productivity in the future. Further research is focused on carbon sequestration by vegetation in disturbed ecosystems, including urban areas. A prototype of the Yenisey Siberia information platform for satellite and ground-based data was created as part of this work. It is planned to conduct ground-based geobotanical and forest mensuration studies, assess the phytomass in typical areas, as well as satellite monitoring using satellite data of medium (Terra MODIS) and high spatial (Sentinel) resolution and unmanned aerial vehicles.

AUTHORS CONTRIBUTIONS

Elena Yu. Zhukova, Elena G. Lagunova, Evgeny A. Minikh, Alexander A. Zhukov, Anton V. Kleshh, Irina Yu. Botvitch, Dmitry V. Emelyanov contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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