Estimation of the above-ground phytomass dynamics in small-leaved linden plantations using multi-time Landsat images (forest case study from the Republic of Bashkortostan)

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Abstract. The study analyses the above-ground phytomass of small-leaved Linden plantations (Tilia cordata) using GIS and remote sensing data. As these data are crucial for forecasting the dynamics of stand development in the future, they are also essential for evaluating the above-ground phytomass of tree plantations. As such, the analysis of these data is currently of great interest to the academic community. Research was carried out on plantations in which small-leaved Linden trees dominated. In order to evaluate the above-ground phytomass, the authors analysed the method of establishing test areas, as well as processed Landsat-5 and Landsat-8 images from different time periods. The authors used images of 1991 and 2020 to calculate the vegetation index values (NDVI). The research outcomes revealed a close correlation with the above-ground phytomass data obtained by the onsite surveying method (the coefficient of determination was equal to 0.68). In order to determine the above-ground phytomass of forest plantations based on the NDVI index, an exponential equation was calculated using the fundamentals of statistical processing. Thematic maps of above-ground phytomass obtained for 1991 and 2020 made it possible to analyse changes in the condition of tree and shrub vegetation over a nearly 30-year period. They also helped the authors identify areas in which the above-ground phytomass had significantly declined.

1 Introduction

The above-ground phytomass of forests is the most significant component of the global carbon cycle [1]. It is necessary to monitor and map this component in order to analyse the carbon balance, tackle theoretical and practical forest management issues, characterise the condition and changes in climate, and describe the biodiversity of forests [2-3]. In forest

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science, the above-ground phytomass is measured using ground-based forest inventory and computational methods [4].

Land surveying methods are based on modelling forest productivity, measuring carbon fluxes, and using remote sensing [3, 5]. Research that comparatively analyses data from remote sensing and field measurements has become increasingly prevalent in recent years [3-4]. Landsat images provide medium spatial (30x30 m) and temporal (16 days) resolutions and cover vast areas, which makes them widely used in the estimation of forest phytomass complemented with sampling ground measurements [5-6].

Landsat images provide spectral information that can be compared with the results of forest inventory [7]. The assessment of phytomass using remote sensing methods is addressed by national and international scholars [2–8] as well as in group studies [9]. Using Landsat satellite imagery, the study aims to assess the above-ground phytomass and its dynamics over a thirty-year period.

2 Materials and methods

The research area is located in the South Ural forest-steppe region in the European part of the Russian Federation. The study region is situated between 54°46'-54°49' north latitude and 55°43'-55°49' east longitude, on the site of the Dmitrievsky district of the Ufimskoe forestry enterprise.

Natural, even-aged secondary forest that regenerated at the place of clear cutting dominates the area. With 432.7 hectares (or 50.2% of the total area of forested land), linden forests of the II–III quality classes predominate.

Ground measurements on permanent and temporary sampling plots were carried out by the method of onsite survey. Phytomass in the research area was estimated in 1991 by the method of felling and immediate weighing the parts of sampling trees, with consequent recalculation of the try mass per hectare. In 2020, conversion coefficients were used for this purpose. Satellite imagery was processed using the quantitative phytomass characteristics that were derived from the data collected at the sampling locations. The original satellite images are as follows: LT05_L1TP_167022_19910723_20180223_01_T1 from the Landsat-5 satellite (date of imagery 07.23.1991) and LC08_L1TP_166022_20200715_20200722_01_T1 from the Landsat-8 satellite (date of imagery 07.15.2020).

The data obtained were processed using the software packages Statistica 6.0, SAGA (ver.2.3.2). Radiometric correction was carried out to eliminate systematic errors and enhance the quality of remote sensing data using the "Tool Top of Atmosphere Reflectance" of the SAGAGIS application. After radiometric calibration, the effects of atmospheric scattering and absorption were removed using atmospheric correction. The Normalised difference vegetation index (Normalised Difference VI, NDVI) reflected the influence of factors such as chlorophyll content, leaf surface area, vegetation density, and structure. NDVI can take values ranging from -1 to 1. For vegetation, it takes positive values, usually from 0.2 to 0.8. In order to display the NDVI index, a standardised discrete scale is used, showing values ranging from -1 to 1 [10].

Over a thirty-year period, classified images of the research area were used to evaluate transient changes. The representativeness of the object samples, the reliability of results that cannot be below 95%, and the comparability of the results with data from similar studies are the three main factors that determine the validity of the data.

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3 Results and Discussion

The values of above-ground phytomass were calculated using the method of field sampling comparatively analysed against satellite images (Table 1).

Table 1. Above-ground phytomass in plantations under study (1991/2020).

Age of stand, years	Composition*	Number of trees, trees/ha	Stand density	Stock, m^3/ha	Phytomass (tons/ha)	
					onsite	Satellite imagery
57	9L1B+OK+EM	910	0.8	313	152.8	96.1
85	10L+OK	749	0.7	388	187.5	74.4
47	8L1B1OK	1335	1.0	313	162.5	144.6
75	10L+EM	780	1.0	388	174.6	159.0
65	9L1OK+EM	539	0.8	322	164.0	78.5
97	9L1MP+EM	830	0.8	326	175.0	60.3
64	7L2B1OK+EM	472	0.5	223	136.0	130.6
96	7L2B1EM	456	0.5	279	177.6	163.2
75	10L	686	1.0	363	319.0	216.4
100	9L1BI+OK+EM+MP	625	1.0	426	334.8	266.2

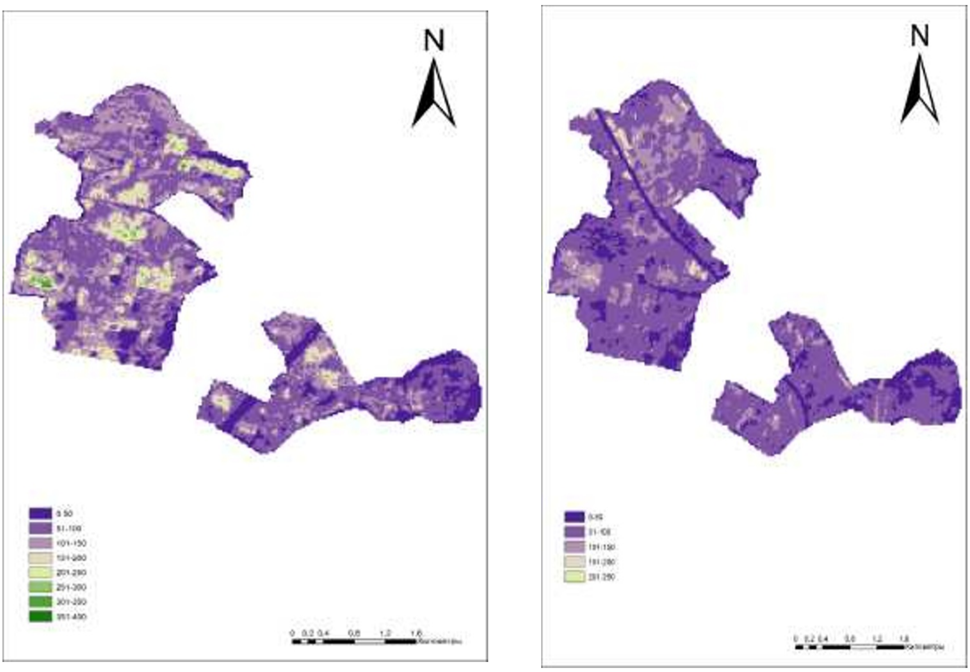
*lime– L, birch – B, oak – OK, elm – EM, maple – MP

The results of field research revealed that in 1991, the above-ground phytomass ranged from 136.0 tons/ha (low-density stand of age class VII) to 319.0 tons/ha (with a stand density of 1.0, age class VIII). The 2020 phytomass inventory demonstrated a naturally occurring increase in phytomass, with a maximum value of 334.8 tons/ha, which is typical for a 100-year-old stand, as indicated by the increase of stock with age. It has been determined that the findings of field research correspond to data from satellite imaging. The NDVI index values were computed for the whole area under study using imagery from the Landsat-5 and Landsat-8 satellites at different time periods. In 1991, the values varied from -0.04 to 0.66, and in 2020, they were between -0.10 and 0.60. Figure 1 displays thematic maps of the NDVI indices over the study years.

a) 1991 b) 2020

Fig. 1. Thematic maps of NDVI in 1991 and 2020.

The correlation analysis indicated a moderate association (r = 0.68) between the above-ground phytomass (*Y*) and the NDVI index (*X*) values. In order to calculate the above-ground phytomass of the remaining plantations in the quarters under study and develop cartographic images of the distribution of above-ground phytomass in the sampling plot, a significant dependence equation $Y = 0.4375*exp\ (10.176*X)$ with probability $p = 0.029$ was used. The results are shown in Figure 2 and in Table 2.



a) 1991 b) 2020

Fig. 2. Thematic map of forest stand above-ground phytomass distribution.

Table 2. Distribution of above-ground phytomass data.

Value of above-ground phytomass, tons/ha	Number of pixels, items		Area, ha		Dynamics of above-ground phytomass (2020 compared to 1991)	
	In 1991	In 2020	In 1991	In 2020	Tons/ha	%
0-50	1560	2065	140.4	185.85	+45.45	+32.37
51-100	5000	7323	450	659.07	+209.07	+46.46
101-150	3294	1550	296.46	139.5	-156.96	-52.94
151-200	871	153	78.39	13.77	-64.62	-82.43
201-250	296	3	26.64	0.27	-26.37	-98.99
251-300	56	0	5.04	0	-5.04	-100.00
300-350	14	0	1.26	0	-1.26	-100.00
350-400	3	0	0.27	0	-0.27	-100.00
	11094	11094	998.46	998.46		

As it is evidenced from the data provided in Table 2, plantations with an above-ground phytomass of more than 250 tons/ha disappeared by 2020. The average above-ground phytomass of the sampling plots in 1991 was 71.65 tons/ha, and in 2020, it was 48.12 tons/ha. Reduced average above-ground phytomass in the forest area is a result of increasing anthropogenic impact on forest ecosystems and a growing area of non-forest lands.

4 Conclusion

In order to assess the dynamics of above-ground phytomass, along with the methodology of field studies, remote sensing methods were used to cover vast territories and promptly identify negative impacts on forests. Since the relationship between the amount of above-ground phytomass and the vegetation index (NDVI) has been established, the distribution of above-ground phytomass can be thematically mapped.

Depending on the age, stock, and density of the stand, the phytomass research in the sample locations revealed values varying between 136.0-319.0 tons/ha in 1991 and 174.6-334.8 tons/ha in 2020. Since stock increases with age, the phytomass assessment in 2020 revealed a naturally occurring increase.

The acquired results from land forest inventory are consistent with data obtained from GIS and remote sensing. This attests to the accuracy of the data regarding variations in the area, composition, and phytomass of plantings, both within specific research quarters and over the entire study area.

The examined small-leaved linden plantations have changed over the past 30 years, as shown by the examination of fixed NDVI data. As a result of this transition, the above-ground phytomass of the forest area and the average value of the NDVI both decrease. These changes are caused by bacterial dropsy, ageing of plantations, construction of infrastructure facilities, and forestry activities.

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