Remote Sensing Monitoring on the Territory of the Volga Carbon Polygon (Republic of Tatarstan, Russia)

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Abstract. Remote sensing technology and geographic information systems allow the assessment of terrestrial carbon stocks in large areas. The article considers the procedure of remote monitoring organization in the forest and water parts of the Volga Carbon polygon (Republic of Tatarstan, Russia). The main purpose of the article is to present the structure of remote monitoring of the polygon, show the results of the first year of remote research, and discuss the need to use other remote sensing methods. This study reviews and highlights the advantages and limitations of various remote sensing methods and sensors, including optical, multispectral, radar, and lidar, which are widely used for above-ground biomass (AGB) and carbon stocks (CS) estimation. The first results of field studies by unmanned aerial vehicle (UAV) at the Volga Carbon polygon are presented: orthophotomaps, digital terrain and relief models, bathymetric map and multispectral image time-series. Different remote sensing methods from echolocation to the multispectral survey are used, and the most optimal remote sensing data and processing methods are determined. For the first time for the Republic of Tatarstan, an integrated carbon balance monitoring system has been developed.

1 Introduction

The most accurate and reliable approaches for carbon balance monitoring are eddy covariance measurements and soil camera surveys [1]. However, when it is necessary to measure the total carbon flux over a wide area, various remote sensing tools are used. Despite the relatively low measurement accuracy of remote systems compared to field methods, the main advantage is the coverage of large areas. The use of both space and aerial surveys makes it possible to conduct research with various sensors at different scale levels.

The main area of use for remote sensing in carbon polygon monitoring is the assessment of Above-ground biomass (AGB), as vegetation biomass plays a critical role in understanding the contribution of an ecosystem to the global carbon cycle [2]. Among the

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global open AGB maps are the Baccini map (2000) [3]; the GEOCARBON 2007–2010 map [4]; CCI (Climate Change Initiative) Biomass 2017-2018 map [5]; GlobBiomass 2010 map [6]. It is also worth mentioning the approaches based on the assessment of the gross primary production of ecosystems [7].

Various types of satellite data are used to estimate biomass and carbon sequestration, either alone or in various combinations. The main ones are: MODIS Vegetation indices [8]; Sentinel-2 [9] and Landsat [10]; Multispectral imaging; Sentinel-1 and ALOS2 radar data (most often in combination with Sentinel-2 and Landsat) [11]; Lidar survey [3-4, 12].

Recently, the issue of carbon sequestration on abandoned arable lands of the post-Soviet space, including Russia, has been actively studied [6,13]. One of the problems of reliable assessment of the terrestrial carbon balance for the forested lands of Russia by various methods (including eddy covariance) is the lack of up-to-date forest inventory data [14].

For the rapid biomass assessment, field measurement methods are used, based mainly on two approaches - ground-based measurements and surveys from manned and unmanned aerial systems (UAV) [15-16].

The first includes direct measurements of reference samples and extrapolation of the obtained results [17], so-called classical methods, as well as modern geodetic methods – ground photogrammetry, and terrestrial laser scanning (TLS). Photogrammetry methods are also used both in modern form with point clouds obtaining and three-dimensional models construction, and in their classical form with image analysis, fitting primitives, and estimating the volume of woody biomass using empirical formulas, taking into account the trunk diameter, species composition, and tree height. A similar approach is implemented, for example, in the Katam™ software [18].

In the past few years, UAVs equipped with various useful loads have been actively used to estimate vegetation biomass. The most common is aerial photography, which makes it possible to obtain a digital terrain model (DTM) and an orthophotomap of the study area. Orthophotomap can be used for supervised or unsupervised classification of vegetation types, and DTM - for AGB estimation [19]. A more advanced option is the use of a multispectral camera receiving an image simultaneously in several spectral ranges. As a result, it is possible to create both an orthophoto map of the territory in the visible range and to calculate various vegetation indices and metrics [14]. Subsequently, they, together with terrain models, are successfully used for probabilistic assessment of biomass, considering the species composition of vegetation, both tree, and meadow types [20].

The most accurate results for estimating woody biomass volumes can be achieved using UAV lidar surveys [21]. Unlike aerial photography from a UAV, a lidar survey can penetrate through the leaves and branches of plants to capture the terrain. Relief filtering makes it possible to estimate the volume and, as a result, the biomass of wood above the surface [22]. However, UAV lidar surveys have limitations due to the low resolution of point clouds from the lower and middle parts of stems. Therefore, the best results in biomass estimation can be achieved by combining multispectral and UAV lidar surveys, as well as TLS [23].

The project to create carbon polygons in the regions of Russia for the development and testing of carbon balance control technologies should become one of the key elements in the development of a reliable national system for greenhouse gas flux monitoring in the ecosystems of Russia. The Republic of Tatarstan is one of the regions where the pilot project is being implemented, the “Volga Carbon” polygon will open in 2023. However, since 2022 Kazan Federal University (Kazan, Russia) has been conducting research work to develop and test carbon balance control technologies.

This article reflects the creation of a remote monitoring system as a mandatory part of the project. The formation of a remote data bank is carried out at two sites of the “Volga Carbon” polygon (Figure 1). Site 1 “Observatory” – located in the Zelenodolsk region of the Republic of Tatarstan, located in a phytocoenosis widespread in the European part of Russia - a broad-leaved forest, under anthropogenic pressure of medium intensity and with a long history of development. Site 2 “Saraly” – located in the Laishevsky region of the Republic of Tatarstan, on the territory of the Saraly site of the Volzhsko-Kamsky Nature Biosphere Reserve, is planned as an observation site for the Kuibyshev reservoir ecosystems.

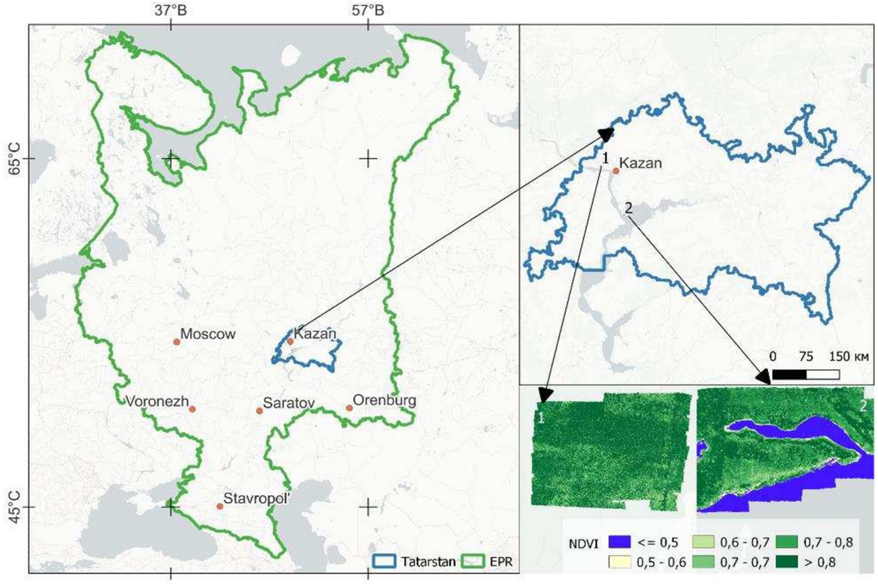

Fig. 1. Study area. Numbers indicate Site 1 “Observatory” and Site 2 “Saraly”. *Source*: Compiled by authors.

2 Materials and methods

Since work on the carbon polygon area has just begun, the main purpose of the article is to present the structure of remote monitoring of the polygon, show the results of the first year of remote research, and discuss the need to use other remote sensing methods.

To obtain a digital basis (orthophotomaps and DEMs) and monitoring observations in carbon polygon areas was solved. The GNSS UAV (quadcopter) Geoscan 401 Geodesia (Figure 2 a) equipped with a Sony RX1R2 camera, Micasense RedEdge-MX multispectral camera (Figure 2 b) and Lidar AGM MS-1 (Figure 2 c) was used. The flight was planned in Geoscan Planner software and carried out at a height of 150 m both above the forest and the water site to ensure proper stitching of the obtained images and, as a result, a clear image of the forest cover. UAV GNSS receiver data is recalculated based on data from the nearest base station of the high-precision positioning service using the PPK method in specialized geodetic software. Received images, as well multispectral images were processed in the Agisoft Metashape photogrammetric software. Lidar data was processed in Lidar 360 software.

Fig. 2. Geoscan 401 with Sony RX1R2 camera (a), RedEdge-MX multispectral camera (b), Lidar AGM MS-1 (c). *Source*: Compiled by authors.

The photogrammetry method cannot provide the construction of DTM underwater, therefore, to obtain a complete morphometric characteristic of the territory of the carbon polygon water area, a bathymetric survey was carried out [24]. The survey was carried out on a Flagman PVC boat and a Garmin GPS Map 178C echo sounder chart plotter with depth coordinate reference in the WGS 84 system. Data processing and depth mapping were carried out using the Golden Software Surfer sofware.

To provide the regional level of carbon polygon monitoring, the task of a space imagery data bank creation was solved. The main open remote sensing data for regional-level monitoring:

- Multispectral survey data from Sentinel 2 MSI and Landsat 8, 9 OLI.
- Sentinel 1 C-SAR radar data.
- Copernicus and MODIS vegetation indices and biophysical parameters.
- Phenological metrics Suomi NPP and NOAA-20 VIIRS (VNP22Q2).
- Open global land cover and land use models.
- High and ultra-high resolution images from Google Earth open sources.
- Open global DEMs.

3 Results

Works on remote monitoring of the Volga Carbon polygon test site started in 2022. As a result of the analysis of existing remote methods for studying carbon polygons and assessing the possibility of their use on the territory of the Volga Carbon polygon, a remote monitoring scheme was developed (Figure 3).

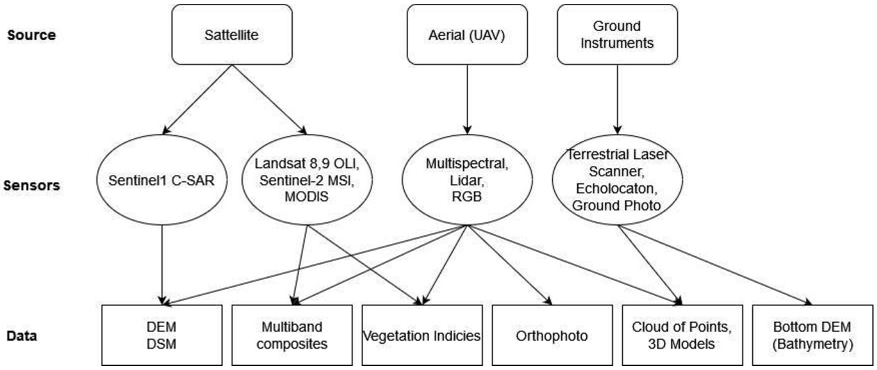

Fig. 3. Basic tools and data for organizing remote monitoring at the Volga Carbon polygon. *Source*: Compiled by authors.

Now remote sensing data is collected and processed, which is necessary at the initial stage. This step includes the creation of satellite data sets, field activity to obtain orthophotomaps, digital terrain and relief models, and UAV multispectral image time-series obtaining. A monitoring program for the next years of observation is also being developed with a description of the methods and obtained results.

3.1 Satellite data

Satellite data are being selected to extrapolate the predictors, relations, and trends of carbon sequestration identified within the polygon to the territory of the Republic of Tatarstan. For this, a vegetation map with a spatial resolution of 100 m using satellite data is created. In contrast to the existing global open models of land use and land cover, vegetation communities will be recognized as classes. However, such models will be used as reference or ancillary data, for example, as masks to exclude areas without vegetation. Thus, the Global Surface Water Explorer data [25] can be applied as a mask for water bodies, and GHS-BUILT-S (Global Human Settlement Layer) [26] for anthropogenic objects. Information on projective vegetation cover and canopy height also could be useful: Global Forest Change [27] and Global Land Cover and Land Use 2019 [28]. The approach implies the creation of a probability spatial model of vegetation communities based on two main blocks. The first one is the modeling of habitat conditions based on topographic indices of wetness, lighting, and warm distribution. These factors will be created using a digital elevation model. As the main data the DEM of the Tatarstan Republic at a scale of 1:200000 based on topographic maps will be used [29]. In addition, soil data will be used as one of the key factors in habitat conditions modeling. The second block is the recognition of vegetation types on a series of multi-season long-term data from Landsat 8 and 9 and Sentinel 2 [30]. To take into account phenological and biophysical features, data from Copernicus, MODIS, and VIIRS will be used [31-32]. The data of geobotanical descriptions from the "Flora"" database [33-34] will be used as a training set and control data. Combining the results obtained within the described two blocks will make it possible to create a vegetation communities model with high accuracy and detail.

3.2 Unmanned aerial vehicle

Unlike satellite data, the UAV allows to survey and obtains cloudless data with the required periodicity, and creates time-series for further analysis[35]. Initially, based on the results of the UAV survey with a Sony RX1R2 camera in the visible wave range, high-resolution orthophotomaps were obtained (Figure 4 a). Using these data and GIS, high-detailed plans of the polygon sites were created, as well as maps of the species composition of vegetation cover. In addition, the survey results are used to create a detailed digital terrain model (DTM) of the polygon using photogrammetry. To obtain a digital model of the relief under a forest canopy, considering problems to obtain accurate ground surface by photogrammetry in forest areas, use a low-altitude survey with the AGM MS-1 LIDAR. As a result, a digital model of the relief located under the forest cover and a tree height map were built (Figure 4 b). Obtained data will be used to calculate morphometric characteristics and to consider relief heterogeneities in the emission calculation. Moreover, DEM also used to calculate the forest canopy height by comparison with a digital surface model of the forested area (Figure 4 b).

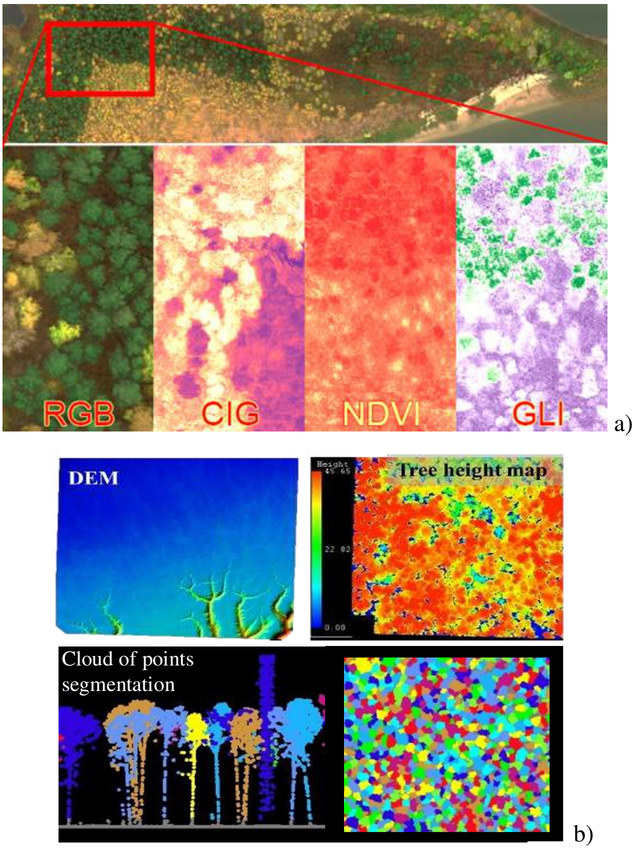

Fig. 4. Orthophotomaps and vegetation indicies (a) and results of AGM MS-1 LIDAR survey (b) for the forest site of the Volga Carbon polygon. *Source*: Compiled by authors.

Using the Lidar 360 application, the point cloud was segmented into individual trees, which made it possible to obtain morphometric characteristics of the crowns for subsequent determination of AGB (Figure 4 b).

An important role in ongoing research is given to spectrometric research. To analyze the spectral characteristics, a regular survey of the polygon territories is carried out with the Micasense RedEdge-MX spectral camera installed on the UAV. The NIR and Red Edge ranges are used to calculate vegetation indices. It allows us to find the dependencies between the vegetation indices and the biomass values, and, consequently, with carbon deposits in the polygon area and extrapolate the obtained results to territories with similar vegetation communities. In 2022, 6 surveys of the forest site were carried out. Figure 4 (a) shows an example of the obtained vegetation indices for a fragment of the forest site of the polygon.

3.3 Ground survey

On October 19, 2022, a bathymetric survey of a section of a channel on the territory of the Volga-Kama State Biosphere Reserve was carried out to obtain the bottom topography. Obtained data was also used to technically justify the organizing of the observation site on the water side of the Volga Carbon polygon. The dead-end channel is a flooded inter-ridge depression of the Volga River floodplain. At the survey site, many flooded stumps from cut-down trees are mapped (consequences of the territory preparation during the Kuibyshev reservoir creation in 1957).

In total, 3462 depth marks were accumulated during the survey. During postprocessing, 156 marks were rejected. The level of the water's edge on the date of the survey was measured as 51.2 m abs. (Baltic Height System). Based on the results of the survey, a bathymetric map was created (Figure 5).

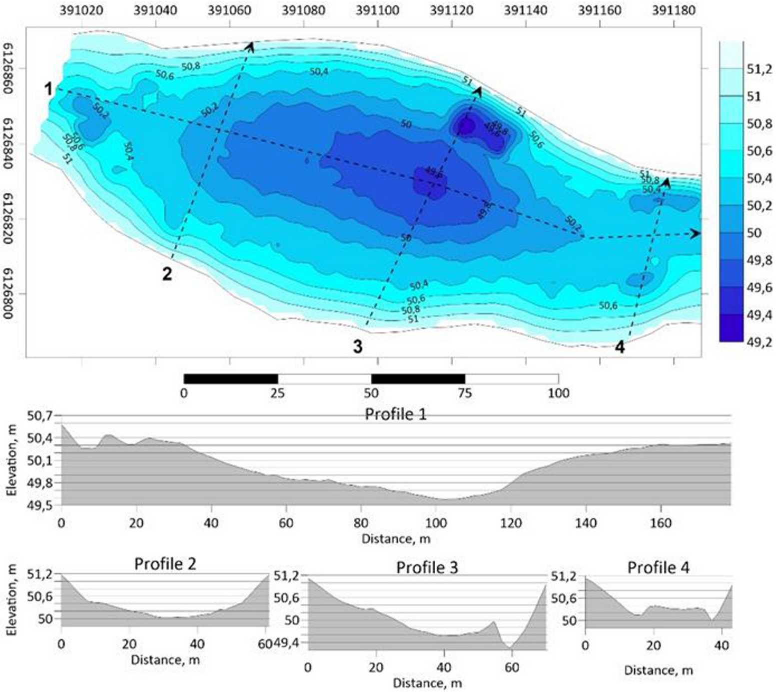

Fig. 5. Relief map of the bottom of the bay at the water site of the Volga Carbon polygon.
Source: Compiled by authors.

4 Discussion

As a result of the analysis of the available fund of aerial and space survey data and available remote sensing methods and based on the experience of observations of the carbon polygons, the authors of the article developed the structure of remote monitoring at the Volga Carbon polygon. In addition to the data presented in the scheme, it is supposed to use ready products, i.e., models of land cover and land use, and biophysical and phenological parameters [28].

As can be seen in Figure 3, the use of UAVs provides the largest data set at the local level, i.e., within the polygon sites. During the first year of data collection, orthophotomaps and DEMs were obtained for both polygon sections, and a digital model of the relief of the water section of the carbon polygon was constructed. The problem of construction of a high-resolution model of the relief in the forested areas can be solved using airborne laser scanning [21,35]. For this purpose, in 2023 an aerial lidar survey performed by AGM MS-1 laser scanner which allows surveying with 600000 points per second from 120-200 m altitudes. The use of aerial lidar surveys also makes it possible to successfully carry out an inventory of forest vegetation [36], estimate the trees' height [23], and calculate AGB [37].

A special place in the study of carbon polygons is occupied by using of multispectral images [20,38]. Using the Micasense RedEdge-MX camera installed on the UAV, a multispectral survey in 5 channels is carried out, which allows the calculation of various vegetation indices, which are actively used in biomass and carbon stock assessment. The world experience of research on carbon polygons has shown that the Chlorophyll Index (CIg), Normalized Difference Vegetation Index (NDVI), Green Leaf Index (GLI), and Soil-Adjusted Vegetation Index (SAVI) are the most representative indices for recognizing dominant species types [38,39]. Comparison of the time series of vegetation indices with regular field observations will make it possible to determine the relationship between the value of vegetation indices and the value of biomass stocks, and, therefore, with the carbon stocks in the study area of the polygon and to extrapolate the obtained results to the areas with similar vegetation communities.

A multispectral survey of the water section of the Carbon polygon is planned in 2023, together with field observations, which will make it possible to estimate vegetation properties of aquatic vegetation, as well as to monitor aquatic phytomass by calculating appropriate indices and comparing them with data from field studies [25].

Recognition of undergrowth formed by forests and shrubs is planned by lidar surveys from UAVs and ground-based laser scanning to control lidar data in key areas. Also, biomass estimation will be conducted at key sites using the well-proven forestry software Katam Forest™ [18], which allows partially automated collection of information on wood diameter using video from a quadcopter or smartphone.

5 Conclusion

The technological scheme of the organization of the complex system of carbon balance monitoring at two levels was created: local (within the polygon) and regional (Republic of Tatarstan). On the local level, the main sources of data will be surveys from UAVs by various sensors (multispectral, lidar, etc.) and ground instruments (TLS, Katam™, side-scanning sonar (SSS), etc.). Based on the patterns of carbon sequestration identified at the test site spatial models on a regional scale will be built. Here, a set of modern satellite data obtained by different imaging systems will be used as the main data. The complexity of the scheme used and considering different levels of generalization at all stages from the collection of information to the presentation of the results, as well as considering international experience in assessing the carbon balance, which will allow to obtain adequate estimates of the sequestration potential of the areas under study, as well as to extrapolate it to other regions.

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