



Research Article

Organic matter temporal dynamics in the river ecosystem basin using remote sensing

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Academic editor: Ashwani Kumar

Received: 25 Nov 2020 | Accepted: 26 Jun 2021 | Published: 06 Jul 2021

Citation: Trifonova T, Mishchenko N, Shutov P (2021) Organic matter temporal dynamics in the river ecosystem basin using remote sensing. One Ecosystem 6: e61357. <https://doi.org/10.3897/oneeco.6.e61357>

Abstract

Environmental research addresses ecosystems of various hierarchical levels. One of the ecosystem types is the river basin. The basin approach has been applied in the research. We consider the river basin as a single ecosystem of complex landscape structure. The research objective was to assess the biological processes in various landscapes within a holistic natural geosystem – a catchment area. The Klyazma River Basin (a part of the Volga River of 40 thousand km² area) was the research object. It is a complex combination of different landscapes, each marked by a diverse composition of geomorphological and soil-vegetation structures. According to the geomorphological structure and soil and vegetation cover, four landscape provinces and eight key sites have been identified in the studied catchment area where the ecosystem parameter have been measured. The study is based on remote sensing data and the Trends. Earth Land Degradation Monitoring. The calculation of productivity indicators (GPP, NPP) in carbon units and the land use structure analysis are based on Modis data. The soil organic carbon pool was determined by the UN FAO's data, based on Trends. Earth and QGIS 2.18. The two-factor variance analysis ANOVA has been used for the data statistic processing. The cartographic analysis of the land use structure dynamics of the entire Klyazma Basin resulted in revealing the areas where various land transitions from one category to another have been identified. They are basically associated with the agricultural land overgrowth. The forest area increased by 9% during the period from 2001 to 2017. Considerable increase in the waterlogged, wetlands

areas was observed in the eastern part of the Basin, in the Volga-Klyazma Province. The landscapes react differently to changes in climatic parameters and land use. Thus, the active revegetation of farmland by forests gives the increased rate of carbon accumulation in the soil. Landscapes covered with grasses and shrubs are more productive those covered with forest. On the other hand, woody biotopes are more stable in their development over time. Statistical analysis using the two-factor variation analysis ANOVA method resulted in demonstrating that phytoproductivity dynamics of the key sites does not depend on their productivity parameters nor on the site landscape structure, but is mainly determined by a time factor. In different landscapes the biological processes, characterising the organic matter dynamics in the form of plant production, organic matter accumulation and others are shown to differ both in rate and intensity and ambiguously respond to changes in climate parameters and land use. The river basin, as a single ecosystem, showed sufficient stability of the dynamic processes. This suggests that holistic natural ecosystems, such as catchment areas, have internal compensatory mechanisms that maintain the development stability for a long time, while unplanned land use remains the main damaging factor.

Keywords

landscapes, river basin, phytoproductivity dynamics, remote sensing data, carbon balance

Introduction

Environmental research addresses ecosystems of various hierarchical levels. One of the ecosystem types is the river basin, which is considered to be an integral natural ecosystem (Trifonova and Mishchenko 2018, Trifonova 2005, Trifonova 2008). Geographically, any basin is developing within the boundaries determined by a number of natural and climatic factors. The study is based on the basin approach. We considered the basin approach as a natural ecosystem formed by various landscapes integrated in a single entity by the river water flow.

Practical implications of environmental research on a planetary scale have become more substantial as a result of the development of space-borne remote sensing, which allows examining the surface condition of vast areas with high spatial and temporal resolution. When studying carbon assimilation by forest ecosystems on a large territory, remote sensing data make it possible to estimate such an important indicator as the rate of metabolic processes involving carbon (Goetz and Prince 1999, Ovington 1962, Salunkhe et al. 2018).

Remote sensing data are also useful for assessing components of the ecosystem services (biological productivity, soil formation, absorption and fixation of nutrients in various media) (Truchy et al. 2015, Wang et al. 2015, Wang et al. 2007, Host et al. 2007).

Recently, there have appeared ecosystem productivity evaluation models that use remote sensing data and operate important measurable indices, such as Normalised Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR) [Hashimoto et al. 2012, Chen et al. 2019]. However, despite this interest in remote sensing applications, there is still a need for commonly accepted approaches to assessing, analysing and forecasting the biological productivity of ecosystems (Xuejian et al. 2019, Varghese and Behera 2019, Robinson et al. 2018).

The open-source global data on gross primary productivity (GPP) collected by the MODIS sensor are increasingly used to study the carbon cycle associated with terrestrial ecosystems (Turner et al. 2006, Wu et al. 2010).

Researchers are developing approaches to determining the balance of soil carbon, based on remote data and investigating the equilibrium between inputs and losses of soil carbon and the accumulation of soil carbon (Guo and Gifford 2002, Krasilnikov 2015, Van der Werf et al. 2002, Deng et al. 2014, Deng et al. 2016). Global data on the soil cover can help quantify various types of land in order to find optimal paths for land use, predict the availability of land resources and rationalise nature management (Meyer and Riechert 2019, Dong et al. 2019). Some works have addressed the relationship between land use change and spatiotemporal dynamics of carbon flows (Novick et al. 2015).

According to many researchers, the most important characteristics of the vegetation cover state are the indicators of its productivity. The vegetation cover productivity has been factored into the studies of the natural resource and bio-resource potentials of the landscape (Bazilevich et al. 1986, Isachenko 1991, Odum 1983, Dedeoglu et al. 2020, Sun et al. 2019, Tian et al. 2015, Qader et al. 2015).

Gross Primary Productivity (GPP), Net Primary Productivity (NPP) and Ecosystem Respiration (RE) are the key indicators that determine the carbon balance of ecosystems (Kudeyarov V. N. 2007, Valentini et al. 2000, Lu et al. 2009).

However, at present, it is difficult to name any uniform methods for studying fundamental spatial geosystems, especially from the perspective of GIS, carbon content modelling and assessment of the land cover and the productive biomass, based on remote sensing data.

The *purpose of study* was to assess the state and the functioning dynamics of organic matter in the soil and vegetation cover of the Klyazma River Basin over a 15-year period using remote sensing data and QGIS Trends.Earth.

Materials and Methods

The object of study

The object of study was the catchment basin of the Klyazma River located in the centre of the East European Plain. It is a 686 km long left tributary to the Oka with a west-east

trending catchment basin of 42,500 km² Fig. 1. In this work, the Klyazma River Basin was considered as a single ecosystem, albeit marked by certain internal diversity (Trifonova 2018).

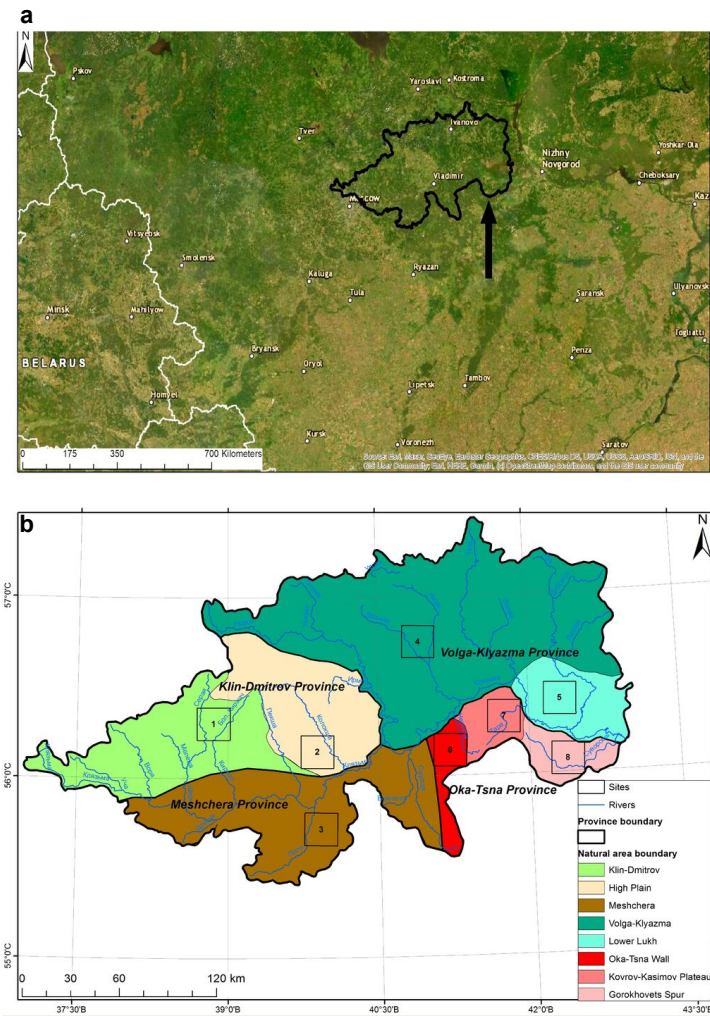


Figure 1.
Sites in the identified landscape provinces
a: The Klyazma River Basin.
b: Landscapes within and the Klyazma River Basin and the sites.

The *subject matter of study* was the soil and vegetation cover that determines the landscape diversity of the Klyazma River Basin. On its territory, there are different natural areas with varying degrees of anthropogenic impact. The vegetation state was assessed as an integral basin and individually on eight sites located in the natural areas of the identified landscape Provinces (Figs 1, 2). The eight sites were the following:



Figure 2.

Satellite images of the sites (Sentinel-II, Aug 2018).

a: Klin-Dmitrov Ridge

b: Vladimir High Plain

c: Meshchera Site

d: Nerl-Klyazma Lowland

e: Lower Lugh Site

f: Oka-Tsna Wall

The Klin-Dmitrov Province is represented by two sites corresponding to natural areas significantly different in the peculiarities of soil and vegetation cover.

Site 1. Klin-Dmitrov Ridge

Sod-weak and medium-podzolic soils predominate. Forest covers about 30%. Ploughing area is about 45%.

Site 2. In the Vladimir High Plain.

The soil cover forms mainly as a combination of grey forest soils on the hilltops and in the upper part of the slopes, dark grey forest soils in the lower part of the slopes. The hill tops and slopes are mostly ploughed or occupied by deposits (over 60% is ploughed), the meadows along the basins bottoms vary in moisture — even swampy.

The Meshchera Province has a uniform landscape and is represented by one site.

Site 3. The *Meshchera Site* is a flat boggy alluvial Upper Pleistocene-Holocene plain in the Middle Klyazma woodland. Podzolic and sod-podzolic gley soils prevail in the interfluves; peaty-podzolic gley soils, on the slopes of elevations; and peaty bog soils, in the depressions. The Middle Klyazma woodland is covered with forests by about 85%. Pine trees are abundant, occupying 75 to 90% of the woodland.

The Volga-Klyazma Province had two sites.

Site 4. The Nerl-Klyazma Lowland. The soils are sod-podzolic loamy and sabulous on the elevated interfluves, peaty in the lowlands and alluvial argillo-arenaceous within the river terraces and floodplains. The forest cover is unevenly preserved, occupying from 35 to 95% of the territory in different areas. Agricultural development is insignificant.

Site 5. The Lower Lugh Site is the most waterlogged area in the lower reaches of the Lugh River, with swamps sprawling out. Under the conditions of surface waters stagnation, the peat-gley soils were formed with sandy sod-podzolic patches, marking the ancient deltas of glacial water flow. There are evergreen coniferous forests with abundant spruce and pine species. Cereal-herbaceous phytocenoses dominate the flood meadows.

The Oka-Tsna Province was represented by three sites due its diverse landscapes.

Site 6. The Oka-Tsna Wall. It is characterised by the wide karst development, deep ground water level and extreme underdevelopment of the hydraulic network. The anthropogenic development of the landscape district is low. The soil cover is represented by sod-weak and medium-podzolic soils. A unified forest cover (pine and birch-pine lichen-dry grass forests) is usually disturbed only by rare open agricultural areas surrounding villages.

Site 7. The karstic phenomena are well developed. The soils are soddy modal podzols, weakly gley soddy podzols and gley soddy podzols. The site is unevenly covered (about 70%, sometimes less than 30%) with boreal forests. Open spaces formed by agriculturally used areas are rather vast, although a significant part of these farmlands have been abandoned and turned into laylands.

Site 8. The Gorokhovets Spur is an intensely erosion-dissected gently undulating Dnieper morainic-glacial plain. The soils cover includes soddy modal podzols and washed-off truncated soddy podzols on the high interfluves, truncated soddy podzols on the slopes and washed-off and alluvial soils at the footslopes and in the gullies and ravines. Forests

occupy about 35% of the site and are confined to steep slopes and ravines. Flat tops of the watersheds are small and nearly all ploughed up.

Figs. 1 and 2 show the sites on the map and their satellite images.

Methods

The geoinformation analysis of remote sensing data and cartographic information on the soil and vegetation cover was performed by applying the catchment area approach.

The river network vectorisation and the boundary determination were carried out on the basis of the digital elevation model (DEM). The input data were the Shuttle Radar Topography Mission (SRTM) 90 m data. Having prepared the DEM, the river network and the catchment area boundaries were vectorised by automated geo-modelling methods in ESRI ArcGis10.4 using the Hydrology toolset (Ermolayev et al. 2014).

The land types were identified by HDF raster images made on the same four dates in 2001, 2005, 2009 and 2017 according to the MODIS open-source data of Friedl and Sulla-Menashe 2015.

For a more detailed analysis and trends identification in land area changes, we resorted to the Trends. Earth Land Degradation Monitoring Project (Land Cover Dataset, European Space Agency 2015, 300 m spatial resolution) implemented using open-source Quantum GIS 2.18 (Fig. 2) (National Aeronautics and Space Administration 2018).

The productivity indicators were calculated in carbon units, based on the MODIS GPP/NPP data HDF format, scene size 2400*2400, spatial resolution 500 m (Running and Mu 2015). The original space images of gross and net productivity were processed by the reclassification tool according to the created reclassification table, resulting in raster layers with classified pixel values. At the next step, the zonal statistics tool was used to compile attribute tables with productivity indicators in carbon units.

When calculating the carbon balance, we obtained the gross primary production (GPP), net primary production (NPP) and the costs of autotrophs respiration (RE) values (all in gC/m^2) for 2000–2015.

The soil organic carbon pool was determined by the UN FAO's data, based on Trends.Earth and QGIS 2.18 (National Aeronautics and Space Administration 2018). The data were generalised according to the Soil Grids global database of the International Soil Reference and Information Centre with a 250 m spatial resolution at a depth of 0 to 30 cm for 2001–2015 (ISRIC — World Soil Information 2017). The dynamics of soil and vegetation cover for 2001–2015 were calculated in the whole Klyazma River Basin and in each site using Trends.Earth and QGIS 2.18 (National Aeronautics and Space Administration 2018).

The weather statistics were taken from weather website rp5.ru (Anonymous 2019). To assess the climate, the data on temperature and precipitation for the period from 2001 to

2015 were used. The data were mathematically processed using two-factor analysis of variance ANOVA in the software environment STATISTICA 10 and Microsoft Excel.

The variance analysis has been carried out to identify the factors affecting the phytoproductivity indicators of various key sites.

Results

Dynamics of Land Use in the River Basin

According to the classification of the International Geosphere-Biosphere Program, the Klyazma River Basin includes *ten classes of land cover*. As of 2017, almost 60% of the basin was covered by mixed forests, about 20% were occupied by grasses, shrubs and open woodlands and about 14% were arable lands.

The conjoint quantitative and graphical analysis of data on the land use structure in 2001–2017 revealed the following changes in the area of different lands in the Basin (Fig. 3):

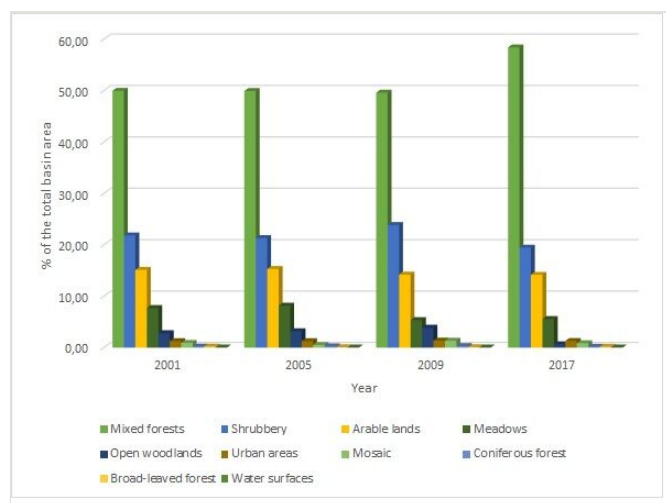


Figure 3.

Dynamics of land structure in the Klyazma River Basin according to MODIS (%).

1. the area of mixed forests that form the main vegetative cover of the basin increased by 9.0%;
2. the area of shrub vegetation and open woodlands decreased by 2.3 and 2.2%, respectively, primarily as a result of succession and their subsequent transition to the forest class;
3. the area of natural meadows, ploughlands/pastures and broad-leaved forests decreased by 2.1, 1.0 and 0.1%, respectively;

4. there was a 1% increase in the area of urbanised territories; water surfaces and swamps also slightly grew.

Dynamics of Land Use in the Landscape Provinces

The catchment area of the Klyazma River has a complex landscape structure and to make a detailed analysis of the main trends in the different parts of the basin, we took remote data from Trends.Earth with of 300 m spatial resolution for six types of lands.

It was found that the trend has been towards the sprawl of forest vegetation and the reduction of ploughlands and pastures in the entire Basin. The only exception is the interfluvium with the Lukh River, where a transition of forest lands into bogs can be observed. The selected sites feature the changes in the land use structure of the main landscape Provinces (Table 1, Fig. 4).

Table 1.

Dynamics of land use on the sites.

Province	Site	Year	Land use structure (%)					
			Forests	Pastures	Ploughlands	Bogs	Other	Water
Klin-Dmitrov	1 – Klin-Dmitrov Ridge	2001	55.9	4.1	38.5	0.0	1.6	0.0
		2015	62.0	0.8	35.0	0.0	2.2	0.0
	Dynamics		6.1	-3.3	-3.5	0.0	0.6	0.0
	2 – Vladimir High Plain	2001	31.4	2.0	65.3	0.0	0.6	0.6
		2015	33.7	0.8	63.7	0.0	1.2	0.6
	Dynamics		2.3	-1.2	-1.6	0.0	0.6	0.0
Meshchera	3 – Meshchera Site	2001	88.8	3.2	6.9	0.1	0.6	0.4
		2015	89.7	2.7	6.2	0.1	1.0	0.4
	Dynamics		0.9	-0.5	-0.7	0.0	0.4	0.0
Volga-Klyazma	4 – Nerl-Klyazma Lowland	2001	71.5	5.4	22.5	0.0	0.4	0.2
		2015	76.9	1.6	20.6	0.0	0.6	0.2
	Dynamics		5.4	-3.8	-1.9	0.0	0.2	0.0
	5 – Lower Lukh Site	2001	85.4	0.1	0.8	12.5	0.0	1.2
		2015	67.0	0.1	1.1	30.6	0.0	1.2
	Dynamics		-18.4	0.0	0.3	18.1	0.0	0.0
Oka-Tsna	6 – Oka-Tsna Wall	2001	86.9	1.6	11.4	0.0	0.0	0.1
		2015	89.3	0.3	10.2	0.0	0.0	0.1
	Dynamics		2.4	-1.3	-1.2	0.0	0.0	0.0
	7 – Kovrov-Kasimov Plateau	2001	76.4	2.8	20.3	0.0	0.2	0.2
		2015	81.1	0.2	18.0	0.0	0.4	0.2
	Dynamics		4.7	-2.6	2.3	0.0	0.2	0.0

Province	Site	Year	Land use structure (%)					
			Forests	Pastures	Ploughlands	Bogs	Other	Water
	8 – Gorokhovets Spur	2001	54.3	5.8	38.2	0.2	0.4	1.0
		2015	59.8	2.3	35.8	0.2	0.9	1.0
	Dynamics		5.5	-3.5	-2.4	0.0	0.5	0.0
Total Basin		2001	60.5	4.9	32.1	0.4	1.4	0.7
		2015	63.7	2.3	30.4	0.8	2.1	0.7
	Dynamics		3.2	-2.5	-1.7	0.5	0.6	0.0

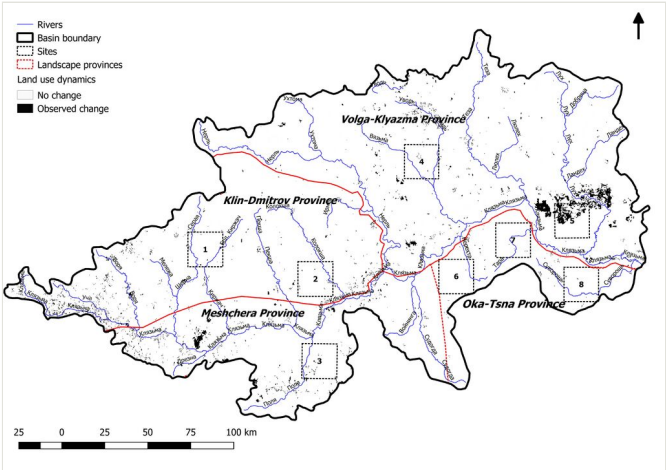


Figure 4.
Land use dynamics in the Klyazma River Basin in 2001–2015.

The land structure in the Meshchera Province is the most stable: almost 90% of the Province is occupied by forests and their area have changed insignificantly.

The revegetation of ploughlands with grey wood soils and soddy podzols differs. For example, the Klin-Dmitrov Province has both types of soils. Forests most actively overgrow the pastures and ploughlands with soddy cryptopodzols and mesopodzols, which can be observed on Site 1 (the Klin-Dmitrov Ridge). Here, the revegetation rate is the highest (-3.5%) in the Klyazma River Basin. The grey wood soils, represented on the Vladimir High Plain, are the most fertile and agriculturally developed, hence they become overgrown significantly less (Site 2).

The cartographic analysis revealed areas where various lands transitioned from one category to another (refer to Fig. 4). Such transitions mainly occurred due to revegetation of agricultural land with shrubs and grasses. There was also a significant enlargement of waterlogged areas and bogs in the eastern part of the basin: in the Volga-Klyazma Province (interfluvium of the rivers Lukh and Klyazma, Site 5) and in the Oka-Tsna Province (near the Gorokhovets Spur, Site 8).

Productivity of the Vegetation Cover

To quantify the productivity of the vegetation cover in the catchment area, the GPP, NPP and RE values were determined in gC/cm^2 at the *height of vegetation season* (mid-July) in 2000–2015, based on the MODIS data.

On average, the GPP was $59.1 \text{ gC}/\text{cm}^2$ and the NPP was $39.5 \text{ gC}/\text{cm}^2$ for the studied period at the height of the vegetation season in the entire territory of the Klyazma River Basin.

The GPP was unevenly distributed across the Basin (Table 2). Fertile grey wood soils of the Vladimir High Plain do not have high gross productivity, which, in that zone, is even slightly lower than the average, due to the predominance of agrocenoses there. The Gorokhovets Spur area (Oksko-Tsninsk Province) is characterised by the highest gross productivity, it is higher than average for the Klyazma River Basin. In this area, in comparison with others, there are more grasses and shrubbery that are more productive than forests. Phytoproductivity of the other landscapes corresponded to the average values in the Basin.

Table 2.

Statistical indicators of productivity distribution.

Province	Site	Indicator	Productivity (gC/m^2)		
			GPP	NPP	RE
Klin-Dmitrov	1 – Klin-Dmitrov Ridge	$\bar{x} \pm \sigma$	56.5 ± 13.2	38.4 ± 10.1	18.0 ± 6.0
		V(%)	23.3	26.3	33.1
		r	0.92	0.93	0.94
	2 – Vladimir High Plain	$\bar{x} \pm \sigma$	58.4 ± 11.4	38.9 ± 10.5	20.0 ± 6.0
		V(%)	19.5	24.3	28.5
		r	0.97	0.98	0.92
Meshchera	3 – Meshchera Site	$\bar{x} \pm \sigma$	59.6 ± 11.0	40.2 ± 9.2	19.0 ± 5.0
		V(%)	18.5	22.8	26.2
		r	0.94	0.97	0.91
Volga-Klyazma	4 – Nerl-Klyazma Lowland	$\bar{x} \pm \sigma$	59.9 ± 13.3	40.5 ± 10.0	19.0 ± 6.0
		V(%)	22.2	24.7	31.8
		r	0.93	0.96	0.91
	5 – Lower Lukh Site	$\bar{x} \pm \sigma$	50.9 ± 11.0	37.5 ± 9.0	13.4 ± 4.2
		V(%)	21.7	24.1	31.3
		r	0.86	0.86	0.81
Oka-Tsna	6 – Oka-Tsna Wall	$\bar{x} \pm \sigma$	61.7 ± 10.6	41.2 ± 9.1	20.0 ± 5.0
		V(%)	17.2	22	26.2
		r	0.96	0.98	0.90

7 – Kovrov-kasimov Plateau	$\bar{x}\pm\sigma$	61.7±12.3	41.4±9.8	20.0±6.0
	V(%)	19.9	23.7	28.1
	r	0.92	0.94	0.91
8 – Gorokhovets Spur	$\bar{x}\pm\sigma$	63.1±11.8	41.1±10.2	22.0±6.0
	V (%)	18.7	24.7	25.6
	r	0.90	0.91	0.93
Klyazma River Basin	$\bar{x}\pm\sigma$	59.1±10.9	39.5±9.0	19.6±5.5
	V(%)	18.5	22.7	27.9
	r	1.00	1.00	1.00

Note: \bar{x} is the arithmetic mean, σ is the standard deviation, V(%) is the coefficient of variation and r is the coefficient of correlation.

The productivity indicators differed significantly over the years both generally in the Basin and separately by the sites. The coefficient of variation characterising the samples was rather significant (Fig. 5, Table 2).

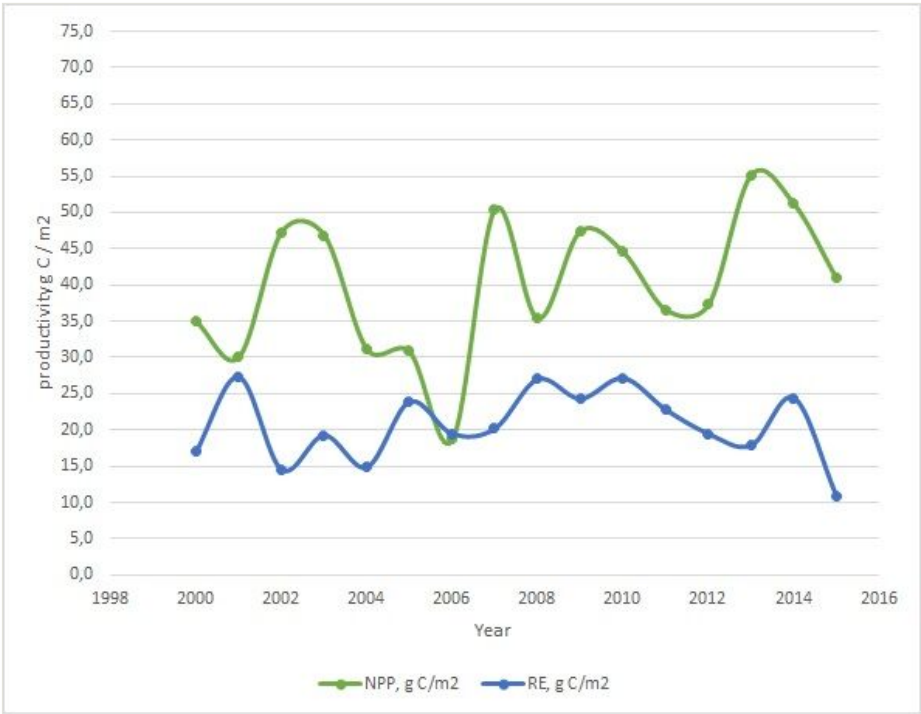


Figure 5. Long-term productivity dynamics in the Klyazma River Basin: blue stands for NPP, red stands for RE and a whole column stands for GPP.

We compared the phytoproductivity dynamics of the whole River Basin and individual landscape Provinces, represented by the sites (Fig. 6).

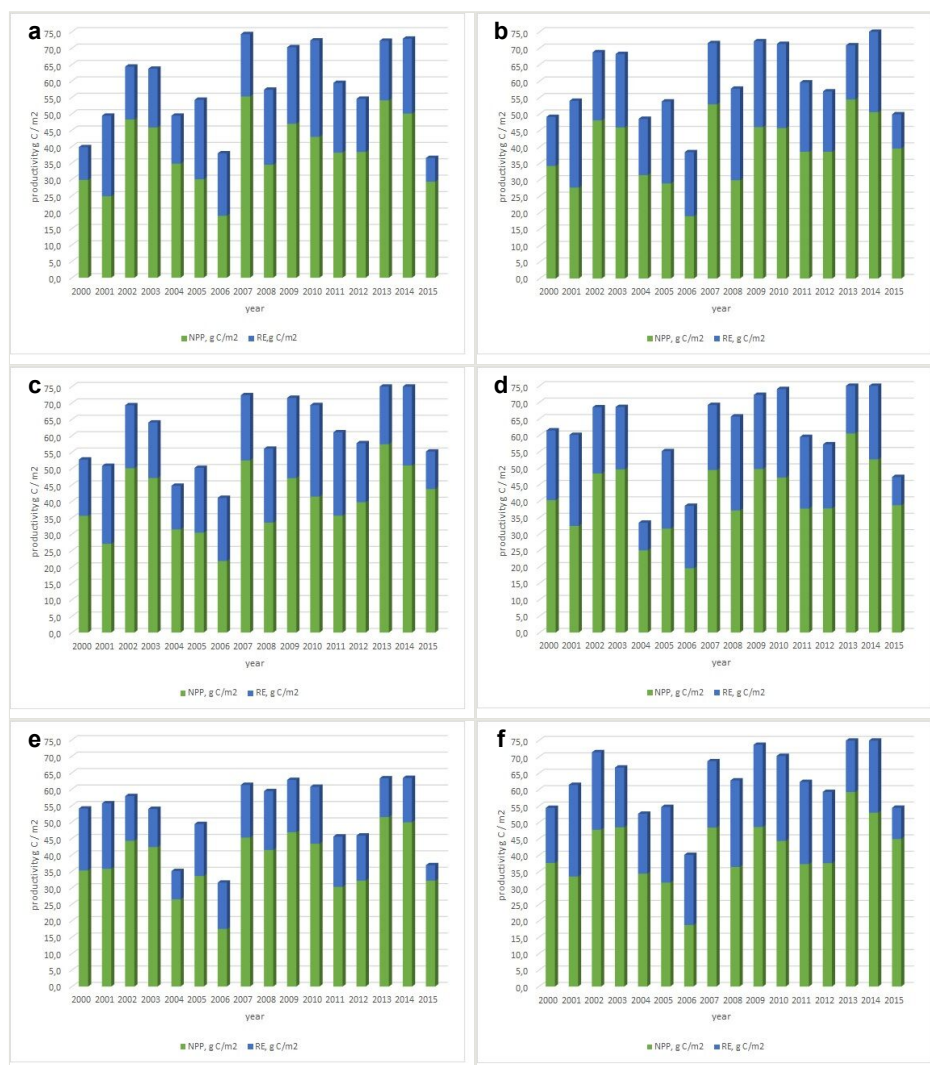


Figure 6.

Graphical distribution of GPP, NPP and RE over the course of 15 years in the landscapes of the Klyazma River Basin.

- a:** The Klin-Dmitrov Ridge
- b:** The Vladimir High Plain
- c:** The Meshchera Site
- d:** The Nerl-Klyazma Lowland
- e:** The Lower Lugh Site
- f:** The Oka-Tsa Wall

The variance analysis was used to describe the impact of the temporal factor and landscape belonging of eight key sites regarding gross primary productivity (Table 3).

Table 3.				
Results of ANOVA dispersion analysis of soil organic carbon content and biological productivity dependence on the studied parameters.				
Effect	"One-dimension significance criterion for soil carbon, t/hec Sigma-restricted parameterisation Effective hypothesis decomposition"			
	Ffact	Critical F at p < 0.05	$\bar{x}-\Delta$ 0.95	$\bar{x}+\Delta$ 0.95
Time	0.001	1.000	112.041	128.662
Land use structure	17 . 734	0 . 0001		
Time * Land use structure	0.002	1.000		
Effect	"One-dimensional significance criterion for gross primary productivity, g S/m ² Sigma-restricted parameterisation Effective hypothesis"			
Time	4 . 803	0 . 0004	58.612	62.911
Site	0.025	0.976		
Time* Site	0.352	0.991		
Effect	t	Critical t at p < 0.05	$\bar{x}-\Delta$ 0.95	$\bar{x}+\Delta$ 0.95
Forest land	5 . 713	0 . 0001	168.283	177.941
Grassy vegetation	3 . 626	0 . 0001	155.910	171.238
Arables	-0.098	0.922	142.140	150.949
Swamp lands	4 . 917	0 . 0001	108.016	141.011

Note: F – F value of Fisher criterion, p – significance levels, t - t Student criterion, $\bar{x}-\Delta 0.95$ – lower confidence limit, $x+\Delta 0.95$ - upper limit of the confidence interval.

Carbon Balance in the Soil Cover

The data in Tables 2 and 3 indicate the change in carbon content in the soil in 2001–2015. In general, the Klyazma River Basin ecosystem increased carbon reserves by 0.6%, but the data on the sites showed that the rate and the direction of this process varied in the different landscape Provinces of the studied catchment area.

Table 4. Balance of organic carbon in the soil.				
Landscape province	Site	Area (km ²)	Balance (Cton/km ²)	C (Δ%)
Klin-Dmitrov	1 – Klin-Dmitrol Ridge	420	96.2	growth +0.7
	2 – Vladimir High Plain	405	7.4	growth +0.1

Landscape province	Site	Area (km ²)	Balance (Cton/km ²)	C (Δ%)
Meshchera	3 – Meshchera Site	410	-24.1	loss -0.1
Volga-Klyazma	4 – Nerl-Klyazma Lowland	410	125.9	growth +0.9
	5 – Lower Lukh Site	368	73.9	growth +0.3
Oka-Tsna	6 – Oka-Tsna Wall	381	119.3	growth +0.7
	7 – Kovrov-kasimov Plateau	402	125.2	growth +0.9
	8 – Gorokhovets Spur	257	253.5	growth +1.5
Klyazma River Basin		42500	92.8	growth +0.6

Discussion

Analysis of the Productivity Dynamics in the River Basin

From 2000 to 2015, the GPP, NPP and RE values in the ecosystem of the Klyazma River Basin were fluctuating both up and down as compared to the respective average values. No sustainable trends in growth or decline in productivity were observed. The distribution histograms showed periods of growth, decline and steady state of productivity, which can be mainly associated with the weather conditions.

Both GPP and NPP were stable from 2007–2010 when the gross productivity was in the range from 70 to 71 gC/m² and the net productivity was 44 gC/m² on average. Despite the hot and arid summer of 2010, when the average temperature in July reached 24.8°C, the total precipitation in June and July was 54 mm, the number of days with weather elements was only 22 and the relative humidity did not exceed 60%. The considered indicators remained at a relatively high level: GPP was 71 gC/m² and NPP was gC/m². On the other hand, the consumption for autotrophic respiration was also rather high: RE was 27 gC/m². It could have been caused by adverse weather conditions and large-scale summer fires.

The GPP and NPP maximums occurred during the humid summer of 2014 and reached 75 and 51 gC/m², respectively. In July 2014, the average temperature in July 2014 was 19.3°C, the total precipitation in June and July was 156 mm, the number of days with adverse weather elements was 30 and the relative humidity did not exceed 66%.

The worst period for the land cover was year 2006 when GPP dropped to 38 gC/m² and NPP was 18 gC/m², the average temperature in July was below normal and amounted only to 16.6°C and the total precipitation in June and July was 77 mm. A relatively small amount of precipitation in May and June, amounting to 62 mm, could also have had a negative impact on productivity, which apparently contributed to a decrease in groundwater levels by July and formed the conditions of water deficit.

Productivity Dynamics in the Landscape Provinces

It is shown that, although, on the one hand, the studied landscapes differ from each other in absolute indicators of gross and net biological productivity, however, their dynamics do not depend on the initial indicators (as evidenced by the Fisher criterion ($F = 0.02$) below critical F (0.97) at $p < 0.05$) (Table 3).

The crucial role here belongs to the temporal factor, determining the annual change in productivity indicators in all the studied areas, which is confirmed by the value of F actual 4.8 with F critical 0.0001 ($p < 0.05$). As a result, the course of the curves that reflect the change in gross and net productivity over the years for 15 years in different areas coincide, although their absolute values differ. As a result, the curved lines reflecting the annual change in gross and net productivity during 15 years in different areas coincide, although their absolute values differ (Fig. 6).

The periods of increased and decreased productivity in different provinces generally coincided; however, the magnitude of these fluctuations was different.

The most significant changes in the productivity indicators from year to year were observed in the Klin-Dmitrov Ridge, which can be confirmed by the maximum coefficients of variation for GPP (23.3%), NPP (26.3%) and RE (33.1%). The smallest productivity fluctuations occurred in the Oka-Tsna Wall: here, they are below the Basin average.

The sites were grouped by productivity, based on visual analysis and subsequent comparison of histograms. The sites having similar productivity parameters, but confined to different landscapes, generally had a similar distribution of lands. Thus, the Meshchera Site (Site 3) and the Oka-Tsna Wall (Site 6), both covered with mixed forest by 86–88%, were alike in terms of productivity distribution. The landscapes of the Volga-Klyazma Province (Site 4) and the Kovrov-Kasimov Plateau (Site 7), both covered with mixed forest by 71–76%, were also alike in terms of productivity distribution and differed from the others by the largest variation of indicators.

The most dynamic site was the interfluvium of the rivers Lukh and Klyazma (Site 5), where the structure of land use had taken significant changes. Thus, the forested areas decreased by 18% due to bogging, but the productivity indicators in the studied period were the lowest. On the other hand, the Gorokhovets Spur (Site 8) and the Klin-Dmitrov Ridge (Site 1), both having 50% of mixed forests and 35–38% of arable lands, were grouped according to the ratio of NPP to RE.

The Vladimir High Plain (Site 2) can be isolated as unique in terms of productivity distribution for it bore no similarity to any other site, but had a similar productivity distribution as the River Basin taken as a whole. This plot differs from the others by the degree of ploughing (60% of arable lands, 30% of forests).

On average, in the Klyazma River Basin, the coefficient of variation of GPP was 18.5%, while RE varied more significantly, the coefficient of variation being 27.9%. It should be

noted that *the dynamics of landscape productivity on the selected sites, referring to various landscapes, corresponded to the processes in the whole River Basin in general.*

The coefficients of correlation between the variables GPP, NPP and RE, as a whole for the basin landscapes and the vegetation of these areas, were maximum. However, the dynamics of plant community productivity on the sites of the Vladimir High Plain and the Klin-Dmitrov Ridge most closely corresponded to the dynamics of productivity of the whole River Basin. Since these sites and the River Basin appear to have matching patterns of phytoproductivity dynamics, they can be used as *monitoring sites* for the Klyazma River Basin. On that subject, the Klin-Dmitrov Ridge is even more preferable since it is more consistent with the whole River Basin in terms of land use.

Recommendations for environmental monitoring

The analysis of productivity, land use and carbon accumulation in the soil in the whole Klyazma River Basin and the individual sites associated with different landscapes identified a representative site for environmental monitoring in the studied catchment area, that is *the Klin-Dmitrov Ridge*. It matches to the whole River Basin by several parameters (productivity and its dynamics, land use structure, carbon accumulation) and hence Site 1 can serve as a model of the Klyazma River Basin.

It should be noted that although the catchment area of the Klyazma is rather large, it functions stably enough in the regime of a single ecosystem. This is facilitated by a favourable correlation of climatic parameters, the location of various land areas and a relatively stable anthropogenic load.

Carbon Balance and the State of Soil and Vegetation Cover in the Provinces

We compared the data on the carbon balance in the soil cover of the Klyazma River Basin and the change in land use structure (Tables 1, 4, 3).

Variance analysis ANOVA demonstrated that the temporal factor does not affect soil organic carbon amount, because $F_{\text{actual}} 0.001$ as the criterion is less than $F_{\text{critical}} 1.00$ ($p < 0.05$). It might depend on the fact that the organic carbon amount in soil is changing slowly over time and has remained relatively stable in the studied areas for 15 years.

On the other hand, the effect of the land use structure on organic carbon amount was found in all landscapes, as indicated by $F_{\text{actual}} 17.7$ ($F_{\text{critical}} = 0.0001$, $p < 0.05$). The land sites ratio significantly affects changes in soil organic carbon, which is especially evident in succession processes, ploughing and waterlogging.

Parametric analysis proved that forests make the greatest contribution into the soil organic carbon dynamics ($t = 5.7$ at $T_{\text{cr}} = 0.0001$, $p < 0.05$). Grassy vegetation and wetlands are slightly less affected. In arable land, carbon amount in soil does not change significantly ($t = -0.1$ at $t_{\text{cr}} = 0.9$, $p < 0.05$).

The carbon balance in the soil cover of the whole River Basin was positive, with the exception of the Meshchera Site and the Vladimir High Plain where there were insignificant changes in the dynamics of soil carbon over the period from 2000 to 2015 and, therefore, the carbon balance can be assumed to be zero. The Meshchera Site was marked by a small negative dynamics of soil carbon content that decreased by 0.1%, while the Vladimir High Plain had a 0.1% increase in soil carbon content.

The land use structure of the sites with a zero balance is notably different. On the Meshchera Site, most of the land is occupied by forests (89%) and on the Vladimir High Plain, it is arable land (65%). A common feature of these site is the stability of land. On the Meshchera Site, the area of forest vegetation changed insignificantly and, on the Vladimir High Plain, forested territories grew only slightly and farmland areas remained almost unchanged.

In the other landscapes, the farmlands were actively overgrown with forest vegetation and, at the same time, the rate of carbon accumulation in the soil increased. For the analysed period, this accumulation amounted to 0.6% in the Klyazma River Basin.

On the Klin-Dmitrov Ridge, the rate of carbon deposition in the soil corresponded to the River Basin average (0.7%), which must be taken into account when choosing key sites for environmental monitoring.

The highest rate of carbon accumulation in the soil was observed on the Gorokhovets Spur (1.5%).

Summing up, in the Klyazma River Basin, overgrowing of agricultural land with forest vegetation is accompanied by increasing carbon accumulation in the soil. In the landscapes with a stable land use structure, the carbon balance is zero or slightly negative.

Due to the reduction in the area of arable land and pastures (alienation for urban development, waterlogging), the mass of organic carbon in the soil decreased. This is especially evident in the Meshchera Province that showed a negative trend to accumulate organic carbon in the soil.

As a whole, in the Klyazma River Basin ecosystem, GPP is gC/m^2 , NPP is about 40 gC/m^2 and the carbon content in the soil has grown by 0.6%.

Conclusions

Based on the remote sensing data, the large catchment area of the Klyazma River, representing a complex combination of different landscape structures, i.e. landscape Provinces, has been studied. Each of them is marked by a diverse composition of geomorphological and soil-vegetation structures. Moreover, the biological processes that characterise the dynamics of organic matter in the form of plant production, the accumulation of organic matter etc. are distinguished by both rate and intensity.

The ecosystems differently react to the changes in climatic parameters and land use. Landscapes with herbaceous and shrubby vegetation are more productive than forest vegetation. On the other hand, forest biotopes are more stable in time and development.

Thus, the active revegetation of farmland by forests gives the increased rate of carbon accumulation in the soil. Landscapes covered with grasses and shrubs are more productive than those covered with forest. On the other hand, woody biotopes are more stable in their development over time.

Although, from 2000 to 2015, there were fluctuations of GPP, NPP and RE in the ecosystem of the Klyazma River Basin and the said indicators could have been both above and below average, no stable trends towards an increase or decrease in productivity were noted.

The overgrowing of ploughlands and pastures with forest is accompanied by an increase in carbon deposition in the soil. For the whole Basin, the increase in carbon content was 0.6% over the fifteen-year period from 2000 to 2015. On the sites with a stable land use structure, the carbon balance was akin to zero (the Vladimir High Plain) or slightly negative (the Meshchera Site).

Statistical analysis, implemented by variance ANOVA two-factor analysis method results, demonstrate that phytoproductivity dynamics of key sites do not depend on their productivity parameters and on the site landscape structure, but are determined only by the temporal factor. As a result, the curved lines reflecting the annual change in gross and net productivity during 15 years in different sections coincide, although their absolute values differ.

It can be confirmed that large natural ecosystems, such as river catchment areas marked by a strict territorial certainty of the material and energy flow distribution, have a set of compensation mechanisms to maintain relative functioning stability. The smaller structures that make up the Basin in the form of different landscapes react more dynamically to various impacts of both natural and anthropogenic nature. This must be taken into account when assessing the ecosystem resilience to changes in external conditions.

Funding program

The study was supported by the Russian Foundation for Basic Research, Project ID 19-05-00363 A.

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