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Machine Learning in the Analysis of Carbon Dioxide Flow on a Site with Heterogeneous Vegetation

Ekaterina Kulakova * and Elena Muravyova

Department of Automated Technological and Information Systems, Institute of Chemical Technology and Engineering, Ufa State Petroleum Technological University, Sterlitamak 453103, Russia; muraveva_ea@mail.ru
* Correspondence: kulakova87@list.ru

Abstract: The article presents the results of studies of carbon dioxide flow in the territory of section No. 5 of the Eurasian Carbon Polygon (Russia, Republic of Bashkortostan). The gas analyzer Sniffer4D V2.0 (manufactured in Shenzhen, China) with an installed CO_2 sensor, quadrocopter DJI MATRICE 300 RTK (manufactured in Shenzhen, China) were used as control devices. The studies were carried out on a clear autumn day in conditions of green vegetation and on a frosty November day with snow cover. Statistical characteristics of experimental data arrays are calculated. Studies of the influence of temperature, humidity of atmospheric air on the current value of CO_2 have been carried out. Graphs of the distribution of carbon dioxide concentration in the atmospheric air of section No. 5 on autumn and winter days were obtained. It has been established that when building a model of CO_2 in the air, the parameters of the process of deposition by green vegetation should be considered. It was found that in winter, an increase in air humidity contributes to a decrease in gas concentration. At an ambient temperature of 21 °C, an increase in humidity leads to an increase in the concentration of carbon dioxide.

Keywords: air; greenhouse gas; carbon dioxide; carbon landfill; models; distribution

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Citation: Kulakova, E.; Muravyova, E. Machine Learning in the Analysis of Carbon Dioxide Flow on a Site with Heterogeneous Vegetation. *Information* **2023**, *14*, 591. https://doi.org/10.3390/info14110591

Academic Editor: Francesco Fontanella

Received: 7 August 2023
Revised: 29 August 2023
Accepted: 12 September 2023
Published: 1 November 2023

1. Introduction

The issue of climate change, particularly the study of the movement of CO_2 in the atmosphere and its impact on various sectors of the national economy, is the focus of international laboratories [1]. These laboratories utilize data from remote sensing, as well as data collected by stationary and mobile climatic laboratories.

Remote sensing is a passive method for monitoring the content of carbon dioxide in the air over long distances [2]. Satellite observation using the near infrared (NIR) and shortwave infrared (SWIR) spectra from space allows monitoring the target area on a larger scale and for a longer period of time than ground-based operations [3]. In 2009, Japan launched the world's first Greenhouse Gas Observation Satellite (GOSAT), which was equipped with a Fourier Transform Spectrometer (FTS) and Cloud and Aerosol Imaging (CAI) [4]. Then, in 2014, the United States launched the Orbital Carbon Observatory (OCO-2), which was equipped with three high-resolution spectrometers [5,6]. The Sentinel satellite systems, EC Copernicus programs, monitor the Earth's surface in any weather, changes in the surface of the land, ocean, and measure atmospheric gases at various altitudes.

Based on data from the GOSAT and OCO-2 satellites, Japanese scientists have obtained the MICROS-ES2L, MICROS4-Inv models [7]. An increase in the content of greenhouse gases in Malaysia was revealed based on the data of the GOSAT, GOSAT-2, OCO-2, and TROPOMI satellites [8].

The data obtained from the Sentinel-2 satellite were used for the annual change in the primary gross productivity of carbon dioxide in the mangrove forests of Tahura Ngurah Rai (Bali, Indonesia) [9]. It was found that in 2018 the productivity decreased due to changes in the soil cover and the death of mangroves around the port of Benoa.

Global networks of micrometeorological towers enable the measurement and accumulation of data on the levels of climatically active gases in different regions of the planet. One of the largest and most renowned networks is Fluxnet, established by the Lawrence Berkeley National Laboratory [10]. It operates as an eddy covariance station, continuously measuring carbon fluxes within ecosystems. Using this data, studies have been carried out to analyze the daily variations in carbon dioxide, water vapor, and the processes influencing them [11].

The Japanese Forestry Research Institute established the FFPRI FluxNet network to monitor the fluxes of heat, water vapor, and carbon dioxide in the Kawagoe forest: broadleaf forest (Sapporo), beech forest (Appi), temperate deciduous forest (Kawagoe), pine forest (Fujiyoshida), warm-temperate mixed forest on difficult terrain (Yamashiro), and coniferous forest on difficult terrain (Kahoku) [12].

Studies were carried out on the basis of data from stationary monitoring stations. A group of scientists from China from the Institute of Oceanology of the Chinese Academy of Sciences estimated the change in the flow of carbon dioxide between the sea and atmospheric air based on the CMIP6 climate model. It has been established that since 1980, there has been a consistent increase in the global absorption of CO_2 by the oceans [13].

Swedish scientists from Linköping University conducted experiments on changing the concentration and rate of carbon dioxide and methane transport on four boreal lakes: Ovre Björntjärnen, Sörsjön, Bolen, and So ÖdraTeden. It was found that the flow of CO_2 was 1.7 times greater than that of CH_4 [14].

A group of researchers from Uppsala University and the Swedish University of Agricultural Sciences based on 2013–2021 data. The Swedish marine Integrated Carbon Observation System (ICOS) station estimated the CO_2 flow over the Baltic Sea. It has been established that at high and low wind speeds there is a gas exchange of water-yes-air. The seasonality of the gas flow was established [15].

The effect of permafrost on the flow of carbon dioxide was evaluated by Russian scientists. The experiment was carried out using the chamber method. It has been established that the gas flow over the forest ecosystem is higher than on peat soils. With an increase in air temperature, the flows over different ecosystems level out [16]. In addition, Finnish scientists from the Natural Resources Institute Finland (Luke) conducted studies on the balance of CO_2 in forest soils and peatlands. A trend towards an increase in the gas flow on drained forest soils of peat bogs was established [17].

USA scientists studied CO_2 and H_2O fluxes in a deciduous forest based on data from the Environment Canada research station. Gas isotope ratios were calculated [18].

Based on the data of discrete control devices, Korean scientists assessed the impact of livestock farms on carbon dioxide emissions. Korean scientists have assessed the impact of livestock farms on carbon dioxide emissions using machine learning models, including ElasticNet, RFR, and SVR. They found that the random forest model provides the best reproducibility of the experimental data [19].

Scientists at the Hong Kong Polytechnic University have developed an integrated system for capturing and removing carbon dioxide from living quarters [20].

Indian scientists at Ghent University and the Indian Institute of Technology, Bombay, have developed a laminar flow model for a mixture of $H_2/CO/CH_4/CO_2/N_2/$in air at high temperatures and pressure. The resulting multiple regression is consistent with the predictions of the FFCM-1 kinetic model. The error is less than 10% [21].

There are territories where it is impossible to install stationary equipment, for example, due to the lack of proximity to communication facilities. In these cases, unmanned aerial vehicles have been widely applied. For example, they have been used to study the content of SO_2 and CO_2 in volcanic gases [22]. Scientists have developed an intelligent air quality monitoring system based on an unmanned aerial vehicle [23].

In order to implement the order of the Ministry of Science and Higher Education of the Russian Federation No. 74, dated 5 February 2021, on test sites for the development and testing of carbon balance technologies, in 2022 the Eurasian Carbon Polygon was created in the territory of the Republic of Bashkortostan. Currently, there are operating ranges in many administrative territories of Russia. Scientists in Moscow, Novosibirsk, Voronezh, Sverdlovsk, and other regions are studying the problem of climate change and the technical equipment of laboratories for studying the movement of greenhouse gases.

A polygon was created on the territory of the North Caucasus to study the flows of climatically active gases [24]. Scientists are conducting research to determine the flow of CO_2 from oil-contaminated lands [25]. It has been established that an increase in air temperature leads to an increase in the flow of climatically active gas. The turbulent method was used to obtain CO_2 and CH_4 fluxes in the swamps and forests of Northern Eurasia [26].

In Western Siberia, the content of CO_2 and CH_4 in groundwater was estimated by gas chromatography. It was revealed that carbon dioxide prevails in segregation and repeated-wedge ice, and methane prevails in the segregation-migration ice of heaving mound and wedge-shaped ice [27]. In the territory of the Sverdlovsk region at the Kourovskaya Astronomical Observatory, named after K. A. Barkhatova (KAO), researchers have conducted studies on CO_2 and CH_4 using giant chambers [28].

In their publications, researchers share their experience in using various methods for monitoring climate-active gases [29]. Russian scientists at Lomonosov Moscow State University have obtained a model of carbon dioxide transport over a forest. It is based on hydrodynamic and diffusion processes in atmospheric air [30]. A linear mixed effect model has been developed, which, without considering random factors, makes it possible to predict with an accuracy of 47% [31].

The existing studies of scientific laboratories are aimed at studying the parameters of gas flows in a homogeneous area: a swamp, surface water bodies, and forests with homogeneous vegetation. In such studies, the influence of external sources is constant from various directions. The chemical composition of water bodies on the surface in a diameter of 200 m from the observation point is constant. There are no external barriers as the height of the vegetation is the same. This is similar for broad-leaved coniferous forests and swamps. Further development of research is aimed at studying the flows of climatically active gases over a heterogeneous surface. The territory can be characterized by a junction of several ecosystems: the transition of a broad-leaved forest with a coniferous one, the coastal territory of a river, the sea, etc. There are no studies in this direction.

One of the sections of the Eurasian Carboniferous Polygon has a complex structure. It is located near the reservoir, and is characterized by heterogeneous vegetation. The installation of a stationary monitoring station does not allow one to study the carbon balance of each type of flora. Therefore, the use of a mobile gas analyzer with an unmanned aerial vehicle is the best method of research in this area.

The aim of the study is to analyze the flow of carbon dioxide at the site of the Eurasian Carboniferous Range using a gas analyzer and an unmanned aerial vehicle.

2. Materials and Methods

The object of the study is the territory of the educational research and development enterprise "Soluni" (Bashkortostan Republic, Russia) (Figure 1). The area spans 10 ha and the height above sea level is 159 m. It is a water protection zone of the Pavlovka reservoir.

The site is characterized by the following vegetation: dark coniferous-deciduous forests with Siberian spruce, Siberian fir, heart-leaved linden with a grass tier of tall wrestler, forest vine, common pine, broad-leaved boron, Siberian skerdy, under-ripe spear-leaved, common sourdough, and European weekling. The Pavlovskoye reservoir of the channel type is located next to the site.

The territory is an erosion-accumulative terrace of the Ufa River valley on sod-calcareous (including leached and podzolized) soils. The site is characterized by the following vegetation: dark coniferous-broad-leaved forests with Siberian spruce, Siberian fir, little-leaved linden, forest reed grass, goutweed, spreading millet grass, Siberian hawks-beard, spear-leaved cacalia, wood-sorrel oxalis, and European starflower. The Pavlovka reservoir of the channel type is located near the site. The study used a quadrocopter flying around the territory with a gas analyzer installed on it, recording the CO_2 content in the atmospheric air.

Figure 1. Territory of the site.

The gas analyzer Sniffer4D V2.0 (manufactured in China, Shenzhen) with an installed CO_2 sensor was used as the control device.

DJI MATRICE 300 RTK quadcopter (manufactured in China, Shenzhen) was used as the aircraft.

The studies were carried out on 23 September 2022 and 22 November 2022.

The meteorological conditions under which the measurements were taken are shown in Table 1.

Table 1. Meteorological conditions of the research.

Date	Temperature, °C	Atmospheric Pressure, mm Hg	Humidity, %	Wind Direction	Wind Speed, m/s	Total Cloudiness	Horizontal Visibility, m
23 September 2022	21.0	759	46	Wind blowing from the east-southeast	3	No significant cloudiness	10.0 and more
22 November 2022	−5.3	768	73	Wind blowing from the east-northeast	1	90 or more, but not 100%	10.0 and more

The time series obtained as a result of the experiment on 23 September 2022 and 22 November 2022 were used as initial data. They contain the following information: date and time of measurement, CO_2 concentration in ppm, humidity, ambient air temperature at the measurement point, and measurement height.

The article calculates the statistical characteristics of the CO_2 concentration time series recorded on 23 September 2022 and 22 November 2022: mathematical expectation, standard deviation, median, mode, skewness, and kurtosis. Graphs of the distribution of the time series are constructed. The Harke–Beer test was carried out for the correspondence of the experimental data to the normal distribution.

Processing of the initial data was carried out. Summary data were obtained, according to measurements on 23 September 2022 and 22 November 2022, on the average concentration of CO_2 at different heights, different temperatures, and atmospheric humidity. Their stationarity was estimated based on the Dickey–Fuller test.

Linear regression was used as the machine learning method. Models of the dependence of the average concentration of CO_2 on altitude, humidity, temperature, and pressure of the atmospheric air were obtained. To confirm the comparability of models and initial data, the Abbe–Linnik test and the correlation coefficient were used.

A selection of two arrays of experimental data on the concentration of CO_2 over the territory of low-growing herbaceous vegetation and trees was used. For these selections, models of the change in gas concentration at different measurement heights were constructed. The models were evaluated using the correlation coefficient.

3. Results

A flyby map of the territory was obtained in a two-dimensional (Figure 2) and three-dimensional plane (Figure 3).

Figure 2. Two-dimensional map of the flyby of the territory.

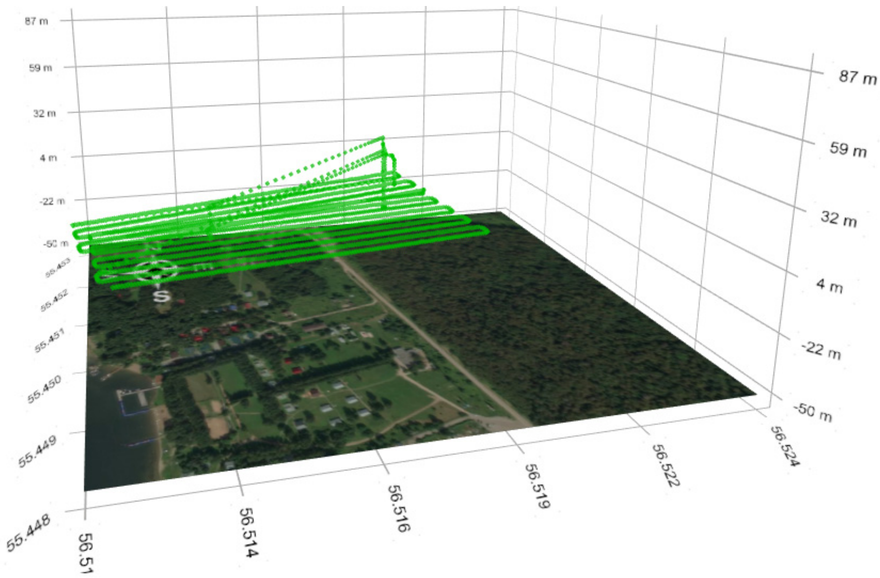


Figure 3. Three-dimensional map of the flyby of the territory.

A calculation of the statistical indicators of arrays of the analytical data obtained on 23 September 2022 and 22 November 2022 was carried out (Table 2).

Table 2. Meteorological conditions of the research.

Date	Mx[CO_2], ppm	Σx[CO_2], ppm	Me[CO_2], ppm	Mo[CO_2], ppm	As[CO_2]	Es[CO_2]
23 September 2022	355.042	1.208	354.771	354.771	0.071	0.010
22 November 2022	468.927	75.743	458.007	458.007	77.435	7.516

Note. mx—mathematical expectation, σx—standard deviation (SD), Me—median, Mo—mode, As—skewness, Es—kurtosis.

On a clear September day, the content of carbon dioxide in the air was 75% lower than at the end of November. Moreover, the SD of the CO_2 array on 23 September 2022 was 62 times lower than on 22 November 2022. The increase in the variation in carbon dioxide content is due to the influence of a large number of highly variable factors. However, the list of parameters that affect the carbon balance of the territory does not change over the year. The index of the influence of each factor on the content of climatically active gas was reevaluated. Let the current value of CO_2 concentration be influenced by n factors with specific gravity K_i. Then, the sum of all coefficients is equal to one:

$$\sum_{i=1}^{n} K_i = 1, \tag{1}$$

where K_i is the specific coefficient of influence on the value of gas concentration in the air.

Then, the carbon dioxide content will be the following equation:

$$C_{co2} = K_1 \cdot x_1 + \ldots + K_n \cdot x_n, \tag{2}$$

where $x_1, \ldots, x_n$ is the factor score; C_{co2} is the carbon dioxide concentration.

Moreover, the factors x_n mean the influence of both individual factors; for example, temperature y1 or atmospheric humidity y2, and their combined influence y1•y2.

The main factors influencing the content of carbon dioxide in the air of an area remote from human economic activity are meteorological and biotic. Biotic parameters are understood as the sequestration ability of vegetation or as the emanation of soil gases. The meteorological data includes the temperature, humidity of the air, atmospheric pressure, wind direction, and wind speed.

An analysis of the changes in the main parameters for the current content of carbon dioxide in the atmospheric air was carried out.

Table 3 shows that according to the data as of 23 September 2022, α11 + α12 + α13 + α14 + α15 + α16 + α17 = 1. When weather conditions change, namely, a decrease in atmospheric air temperature, the appearance of snow cover, the absence of active foliage on trees, and the number of factors influencing the gas composition of the atmosphere changes, α21 + α22 + α23 + α24 + α25 = 1. Thus, the values of the coefficients, the influence that disappears, are redistributed among the remaining parameters.

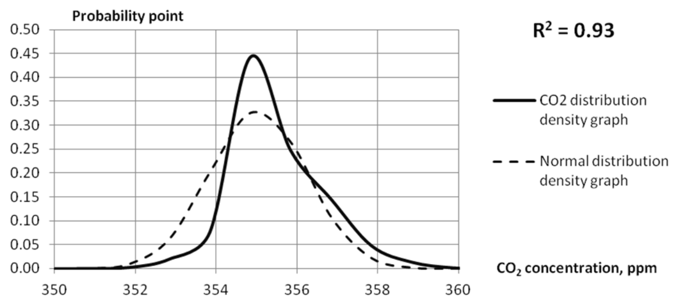
Table 3. Meteorological conditions of the research.

Parameter	Coefficient	Value		Grade
		On 23 September 2022	On 22 November 2022	
Air temperature	K1	α11	α21	α21 > α11
Air humidity	K2	α12	α22	α22 > α12
Air pressure	K3	α13	α23	α23 > α13
Wind direction	K4	α14	α24	α24 > α14
Wind speed	K5	α15	α25	α25 > α15
Emanation of aboveground gases	K6	α16	α26	α16 → 0
Plant sequestration	K7	α17	α27	α16 → 0

According to the obtained results, the influence of parameters α16 and α17 is decisive during the vegetation period of plants (α_16, α_17 ≫ α_11, α_12, α_13, α_14, α_15). They have a constant and unchanging influence throughout the growing season. This causes a low value of the standard deviation of the data array as of 23 September 2022. Meteorological parameters, which are the determining factors of influence in the winter period, are highly variable. Therefore, the CO_2 concentration dataset also has a high SD value.

According to the statistical characteristics (Table 1), the dataset obtained in September has a normal distribution: mx[CO_2] ≈ Mo[CO_2] = Me[CO_2], As[CO_2] ≈ Es[CO_2] ≈ 0. The distribution of data recorded in November differs from the normal one: mx[CO_2] ≠ Mo[CO_2] = Me[CO_2], As[CO_2] >> 0, Es[CO_2] >> 0.

Graphs of the distribution of carbon dioxide concentration in the atmospheric air of the site on 23 September 2022 and 22 November 2022 were obtained (Figure 4).



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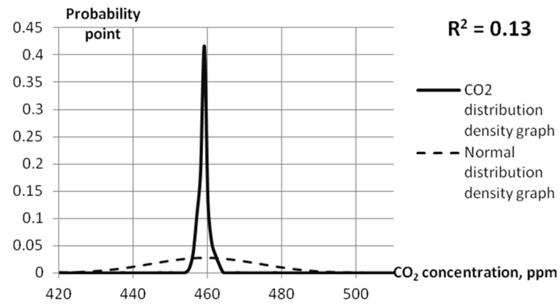


(**b**)

Figure 4. Graphs of the distribution function of the concentration of carbon dioxide in the atmospheric air of section No. 5: (**a**) according to the data registered on 23 September 2022; (**b**) according to data registered on 22 November 2022.

According to Figure 4a, the CO_2 distribution density plot in the presence of active vegetation corresponds to a normal distribution. Moreover, this is confirmed by the Harke–Beer test (JB = 0.614, p-value = 0.88). Figure 4b shows that the distribution of CO_2 during the cold season is not Gaussian. Values of indicators of the Harke–Beer test: JB = 2235602, p-value = 0.00.

It was found that 93% of the graph of the distribution of CO_2 concentration during the growing season coincides with the normal distribution. During the absence of green vegetation, the distribution function of the experimental data is comparable to the Gaussian by 13%.

The graph of the distribution of carbon dioxide content in the air of the Eurasian Carbon Polygon is as follows:

$$f(x) = \frac{1}{2\pi \cdot 1.208} e^{-\frac{(x-355.042)^2}{2\cdot(1.208)^2}} \tag{3}$$

A study was carried out on the change in the concentration of carbon dioxide depending on the height (Figure 5). Linear models of the dependence of the average CO_2 concentration on altitude above sea level were obtained by machine learning. The input data are the values of heights, and the output data are the average concentrations of carbon dioxide.

According to the data obtained during the vegetative period, at different altitudes, the average content of carbon dioxide varies in the range 353. . .358 ppm. The variation is 8 ppm, or 2.2%. During the period of snow cover, the climatically active gas at different heights varies in the range 355–687 ppm. The variation is 332 ppm or 48%. To test the stationarity of the time series of average values of carbon dioxide concentration at each height, the Dickey–Fuller test was carried out. For the time series of data for September, DW = −6.6, which is less than the critical value of −2.59. Therefore, there are no unit roots, and the series is stationary. The value of the test parameter for November data is DW = 2.9, which is more than the critical value of −2.77. The series is non-stationary. This indicates the multiplicity of random factors influencing the change in CO_2 concentration. The absence of a linear relationship is confirmed by the Abbe–Linnik test. Regarding the data for September, the parameter $q = 0.67 > q_{table} = 0.61$; for November, $q = 0.91 > q_{table} = 0.77$.

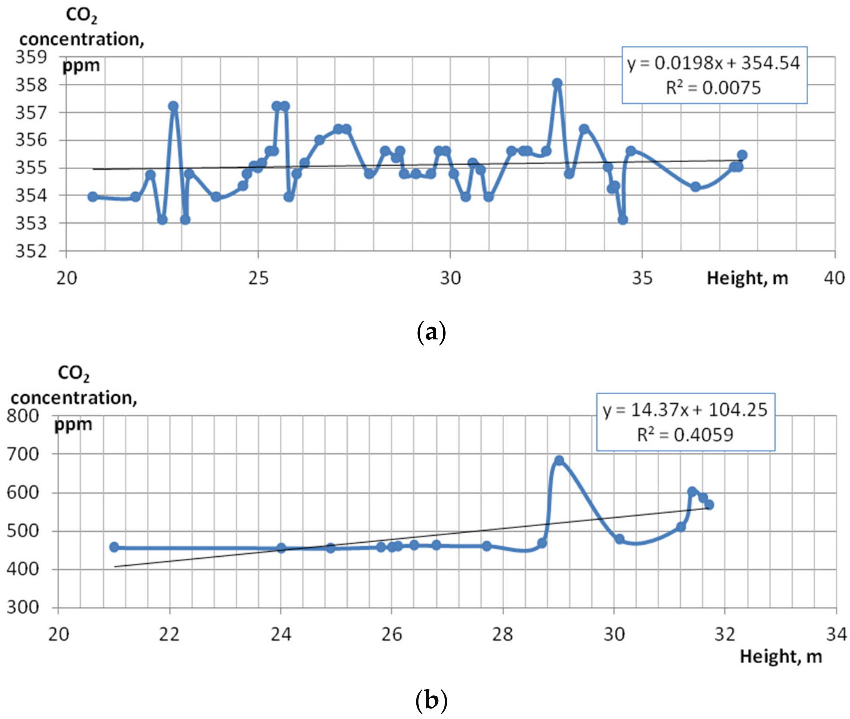


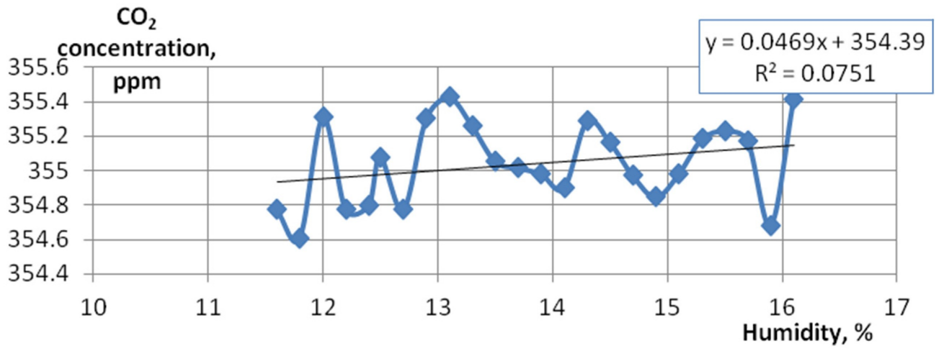
Figure 5. Diagrams of changes in CO_2 concentration depending on the measurement height: (**a**) according to the data registered on 23 September 2022; (**b**) according to data registered on 22 November 2022.

Thus, the presence of an active depositing component (green plants) determines the movement of CO_2 during the vegetative period. The influence of other factors is less than the sequestration process. In winter, the nature of the behavior of the climatically active gas coincides with other gases of global distribution present in the atmospheric air.

A study was carried out on the effect of air humidity on the content of carbon dioxide (Figure 6). Linear models of the dependence of the average CO_2 concentration on atmospheric air humidity were obtained by machine learning. The input data are the values of humidity, and the output is the average concentration of carbon dioxide.

Statistical testing for the presence of a trend in time series of average values of carbon dioxide concentration at different atmospheric air humidity was carried out based on the Abbe–Linnik criterion. For data for September, the parameter $q = 0.93 > q_{table} = 0.68$; for November, $q = 0.61 < q_{table} = 0.67$. So, a significant influence of humidity on the current value of CO_2 concentration in the atmospheric air has been established for the winter period. The substance content decreases with the increasing humidity. The strength of the connection is 0.42, which is significant in conditions of strong stochasticity in the change in the content of substances in the atmospheric air. During the vegetative dry period, a low degree of influence of humidity on the content of carbon dioxide was established. However, there is a slight increase in the concentration of the substance with increasing humidity.

Checking the time series of average values of carbon dioxide concentration at different atmospheric humidity based on the Dickey–Fuller test indicates the stationarity of the data obtained in September (DW = −4.5 < DWcritical = −2.63), and non-stationarity in November (DW = −0.79 > DWcritical = −2.67). The established linear relationship between humidity data and CO_2 concentration is one of the reasons for the non-stationarity of the time series.



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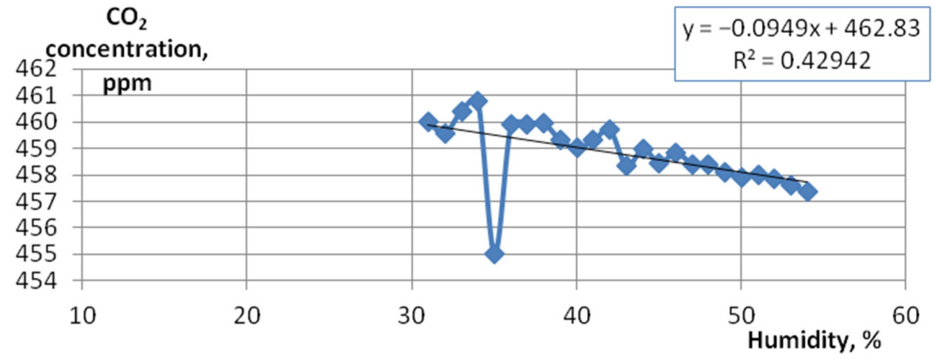


(**b**)

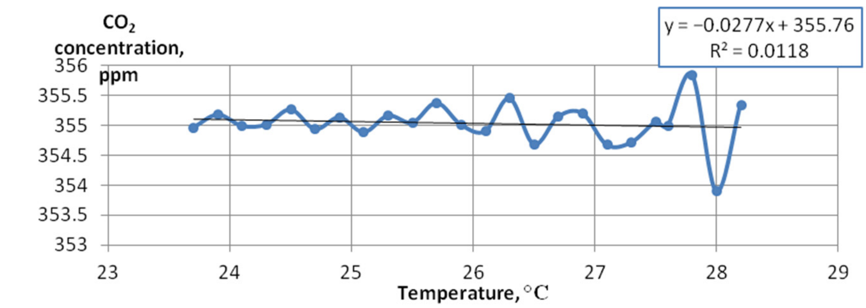
Figure 6. Diagrams of changes in CO_2 concentration depending on the humidity of the atmospheric air: (**a**) according to the data registered on 23 September 2022; (**b**) according to the data registered on 22 November 2022.

A study was carried out on the effect of air temperature on the content of carbon dioxide (Figure 7). Linear models of the dependence of the average concentration of CO_2 on the temperature of the atmospheric air were obtained using the machine learning method. The input data are the temperature values, and the output data are the average concentrations of carbon dioxide.

According to the data obtained, on the territory of section No. 5, the variation in air temperature during the growing season was 4.5 °C, in winter −10 °C. Dependence graphs show that in the presence of sunlight and green vegetation, with an increase in air temperature, the variation in the average content of carbon dioxide increases. At 24 °C the variation is 0.2 ppm, and at 28 °C it is 2 ppm. Similarly, in winter, the variation at −8 °C is 0.1 ppm, and at 0 ° it is C − 2 ppm.

According to the graph of the influence of air temperature on the CO2 content of section No. 5, during the warm period, a decrease in gas concentration with an increase in temperature is noted, despite an increase in variation. In the cold period, on the contrary, with an increase in temperature, the concentration of carbon dioxide increases.

The absence of a linear dependence of the time series of average values of carbon dioxide concentration in September at different temperatures is confirmed by the Abbe–Linnik test: $q = 1.52 > q_{table} = 0.67$. In November, according to the statistical test, there is a linear relationship between the average gas concentration and temperature: $q = 0.48 < q_{table} = 0.76$.



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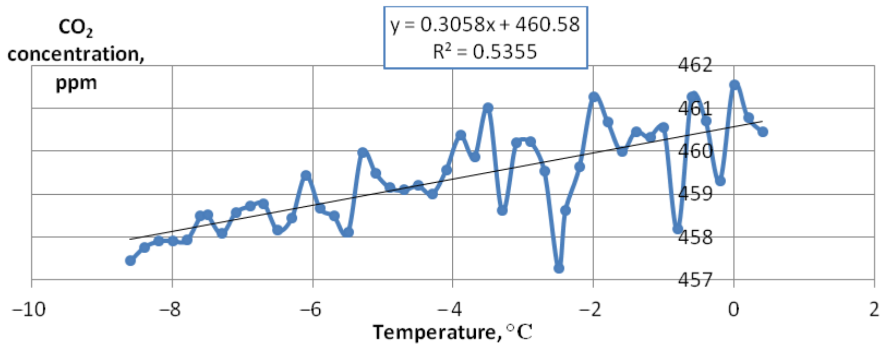

(**b**)

Figure 7. Diagrams of changes in CO_2 concentration depending on the temperature of the atmospheric air: (**a**) according to the data registered on 23 September 2022; (**b**) according to the data registered on 22 November 2022.

According to the Dickey–Fuller test, the time series of average values of carbon dioxide concentration in September at different temperatures is stationary (DW = −2.70 < DWcritical = −2.69), and in November it is non-stationary (DW = 1.24 > DWcritical = −2.60).

The territory of section No. 5 is heterogeneous. It has a reservoir, areas with tree plantations, and areas with grassy vegetation. An analysis of the average concentration of carbon dioxide in various parts of the territory was carried out. To do this, the entire area of the section was conditionally divided into six parts. The average values of the CO_2 concentration are shown in Figure 8.

Figure 8. Scheme of the territory indicating the average concentration of CO_2 in various areas according to the data as of 23 September 2022.

The highest average concentration of carbon dioxide in the atmospheric air is observed in areas with low vegetation. The lowest average CO_2 values are observed in two sites: one is characterized by the presence of tall trees (1); the second is an area with grassy vegetation (2). The remarkable thing is that the second site is surrounded by trees.

Studies have been carried out to identify the nature of the behavior of the gas inside the area surrounded by tree-like plants. The statistical characteristics of the array of values of carbon dioxide concentration in sections No. 1 and No. 2 are calculated (Table 4).

Table 4. Meteorological conditions of the research.

Section No.	Mx[CO_2], ppm	Σx[CO_2], ppm	Max[CO_2], ppm	Min[CO_2], ppm
1	354.93	1.19	359.68	350.67
2	354.95	1.24	358.04	351.49

As can be seen, using the same average value of CO_2 concentration in sections No. 1 and No. 2, the standard deviation and maximum and minimum values diverge. The greatest variation is noted for the site with tall plants. This may be due to the different sequestration capacity of trees in the study area.

The change in the concentration of climatically active gas depending on the height is considered. Linear models of the dependence of the average CO_2 concentration in sections No. 1 and No. 2 on height were obtained using machine learning. The input data are the height values, and the output is the average concentration of carbon dioxide.

In each of the territories under consideration, an increase in the concentration of carbon dioxide with height was found (Figure 9). However, for an area characterized by high stands, a significant decrease in gas concentration is observed at a height of 28 m. From a height of 30 m, the content of a substance in the air increases. This may be due to the influence of the phenomenon of carbon dioxide sequestration by the trees. In plot 2, characterized by low-growing plants, there is an abrupt change in gas concentration with height above the earth's surface. However, there is a clear trend towards an increase in CO_2 content with height.

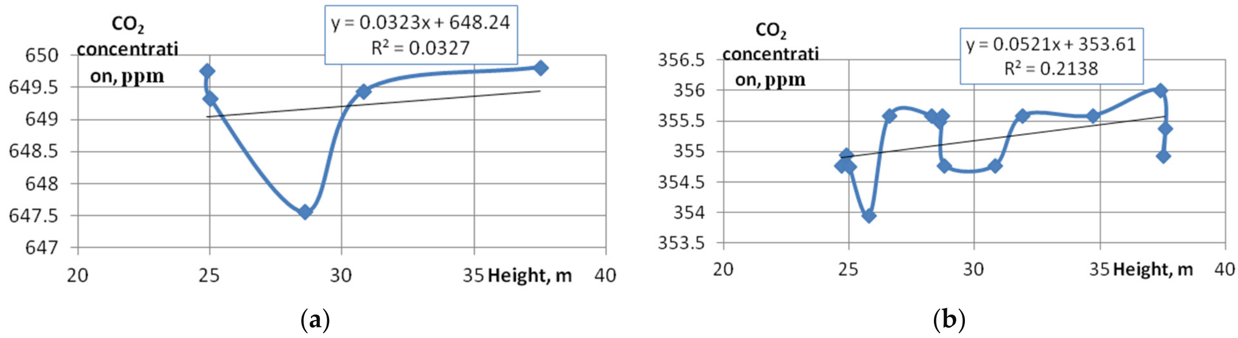

Figure 9. Diagrams of changes in CO_2 concentration depending on height in different areas: (**a**) Section No. 1; (**b**) Section No. 2.

4. Conclusions

A study was carried out to measure the concentration of CO_2 in the air in a territory with a complex terrain and heterogeneous vegetation. It is characterized by the proximity of a reservoir, the presence of separate trees, or a group of them.

The annual pattern of carbon dioxide concentration in the atmosphere is characterized by a decrease during the growing season and an increase in the winter. The difference is statistically significant, accounting for 75%.

A probabilistic model of the CO_2 changes in the air in autumn was developed. Namely, the content of gas during the presence of active green vegetation is determined using the normal distribution law. In the presence of snow cover and the absence of an active process of greenhouse gas storage, the distribution differs from the Gaussian one. The stationarity of the CO_2 concentration data in September and the non-stationarity of the November data are confirmed by the Dickey–Fuller test.

Using the machine learning method, linear models of the change in the average CO_2 concentration from various parameters were obtained. Based on the Abbe–Linnik test and correlation analysis, a linear effect of air temperature and humidity on the change in the average gas concentration in the air during the absence of active vegetation was established.

During the active process of carbon dioxide sequestration by vegetation, the main factor determining the current value of gas concentration is the dynamics of photosynthesis. Thus, when building a CO_2 model in the air, the parameters of the process of deposition by green vegetation should be considered.

The study made it possible to establish the relationship between meteorological parameters and CO_2 concentration in different climatic periods of the year in a territory with a complex landscape. The study revealed the influence of meteorological factors on the change in CO_2 concentration in the air. In winter, an increase in humidity contributes to a decrease in gas concentration. At an ambient temperature of 21 °C, an increase in humidity leads to an increase in the concentration of carbon dioxide. In the presence of snow cover, an increase in temperature contributes to an increase in CO_2. Depending on the altitude, the concentration of carbon dioxide also changes. In winter, the effect of altitude has not been unequivocally established.

Author Contributions: E.K., data curation; review, and editing; formal analysis; investigation. E.M., funding acquisition; data collection. All authors have read and agreed to the published version of the manuscript.

Funding: The publication was carried out within the framework of the state task of the Ministry of Science and Higher Education of the Russian Federation on the topic "Program for the creation and functioning of a carbon polygon in the Republic of Bashkortostan" Eurasian carbon polygon "for 2022–2023 (Publication number: FEUR-2022-0001).

Institutional Review Board Statement: The study was conducted and approved by the Ufa State Petroleum Technological University.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest.

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