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The Impact of Beach Wrack on Greenhouse Gas Emissions from Coastal Soils

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Abstract: The existing management strategies of macrophyte beach wrack are not always environmentally sound. In this study, we tried to assess the impact of the presence or absence of macrophyte beach wrack on the CO_2 flux and the possibility of creating an environmentally sound recycling of macrophyte beach wrack based on their removal from the beach and processing into biochar. The study was conducted on the coast of the Sea of Japan in the bay of Kievka. The Picarro G4301 portable laser gas analyzer was used to measure CO_2 fluxes in areas with and without macrophyte beach wrack. The CO_2 flux was 23 times higher at plots with macrophyte beach wrack, compared with plots without macrophyte beach wrack. In the plots after manual removal of the macrophyte beach wrack, on average, there was a 1.6-fold decrease in flow values compared to the plots with the macrophyte beach wrack. Considering the frequency of emissions in the study area, which is associated with frequent cyclones and storms, it is possible to organize the systematic cleaning of macrophyte beach wrack for the production of biochar. Creating projects based on the conversion of macrophyte beach wrack into biochar can have both environmental and economic benefits. The environmental benefits include the reduction of CO_2 flux at plots after manual removal of macrophyte beach wrack; the long-term storage of carbon from macrophyte beach wrack biomass in the form of biochar; and the reduction of CO_2 flux from soils (carbon sequestration) with the correct technology of introducing biochar into the soil. However, for a more accurate assessment, monitoring seasonal measurements and economic calculations of the entire technological chain of production, risks, and footprint are necessary.

Keywords: marine macrophytes; macrophyte beach wrack; algae; biochar; carbon dioxide; coastal marine ecosystems; Sea of Japan

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1. Introduction

Currently, marine macrophytes are one of the areas of research within the framework of the climate agenda. According to a report by the United Nations Global Program, "Seaweed is arguably one of the most scalable nature-based solutions, offering opportunities for both decarbonization of the economy and carbon capture from the ocean surface" [1,2].

Macrophyte beach wrack is found all over the world throughout the year [3]. Macrophyte beach wrack is a material that accumulates on beaches as a result of storms, tides, tides, and wave phenomena and consists mainly of organic remains of algae and animals with admixtures of inorganic material (both natural and anthropogenic) [4]. For marine ecosystems, the presence of algae residues on beaches is natural, important, and beneficial [5]. For example, the remains of marine macrophytes participate in the nutrient cycle and serve as a habitat for marine and coastal animals [4]. Nevertheless, the presence of the macrophyte beach wrack in tourist areas is a problem, as it can be unsafe and unaesthetic [5]. Research shows that people perceive macrophyte beach wrack as a hindrance and believe that having macrophyte beach wrack has a negative impact [6].

In recent years, as a result of increased ocean eutrophication, the number of marine macrophyte releases to shore has increased [7,8]. The decomposition of algae biomass on beaches is accompanied by environmental and social consequences [4]. Macrophyte beach wrack accumulations emit an unpleasant odor during decomposition, have an unaesthetic appearance, and lead to an increase in the number of insects, which reduces the value of recreational areas [4,9]. Some algae species may contain heavy metals and toxic compounds that pose a risk to human health [8,10]. In addition to polluting chemical compounds, pathogenic microorganisms can also pose a danger, the number of which increases dramatically during the decomposition of marine macrophytes [11]. The decomposition of macrophyte beach wrack accelerates carbon loss in coastal ecosystems and increases total greenhouse gas emissions [7,12–14]. According to some estimates, the CO_2 flux during the decomposition of macrophyte beach wrack on a global scale can reach 19.04 TgS/year [13].

Management strategies for the beach disposal of marine macrophytes are not always environmentally sound [3]. In some recreational areas, macrophyte beach waste is removed and deposited in large piles that rot during the summer and are dumped back into the sea at the end of the summer [9].

According to the European Union (EU) Waste Framework Directive [15], algae should be considered not as waste but as a resource. Marine macrophyte applications range from human food, livestock feed, and fertilizers in agriculture to fuel sources [2,16]. Research suggests various ways to recycle algae, such as composting, paper and pulp production, energy production, and conversion to biochar [5]. Algae are considered a third-generation raw material with promising prospects and the possibility of being used for energy production in the long term [4].

The use of marine markers for business development may become relevant in the coming year [17–21]. It is noted that biochar produced from marine macrophytes has a low carbon content, surface area, and cation exchange capacity but has a high pH value, ash content, nitrogen, and content of inorganic nutrients such as P, K, Ca, and Mg [22]. Since biochar is a long-term carbon conservator, the transformation of coastal emissions of marine macrophytes can have a beneficial environmental effect. A double ecological effect can be obtained by introducing biochar produced from marine macrophytes into the soil. This is due to the fact that the use of biochar in practice leads to a reduction in greenhouse gases [23–25].

Nevertheless, it is pointed out that the creation of ecological projects based on onshore emissions of marine macrophytes is economically unprofitable [7,26]. However, it is also noted that algae processing has a lower cost in Russia compared to production in European countries [26]. In 2023, Verra released VM0044 Methodology for Biochar Use in Soil and Non-Soil Applications, version v1.0, which outlines procedures for quantifying greenhouse gas (GHG) emission reductions from biochar production and use in approved soil and non-soil applications [27]. According to a 2019 Special Report by the Intergovernmental

Panel on Climate Change, biochar could provide mitigation potential of 1 Gt of CO_2 per year by 2050 (conservative estimate) [27].

The creation of climate projects presupposes accurate numerical representations of the role of marine macrophytes in the carbon cycle of coastal marine ecosystems. For such calculations, it is necessary to use modern high-precision measurements directly in the field. Most estimates of carbon uptake by marine algae are based on extrapolation of C uptake rates, C pool size in seaweed biomass, DOC exudation, microbial mineralization, and advection of C fixed by marine macrophytes into sediments or to depth [28]. In other words, estimates of carbon uptake by marine macrophytes are computational methods [1], one of the disadvantages of which is the possible underestimation or overestimation of the processes occurring in natural ecosystems. This problem also concerns the quantification of the net natural fluxes of greenhouse gases from marine macrophytes, both in marine conditions and when they come ashore. The quantitative assessment of net natural greenhouse gas fluxes from marine macrophytes is poorly disclosed in the scientific literature. In this regard, the potential of marine macrophytes as an ecological resource within the framework of socio-economic and economic decisions may be underestimated or overestimated [29].

The purpose of this study is to evaluate the presence or absence of the influence of macrophyte beach wrack on the flow of carbon dioxide and the possibility of the environmentally sound recycling of macrophyte beach wrack.

2. Materials and Methods

2.1. Research Plots

The study plot was located on the coast of Kievka Bay, Sea of Japan, Russia (Figure 1). The study plot is located near one of the sites of the Carbon plots of the Russia "Far Eastern" MBS Zapovednoye (marine biostation Zapovednoye, Zapovednoye village, Primorsky Territory, Russia). The main part of the coastline of the bay is low-lying and occupied by a large sandy beach. The northwestern and southeastern shores of the bay are represented by high capes. The coastline of Kievka Bay is subject to active coastal abrasion. Kievka Bay has free water exchange and intensive coastal runoff, the runoff of the Kievka River, water inflow from the open sea and neighboring bays, the formation/destruction of seasonal stratification, and the autumn upwelling of waters.

The intensity of the appearance of macrophyte beach wrack in Kievka Bay, as well as on the coast of Primorsky Krai, varies throughout the year and is related to the climate of the territory. The temperate monsoon climate of the territory and orographic features determine the seasonality of wind directions and sea waves.

On the territory of Kievka Bay, wave marine phenomena have a seasonal character. In the cold half of the year (from October to March), the western and northwestern rumbas prevail; in the warm half (from April to September), mainly southern, southeastern, and southwestern rumbas prevail. In spring and autumn, due to the instability of the winds, waves are observed, respectively, from southeast to southwest directions (in some cases northwest) and from northwest to southwest directions. Tropical cyclones entering the water area create vast fields of strong, stormy, and even hurricane-force winds that generate large waves. Storms are mainly associated with deep cyclones. The greatest number of days with gale-force winds is observed in December-January, with the intensity of storms decreasing from winter to summer [30].

The coastal marine ecosystems of Kievka Bay are represented by 14 macrophyte communities [31]. The most developed macrophyte communities near the coast area under study are *Saccharina japonica*, *Phyllospadix iwatensis* + *Saccharina Intermedius* + *Costaria costata*, and *Zostera marina* [31]. These communities are a potential biomass for macrophyte beach wrack.

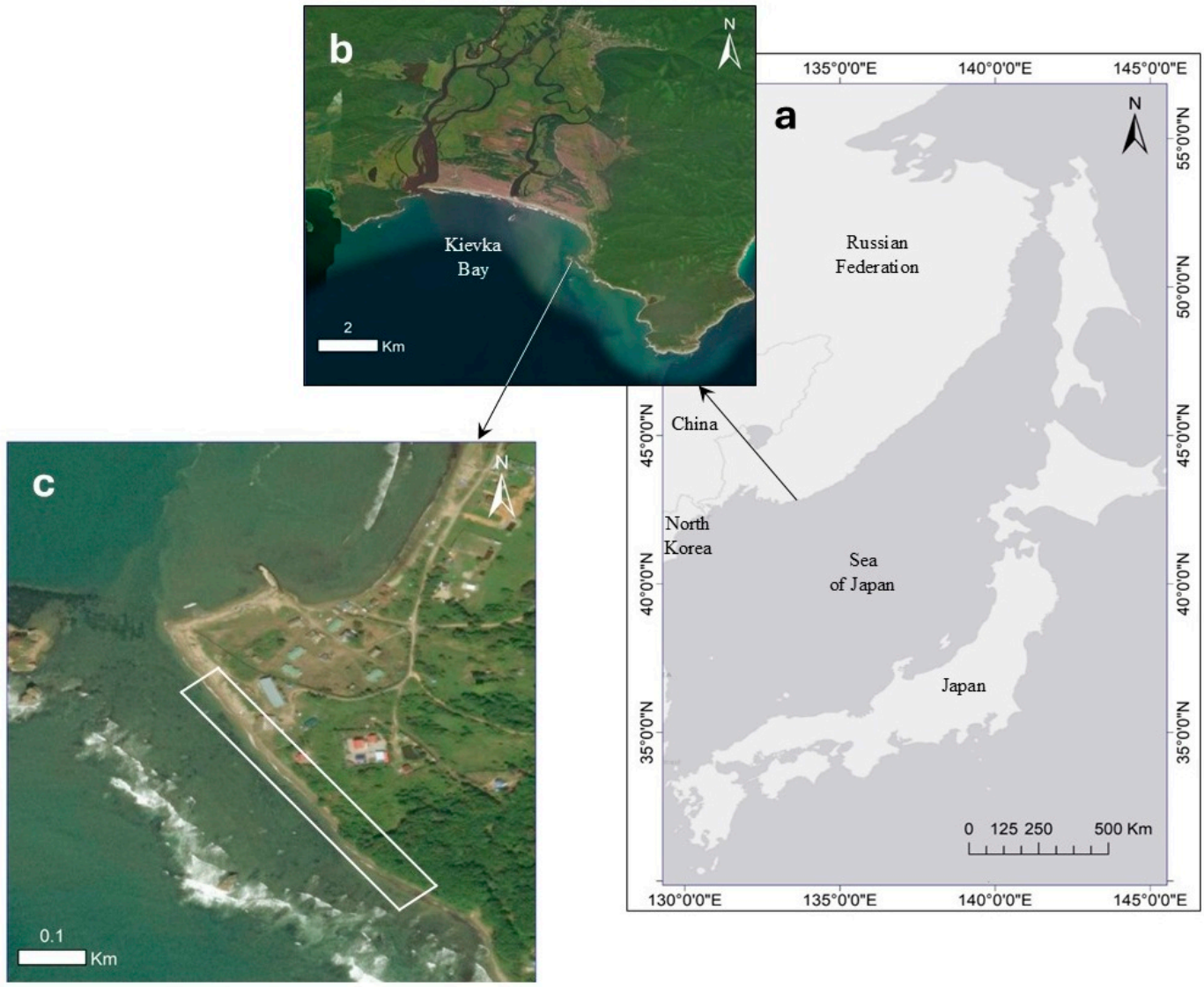


Figure 1. (**a**,**b**) Schematic map of the location of the study area; (**c**) schematic map section of the coast of Kievka Bay where the research was conducted.

The land area adjacent to Kievka Bay has a variety of ecosystems: freshwater reservoirs (river, lake, wetlands); marine coastal areas (sandy beach areas, areas with coarse-grained material, coastal terraces); land areas with different types of vegetation (broad-leaved, meadow, swamp vegetation typical of the territory of Primorsky Krai; a large number of succulents on sea terraces; and plants listed in the Red Book) of relief and soils (maritimate or marching soils [32] or psammozems and alluvial soil according to the Russian soil classification 2004 year [33]). According to the World Reference Base of Soil Resources, the soil in the studied areas is represented by Fluvisols. Until 2014, the land area adjacent to the bay was a buffer zone of the Lazovsky Nature Reserve [31]. In this regard, the bay has a relatively low level of anthropogenic impact on the ecosystem. Currently, the recreational development of its resources is most actively carried out, which requires mandatory monitoring.

2.2. Evaluation of Gas Flows

The study of fluxes from macrophyte beach wrack was conducted on 3 August and 30 September 2023. The measurements in August and September had different research objectives. In August, the main task was to consider the difference in fluxes between plots

with and without macrophyte beach wrack. Thus, four types of coastal plots were selected as objects of research, differing in the conditions of coastal emissions of marine macrophytes: WM, DM, CR, ST (Figure 2). The WM plot is represented by macrophyte beach wracks located on the soil surface near the water's edge, which were exposed to seawater (the surface of marine macrophytes was wet), and their time to reach the beach was minimal. The DM plot is represented by the macrophyte beach wrack, which was located on the surface of the coastal zone further and higher from the water's edge compared to the WM plot. At this plot, the macrophyte beach wrack was significantly less affected by seawater (the surface of marine macrophytes was dry), but since the time spent on the beach of the macrophyte beach wrack was longer compared to the WM plot, the effect of precipitation (rain), as well as the course of decomposition processes, was noted. The CR plot was located on the first bank (further and higher from the water's edge compared to the DM plot) and was mainly represented by pebbles with sand. There was almost no macrophyte beach wrack of marine macrophyte remains at this plot (the presence of marine animal shells was noted). The ST plot was located on the sea terrace and was represented mainly by sand. There was no macrophyte beach wrack from the remains of marine macrophytes in this area, and the presence of terrestrial grass vegetation was noted. The measurements were carried out three times for each plot.

In September, the main task was to compare the difference in CO_2 fluxes between the plots with the macrophyte beach wrack and the plots after manual removal of the macrophyte beach wrack. On 30 September, 10 measurements were made on five random plots of the coast (No. 1, No. 2, No. 3, No. 4, No. 5). The measurement options included: WM—plots with macrophyte beach wrack, which were located on the soil surface near the water's edge and were exposed to seawater (the surface of marine macrophytes was wet), and their time to reach the beach was minimal; and HM—plots after manual removal of macrophyte beach wrack from WM plots. The WM and HM plots geographically coincided, that is, first the CO_2 flux was measured at the WM plot, and then the macrophyte beach wrack was removed and the CO_2 flux was measured at the HM plot. Measurements on 3 August and 30 September were carried out on the same part of the coast.

The coast area and measurement points were selected based on the proximity of seagrass thickets and the intensity of emissions.

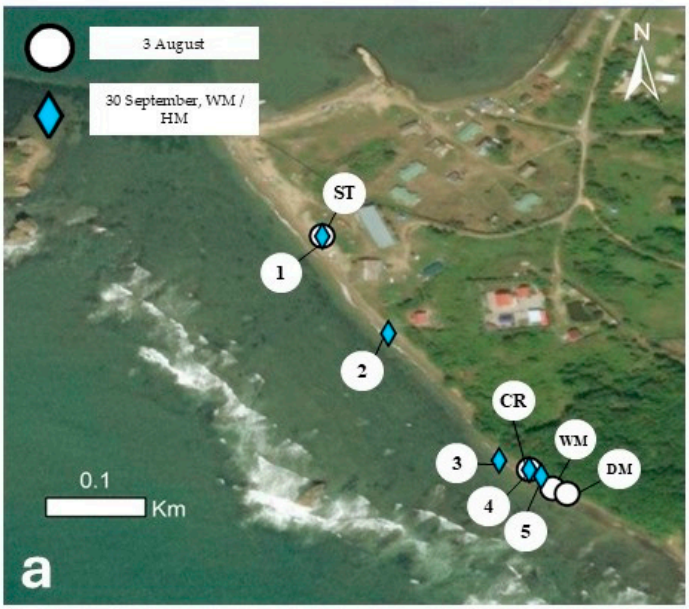
Greenhouse gas concentrations were measured with a portable Picarro 4301 GasScouter laser gas analyzer (Picarro, Santa Clara, CA, USA). The measurement frequency of the gas analyzer is 0.012 Hz. A darkened camera from Picaro Mobile Soul Flex System, A0947 (Picarro, Santa Clara, CA, USA), was used for measurements.

The exposure time at each point, including the data post-processing stage with the removal of statistical emissions, varied in the range of 4–6 min. To ensure high accuracy in recording the dynamics of the process, the data were recorded at regular time intervals (1–1.5 s), which guaranteed the formation of a representative sample. Each measurement cycle included the collection of at least 200 independent data points (denoted as N). Despite the non-normal distribution of the raw data, this sample size ensured sufficient statistical power (>0.95 at α = 0.05) to mitigate the impact of random errors (e.g., microclimatic fluctuations, instrumental noise) through robust averaging.

To calculate the average gas emission using linear regression, Equation (1) is traditionally employed, where the model's reliability is assessed via the coefficient of determination R^2, reflecting the proportion of explained variance in the dependent variable.

$$F_{gas} = \frac{\frac{[Gas]}{t} \times 10^6 \times V \times 3600 \times M[Gas]}{A} \quad (1)$$

where F_{gas} = linear flow of the test gas in (mg (Gas)/m^2 h); Δ [Gas]/Δt—the number of gas particles at time t, expressed in ppm/s; V—the total volume of the chamber, m^3; A—the area of the investigated surface, m^2; ρ—the molar density of air (mol/m^3), defined as P/RT, where P is the air pressure, Pa; R—the universal gas constant, equal to 8.31 Pa m^3/mol^1 × K^1; T—the air temperature, K; 3600—coefficient for converting seconds to hours; M[Gas]—the molar mass of gas.



	Date measurement CO_2	
	3 August	30 September
plots	WM (triple repetition) DM (triple repetition) CR (triple repetition) ST (triple repetition)	No. 1 (WM and HM) No. 2 (WM and HM) No. 3 (WM and HM) No. 4 (WM and HM) No. 5 (WM and HM)



Figure 2. Scheme of flux measurement at plots with and without macrophyte beach wrack in Kievka Bay. (**a**) Plots for 3 August and 30 September. Plots for 3 August: WM—plots with "fresh" macrophyte beach wrack near the water's edge; DM—plots with macrophyte beach wrack subject to partial decomposition and located further and higher from the water's edge compared to WM; CR—plots of the first coastal wall; ST—plots of the sea terrace. Plots for 30 September: WM—plots with "fresh" macrophyte beach wrack near the water's edge; HM—plots after manual collection of macrophyte beach wrack. (**b**) Example of locations of WM, DM, and CR plots on the beach of Kievka Bay.

The coefficient of determination R^2 was used in the calculation of Δ[Gas]/Δt to assess the reliability of the measured flow data.

However, despite the method's simplicity, key limitations relevant to coastal ecosystem analysis were identified. First, linear regression does not allow the estimation of the standard deviation of CO_2 emissions between plots with macrophyte deposits (WM, DM) and those without (CR, ST), which is critical for interpreting significant differences (e.g., there is an order of magnitude higher CO_2 flux in areas with macrophytes.). Second, while R^2 demonstrates the overall alignment of data with a linear trend, it ignores the influence of outliers caused by natural coastal variability (e.g., fluctuations in temperature, humidity, microbial activity, and other factors during measurements). This is particularly significant in the context of our field measurements, where substrate heterogeneity, microbial activity, and microclimatic fluctuations could distort local flux values. Additionally, the method assumes normality of error distribution, which contradicts our data ($p < 0.001$ via the Shapiro–Wilk test), confirming the necessity of transitioning to nonparametric methods (Wilcoxon test). To enhance result reliability, we supplemented the analysis with median difference calculations and 95% confidence intervals, which accounted for distribution asymmetry and minimized the impact of anomalous values. This approach ensured methodological alignment with the real-world conditions of Kievka Bay's coastal ecosystems and improved the credibility of conclusions regarding the potential of converting storm-driven macrophyte deposits into biochar to reduce greenhouse gas emissions.

For statistical processing of the results, a differential of gas concentration values was used depending on the measurement time.

The rate of change of the gas concentration (flow, F) was calculated as the first derivative of the concentration over time. In the discrete case, the derivative is approximated by a finite difference as follows:

$$F(t_i) = \frac{C(t_i) - C(t_{i-1})}{\Delta t} \quad (2)$$

where $F_{(ti)}$ is the gas flow in (mg (Gas)/m^2 × h); $C_{(ti)}$—the gas concentration (ppm) at time t_i (c); $C_{(ti\ -\ 1)}$—the gas concentration at the previous time $ti - 1$; and Δt = 1 s—the time interval between measurements.

The data obtained immediately after the completion of the purge and dehumidification procedure of the gas analyzer was used as the reference (zero) value of the gas flow.

To obtain a representative estimate of the flow, the average value of the concentration change rate ($\overline{F}$) was calculated for all time points as follows:

$$\overline{F} = \frac{1}{N-1} \times \sum_{i=2}^{N} F(t_i) \quad (3)$$

where N is the total number of gas concentration measurements.

The air temperature and pressure required for calculating the flow were measured using a Vaisala WXT520 weather sensor (Vaisala, Helsinki, Finland).

In August, measurements for the WM, DM, CR, and ST plots were conducted in triplicate replicates, with the measurement chamber displaced by 20–50 cm from the previous position for each replicate. This triplicate approach was used to preliminarily assess the convergence of CH_4 and CO_2 flux values within a single experimental plot. The results demonstrated that, in most cases, the CO_2 and CH_4 flux values within the same experimental plot showed comparable magnitudes ($p > 0.05$; see Section 3).

Based on these findings, the methodology was adjusted in September: paired measurements (one measure before [WM] and one after [HM] algae removal) were performed on each of the five experimental plots (No. 1–5). This optimization reduced time expenditures

without compromising accuracy, as the August data confirmed measurement stability within individual plots.

2.3. Biochar

Samples of *Saccharina japonica* algae and a mixture of algae (*Phyllospadix iwatensis* 20%, *Zostera marina* 70%, *Neorhodomela larix* 10%) were taken to obtain biochar on the coast of Kievka Bay.

Saccharina japonica samples were collected on 30 September at the WM plots; their stay on the beach was 2 days after the storm. The samples were not exposed to precipitation and desiccation. The samples, which are a mixture of algae, were taken at the DM plot, where the distance to the water's edge is 2 m. The samples were on the shore for more than 30 days after deposition on the beach, exposed to precipitation and desiccation.

The samples were collected in airtight containers prior to sample preparation. Prior to the start of the pyrolysis process, the samples were not subjected to any additional processing and were used as is. To obtain biochar, algae samples were pyrolyzed in a SAFTherm STZ 1214 furnace (Henan Sante Furnace Technology Co., Ltd., Luoyang, China) in a nitrogen stream (3 L/min) at 500 °C for 30 min, at a heating rate of 8.3 degrees/min. After pyrolysis, the percentage of the obtained biochar relative to the initial biomass was calculated using Equation (4) [34]:

$$\text{Biochar yield\%} = \frac{W_{\text{biochar}}}{W_{\text{seaweed}}} \times 100\% \quad (4)$$

where $W_{biochar}$ is the weight of biochar and W_{seaweed} is the initial weight of seaweed.

SEM images and EDX spectra were performed in crushed biochar samples using a Hitachi S-5500 ultra-high resolution scanning electron microscope (Hitachi, Tokyo, Japan).

The pH value of the aqueous extract of biochar (volume ratio of biochar to distilled water 1:25) was determined using a combined electrode and an electrical conductivity sensor from Mettler Toledo according to the standard method of Rajkovich et al. [35].

2.4. Statistical Analysis

All calculations were performed using the Jamovi open source software (version 2.6; The jamovi project, 2024) and the R programming language (version 4.4; R Core Team, 2024) with packages from the CRAN snapshot dated 8 July 2024. The choice of tools is determined by their reputation in the scientific community, reproducibility of analysis, and support for modern statistical methods. The normality of the data distribution was assessed using the Shapiro–Wilk test ($\alpha = 0.05$), recommended for small- and medium-sized samples ($n < 5000$). In all cases, the distributions deviated significantly from normal ($p < 0.001$), which confirmed the need for nonparametric methods.

Nonparametric methods appropriate to the sample structure were used to analyze the data in the study. September measurements representing paired observations before and after removal were analyzed using the Wilcoxon signed-rank test, which accounts for the dependent nature of the data and their deviation from a normal distribution. For August data, which required a comparison of independent groups with and without outliers, the Mann–Whitney U-test was applied. The critical significance level for both models was set at 0.05. The results revealed statistically significant differences in September—as a consequence of the conducted intervention ($p < 0.05$)—and in August—as the impact of outliers on baseline values ($p < 0.05$). The choice of methods and significance level ensured the validity of conclusions under nonparametric distributions.

For the measurements conducted in August, repeated samples showing no significant differences ($p > 0.05$) were combined into single datasets for subsequent analysis. The effects of interventions (removal of marine emissions) on carbon dioxide and methane

emissions were calculated as the median difference between the combined experimental and control groups, with 95% confidence intervals based on Wilcoxon test statistics. This approach aligns with the assumptions of nonparametric statistics and remains sensitive to shifts in central tendency in asymmetric distributions.

3. Results

3.1. Assessment of the Effect of Macrophyte Beach Wrack on Gas Flows

During measurements of greenhouse gas emissions from the soil, the results of the carbon dioxide flux values were obtained for plots with and without storm emissions. During the measurement, it was revealed that the value of methane concentrations according to the statistical evaluation of the data did not actually change and was within the error range. Therefore, the calculation according to Equation (1) was performed for the flow of carbon dioxide.

As a result of measurements carried out on the coast of Kievka Bay on 3 August, it was noted that plots with a macrophyte beach wrack have a significantly higher CO_2 flux value compared to plots without a macrophyte beach wrack (Figure 3, Table 1).

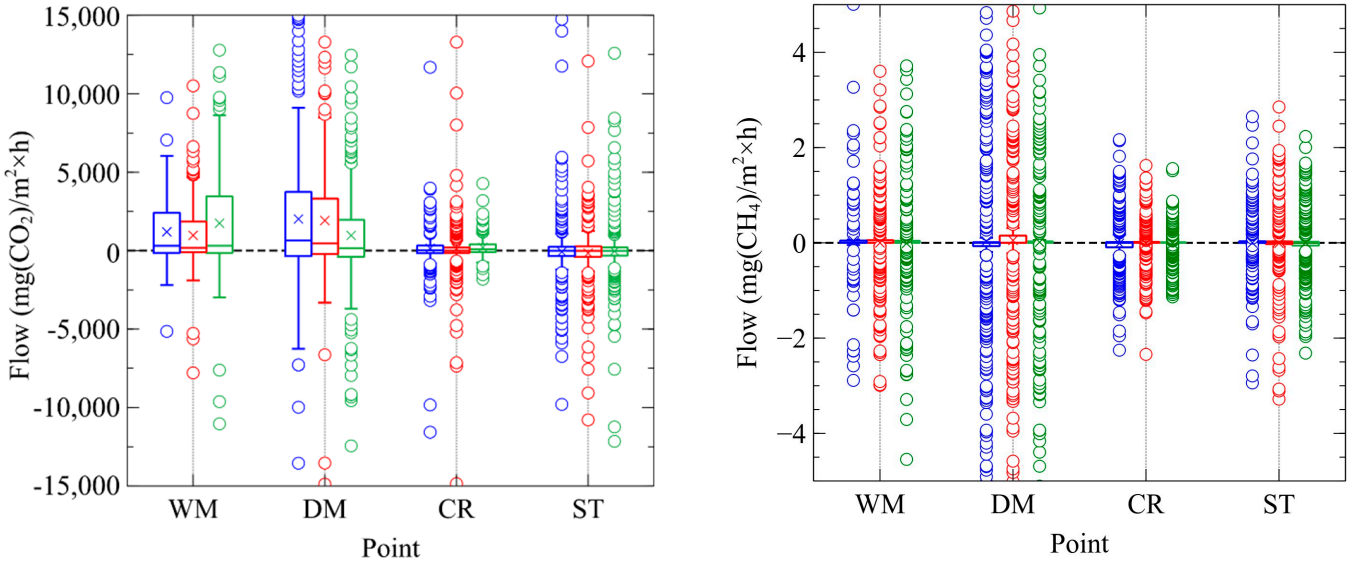


Figure 3. The values of (**a**) CO_2 and (**b**) CH_4 fluxes measured on 3 August; blue, red, and green are repetitions of measurements for one point; whiskers are 1.5 IQR.

Table 1. Average CO_2 flux values (mg $(CO_2)/m^2 \times h$) for 3 August.

Point		N	Mean	Median	SD	SE	Normality Test (Shapiro–Wilk)	
							W	*p*
WM	1	90	1198.9	310.52	2143	225.9	0.881	<0.001
	2	220	974.0	178.22	2035	137.2	0.837	<0.001
	3	192	1747.4	312.44	3513	253.5	0.837	<0.001
DM	1	336	2016	649.9	5941	324.1	0.705	<0.001
	2	281	1920.2	462.95	4324	258	0.772	<0.001
	3	256	971.5	154.94	6050	378.1	0.723	<0.001
CR	1	200	−73.0	−8.45	3052	215.8	0.653	<0.001
	2	171	−159.5	−10.84	3526	269.6	0.616	<0.001
	3	293	−33.6	−12.66	2033	118.7	0.677	<0.001

Table 1. *Cont.*

Point		N	Mean	Median	SD	SE	Normality Test (Shapiro–Wilk)	
							W	*p*
ST	1	278	150.0	21.57	1776	106.5	0.447	<0.001
	2	245	133.1	−6.13	3331	212.8	0.445	<0.001
	3	253	205.5	90.27	615	38.7	0.842	<0.001

Table 1 shows the mean and median values for CO_2 flux.

In plots without macrophyte beach wrack (CR and ST), the lowest mean CO_2 flux was observed in CR. These plots consisted of pebble beaches with almost complete or partially absent washed-up marine macrophytes. During storm periods, these plots were flooded with water and, together with their constituent material, did not allow for the formation of stable microbiological communities that could contribute to CO_2 production. ST plots had higher CO_2 flux values compared to CR plots. This was because ST plots were higher relative to sea level and composed of sand fraction and sparse grass areas. This indicates more stable soil conditions and, consequently, the existence of microbiological processes leading to CO_2 release. In areas with the presence of marine macrophytes, CO_2 flux values were obtained comparable to the values of CO_2 fluxes in August from typical arable soils of Primorsky Krai Luvic Anthrosol, which we noted earlier [36]. In DM plots, the CO_2 value was 20% higher than in WM plots.

The CO_2 fluxes we measured in August on plots with marine macrophytes (WM and DM) were more than an order of magnitude higher than those on plots without marine macrophytes (CR and ST). This excess is significant; however, we assume that with long-term seasonal monitoring, this indicator will be lower in measurements.

To assess the contribution of carbon dioxide and methane to the gas exchange between the atmosphere and the soil, a statistical analysis was performed, showing the reliability of the effect of the contribution of each of the gases on the total flow from the soil. Figure 3 shows experimental data on carbon dioxide and methane fluxes (Equations (2) and (3)) obtained at research plots in the form of a box plot that demonstrates the spread and distribution of data. Visual analysis of the diagrams allows us to conclude that the distribution of experimental values significantly deviates from the normal one. Table 2 shows the results of paired comparisons of the CO_2 flux datasets for three repetitions at each point. Since the samples of values deviated from the normal distribution, the Wilcoxon criterion was used for paired analysis. The analysis showed that for the WM, CR, and ST points, the results of repeated measurements of the CO_2 flux did not differ statistically ($p > 0.05$). At the same time, a significant deviation in the third repetition was found for the DM point, which indicates the presence of statistically significant differences ($p < 0.05$).

Table 2. Paired sample *t*-test for CO_2 flux (mg $(CO_2)/m^2 \times h$) (3 August).

Point			*p*	Mean Difference	SE Difference
WM	1	2	0.069	−225.66	223
	2	3	0.051	−190.57	273
	3	1	0.486	−99.9	303
DM	1	2	0.856	−77.7	489
	2	3	0.002	1187.3	485
	3	1	<0.001	605.16	528
CR	1	2	0.765	14.27	376
	2	3	0.439	−49.25	298
	3	1	0.866	−11.43	245

Table 2. *Cont.*

Point			*p*	Mean Difference	SE Difference
ST	1	2	0.858	7.58	241
	2	3	0.074	−64.89	217
	3	1	0.288	−31.48	112

Table 3 shows the average and median values for carbon dioxide emissions.

Table 3. Average CH_4 flux values (mg $(CH_4)/m^2 \times h$) for 3 August.

Point		N	Mean	Median	SD	SE	Normality Test (Shapiro–Wilk)	
							W	*p*
WM	1	90	0.0472	0.00166	1.3960	0.1471	0.995	0.438
	2	220	-1.17×10^{-4}	0.00011	0.9610	0.0648	0.925	<0.001
	3	192	−0.0105	0.00000	1.2260	0.0885	0.857	<0.001
DM	1	336	0.0345	0.00000	2.2970	0.1253	0.823	<0.001
	2	281	0.0518	0.00041	1.9260	0.1149	0.844	
	3	256	0.0134	0.00238	2.3950	0.1497	0.822	
CR	1	200	-5.42×10^{-4}	0.00000	0.6820	0.0482	0.873	<0.001
	2	171	−0.01080	0.00000	0.9000	0.0688	0.735	
	3	293	8.16×10^{-4}	0.00000	1.0690	0.0624	0.695	
ST	1	278	−0.01050	0.00000	0.5680	0.0340	0.849	<0.001
	2	245	−0.01180	0.00000	0.4680	0.0299	0.838	
	3	253	−0.01380	0.00000	0.3670	0.0231	0.871	

Table 4 shows the results of a pairwise comparison of the methane emission datasets for three independent replicates at each sampling point. The analysis revealed the absence of statistically significant differences between the experimental samples ($p > 0.05$), which indicates a high reproducibility of the results. The data obtained allow us to conclude that methane emissions are uniform, which is probably due to the low velocity of the gas flow in the system under study.

Table 4. Paired sample *t*-test for CH_4 flux (3 August).

Point			*p*	Mean Difference	SE Difference
WM	1	2	0.833	0.00218	0.1912
	2	3	0.620	0.00360	0.1154
	3	1	0.450	0.00880	0.1779
DM	1	2	0.787	−0.04527	0.1806
	2	3	0.638	0.07450	0.1927
	3	1	0.265	−0.00815	0.2048
CR	1	2	0.992	-8.73×10^{-5}	0.0802
	2	3	0.597	0.00371	0.1179
	3	1	0.922	-6.85×10^{-4}	0.0944
ST	1	2	0.979	1.01×10^{-4}	0.0479
	2	3	0.577	0.00136	0.0400
	3	1	0.885	5.23×10^{-4}	0.0434

For carbon dioxide (CO_2), high emission values are observed in the DM plot, which is due to the active processes of aerobic decomposition of plant residues during long-term stay on the shore. In the case of methane (CH_4), all values are close to zero, which indicates the absence of a stable flow of this gas.

Table 5 shows the average and median values calculated after combining the repeats into a single sample. The exception was repetition number 3 for the DM point, which showed a statistically significant difference from the other two samples. For carbon dioxide (CO_2), high emission values are observed at the DM plot, which is due to the active processes of aerobic decomposition of plant residues during a prolonged stay on the shore. In the case of methane (CH_4), all values are close to zero, which indicates the absence of a stable flow of this gas.

Table 5. Calculated values of CO_2 and CH_4 emissions (3 August).

Flux (mg/m^2 × h)	Point	N	Mean	Trimmed Mean (10%)	Median	SD	SE
CO_2	WM	502	1310	958	262	2731	122
	DM	617	1972	1440	530	5263	212
	CR	664	−78	−81	−11.8	2794	108
	ST	776	163	100	28.4	2178	78.2
CH_4	WM	502	0.0044	0.00867	0.0001	1.15	0.0513
	DM	873	0.0339	0.01746	0	2.21	0.0749
	CR	664	−0.00259	0.00711	0	0.922	0.0358
	ST	776	−0.012	−0.0093	0	0.477	0.0171

Table 6 presents the results of the comparison of methane and carbon dioxide fluxes using the Mann–Whitney U-test. The test was applied to assess the statistical significance of differences between independent samples, as the data did not meet the assumptions of normal distribution. To improve the accuracy of the analysis, the table includes the U-statistic, significance level (p-value), and effect size (rank-biserial correlation), which reflects the magnitude of differences between the groups.

Table 6. Comparison of methane and carbon dioxide fluxes: Mann–Whitney test results (U-statistics, significance level, and effect size).

Pairs		p	Mean Difference	95% Confidence Interval		Effect Size (Rank-Biserial Correlation)
				Lower	Upper	
CO2	WM/DM	0.164	−128	−309	52.3	0.0483
	WM/CR	<0.001	533	373	756	−0.311
	WM/ST	<0.001	307	212	422	−0.241
	DM/CR	<0.001	871	647	1135	−0.327
	DM/ST	<0.001	570	418	757	−0.269
	CR/ST	<0.001	−89.9	−142	−41.1	0.111
CH4	WM/DM	0.478	2.82×10^{-8}	-4.52×10^{-5}	0.00268	−0.0228
	WM/CR	0.375	3.82×10^{-5}	-2.25×10^{-6}	0.00388	−0.03
	WM/ST	0.104	4.13×10^{-6}	-6.96×10^{-6}	0.00634	−0.0533
	DM/CR	0.811	5.06×10^{-5}	-4.47×10^{-5}	7.68×10^{-5}	−0.00706
	DM/ST	0.22	4.66×10^{-5}	-2.06×10^{-5}	0.00176	−0.0346
	CR/ST	0.346	4.97×10^{-5}	-3.96×10^{-5}	0.00208	−0.0285

According to the analysis, there are no statistically significant differences only for the WM-DM pair ($p > 0.05$), which indicates that there is no effect of macrophyte beach wrack humidity on CO_2 flux. Thus, a decrease in CO_2 emissions is observed exclusively during

the transition from the macrophyte beach wrack zone to the coastline. For methane (CH_4), all samples do not differ statistically (Table 6), which indicates that there is no dependence of the emission level on the location of the measurement points.

Since we have proven that macrophyte beach wrack can affect the flow of greenhouse gases from soils, we conducted an experiment to assess the stability and intensity of the flow when removing storm emissions from the soil surface. Therefore, in September, a comparison of CO_2 fluxes at plots with macrophyte beach wrack (WM) and after their manual removal (HM) was carried out. As for the measurements in August, it was revealed that the value of methane concentrations, according to the statistical assessment of the data, did not actually change and was within the error range.

Three of the five plots showed a decrease in the CO_2 flux after the manual removal of macrophytes from the measured surface. On average, the flow value in the plots after manual collection of macrophytes was 1.8 times lower than in the areas with macrophytes (Figure 4, Table 7). It is worth noting that the values of the CO_2 flux in the WM plots differed significantly from each other. As noted in the literature, this may be due to the different intensity of coastal emissions of marine macrophytes; their temperature, humidity, and species composition [7,9,14]; and the degree of decomposition.

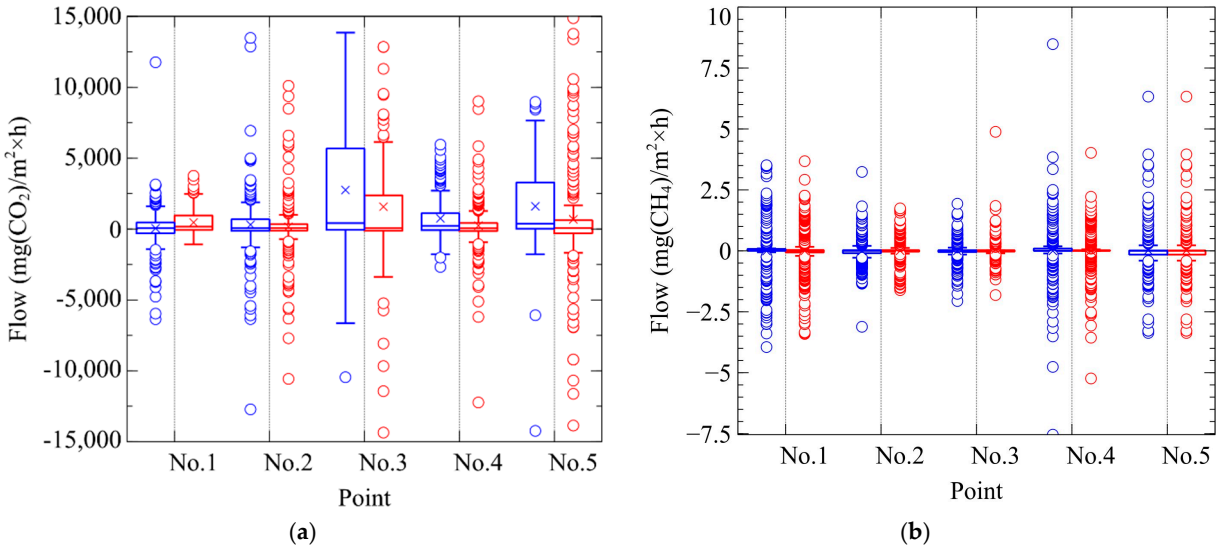


Figure 4. The values of (**a**) CO_2 and (**b**) CH4 fluxes measured on 30 September; blue—WM, red—HM, whiskers—1.5 IQR.

Table 7. Average values of CO_2 flux (mg $(CO_2)/m^2 \times h$) (30 September).

Point		N	Mean	Median	SD	SE	Normality Test (Shapiro–Wilk)	
							W	*p*
No. 1	WM	212	52.8	61.8	1547	106.2	0.768	<0.001
	HM	212	509.8	174.4	861	59.1	0.905	
No. 2	WM	197	233.5	50.2	9195	655.1	0.233	
	HM	197	164.3	68.2	2218	158.0	0.732	
No. 3	WM	120	3181.7	384.2	6116	558.3	0.756	
	HM	120	1573.4	60.7	8388	765.7	0.690	
No. 4	WM	223	752.4	223.7	1443	96.7	0.847	
	HM	223	250.0	67.3	2012	134.7	0.629	
No. 5	WM	186	1566.9	365.2	2547	186.7	0.832	
	HM	186	681.7	72.8	5410	396.7	0.785	

Figure 4 shows experimental data on CO2 and CH4 fluxes obtained at research plots in the form of a box plot that clearly demonstrates the spread and distribution of data. Visual analysis of the diagrams allows us to conclude that the distribution of experimental values significantly deviates from the normal one. This deviation may be due to a number of factors, such as the presence of a macrophyte beach wrack, the heterogeneity of measurement conditions, or the influence of external influences characteristic of the plots under study.

Tables 7 and 8 provide summary statistical characteristics of CO_2 and CH4 fluxes, including mean and median values, standard deviation, and standard error, before and after removal of the macrophyte beach wrack. These data allow us to assess the impact of outlier removal on the distribution and variability of flows. The average values reflect the overall flow rate for each gas, while the median values show a central trend resistant to the influence of the macrophyte beach wrack.

Table 8. Mean values of the CH4 flux (mg (CH_4)/m^2 × h) (30 September).

Point		N	Mean	Median	SD	SE	Normality Test (Shapiro–Wilk)	
							W	*p*
No. 1	WM	212	−0.00988	0.00584	1.186	0.0814	0.862	<0.001
	HM	288	−0.00576	0.00000	0.930	0.0548	0.859	
No. 2	WM	251	−0.00559	0.00000	0.536	0.0338	0.801	
	HM	197	0.00425	0.00000	0.555	0.0395	0.858	
No. 3	WM	197	−0.00443	0.00000	0.490	0.0349	0.833	
	HM	120	0.05614	0.00000	0.663	0.0606	0.683	
No. 4	WM	223	−0.00303	0.00000	1.248	0.0836	0.735	
	HM	261	−0.00132	0.00000	0.881	0.0545	0.802	
No. 5	WM	200	0.00629	0.00000	0.777	0.0550	0.813	
	HM	186	0.02073	0.00000	1.105	0.0810	0.772	

Methane is characterized by extremely low flow values, which largely assume negative values, indicating the predominance of gas absorption (sorption) processes over its flow (Table 8). At the same time, the median values of the flow for most measurements are close to zero. This pattern may indicate instability or the absence of a pronounced source of methane in the system under study.

Thus, the observed characteristics of the methane flow reflect the predominance of its absorption processes over production under the studied conditions. This is consistent with data for many terrestrial ecosystems, where methane plays a secondary role in the carbon cycle compared to carbon dioxide. To confirm the hypotheses about the mechanisms of CH_4 absorption, it is advisable to conduct additional microbiological and soil studies.

The experimental data are characterized by a significant variation in values, which may indicate a high spatial and temporal heterogeneity of the gas flows. Such variability may be due to a few factors, including the heterogeneous thickness of the macrophyte beach wrack and the time they were on land, the different composition and number of living organisms living in these areas, the composition and properties of the soils located above, geochemical conjugation, etc.

Thus, the observed variability of experimental values reflects the complexity and versatility of the processes affecting the gas flows and requires careful analysis to understand their nature and account for further research.

Table 9 shows the magnitude of the effects exerted by the removal of the macrophyte beach wrack on methane and carbon dioxide fluxes.

Table 9. Effect of algae removal on emissions: results of the paired Wilcoxon test for September measurements.

Point		*p*	Mean Difference	SE Difference	95% Confidence Interval		Effect Size
					Lower	Upper	
CO_2	No. 1	<0.001	−494	122	−700	−287	−0.3533
	No. 2	0.881	27	675	−284	355	0.0124
	No. 3	0.003	2187.5	989	739	3880	0.3171
	No. 4	<0.001	255.4	154	110	453	0.2837
	No. 5	<0.001	1542.2	452	749	2208	0.2933
CH_4	No. 1	0.966	−0.00445	0.1026	−0.2246	0.19901	−0.00345
	No. 2	0.608	−0.03161	0.0563	−0.1365	0.08261	−0.0422
	No. 3	0.968	−0.00314	0.0755	−0.1377	0.11864	−0.00441
	No. 4	0.628	−0.00231	0.1046	−0.0166	0.00755	−0.03898
	No. 5	0.691	0.03152	0.0972	−0.1326	0.19709	0.03375

According to the presented results, the removal of macrophyte beach wrack has a heterogeneous effect on the amount of CO_2 flux. In the case of CH4, no statistically significant changes were detected before and after the removal of the macrophyte beach wrack, which confirms the hypothesis that the CH4 flux tends to zero and is independent of the external factors studied.

Ambiguous results are also observed for the CO_2 flux, in particular, the removal of the macrophyte beach wrack reduces the flux only for points No. 3, No. 4, and No. 5. For point No. 1, on the contrary, an increase in the CO_2 flux is observed, while for point No. 2, no statistically significant effect was found.

The results of the calculation of the rank-biserial correlation show that the greatest positive effect when comparing pairs of samples with and without macrophyte litter is observed for point No. 3. This indicates that removing the macrophyte beach wrack at this point reduces the CO_2 flux to the greatest extent. If we consider the points in descending order of the positive effect on reducing the CO_2 flux, they can be arranged as follows: No. 3 > No. 5 > No. 4 > No. 2. Thus, point No. 3 shows the most pronounced effect of removing the macrophyte beach wrack, while point No. 2 is the least sensitive to this effect. At the same time, point No. 1 demonstrates the opposite effect, when the CO_2 flux increases by almost 10 times after the removal of the macrophyte beach wrack.

3.2. Characteristics of Biochar from Marine Macrophytes

Since storm emissions are a source of greenhouse gases, the issue of their processing becomes very relevant. Based on our own experience in obtaining positive effects from the use of biochar as a fertilizer on soils of heavy granulometric composition [36] and publications suggesting the processing of macrophyte beach wrack into biochar [37,38], we came to the conclusion that the production of biochar from macrophyte beach wreck can be a good strategy to reduce the flow of greenhouse gases from the soil. For a preliminary assessment of the potential of macrophyte beach wrack as a source of biochar, we obtained two types of biochar and analyzed their composition.

Figure 5 shows the EDX spectra of biochar obtained from kelp (Figure 5a) and a mixture of algae (Figure 5b).

In addition to carbon and oxygen, these biochars contain sodium, potassium, magnesium, sulphur, and chlorine, elements that are components of seawater. Their presence is due to the insufficient washing of samples at the sample preparation stage. The sample obtained from a mixture of algae is characterized by a high content of aluminum and silicon. This may be due to the presence of irregularly shaped aluminosilicate particles

less than 5 microns in size, visible on the SEM image. In addition, this biochar sample is characterized by a lower sodium and chlorine content, which may indicate prolonged exposure to precipitation on the feedstock, which contributed to the leaching of salts. The presence of aluminosilicates can be explained by contamination with soil particles during a prolonged stay on the shore and the lack of additional washing at the sample preparation stage. In addition, the formation of aluminosilicates in algae biomass may be due to the presence of fouling organisms such as sponges, etc. [31]. Based on the data obtained, we see that biochars from marine macrophytes may be promising in terms of obtaining biochar, but depending on the condition (both for DM and WM points), they need preliminary preparation.

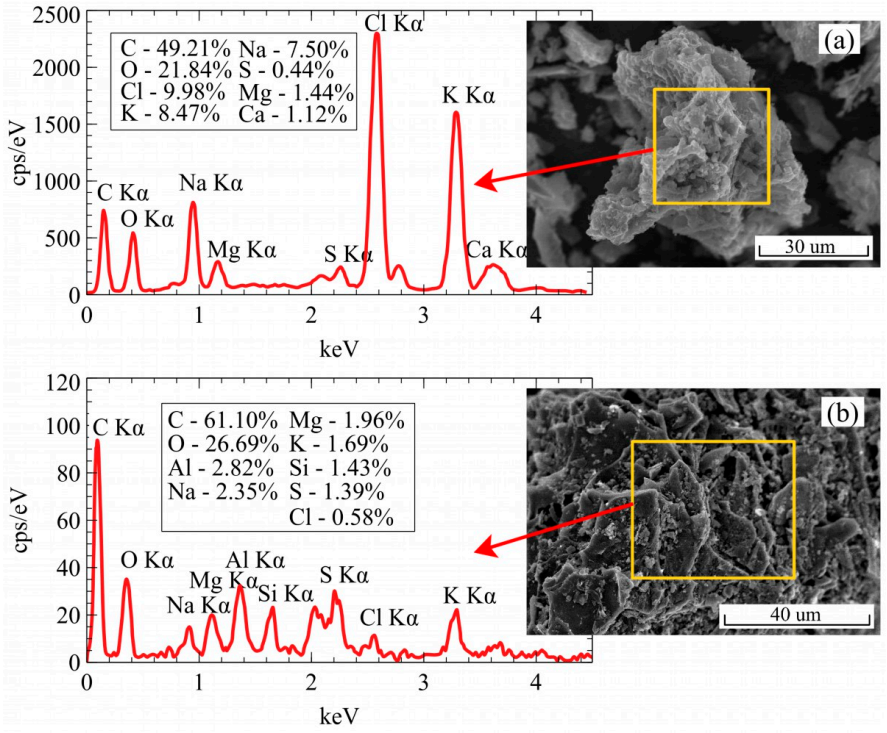


Figure 5. Scanning electron microscopy–energy-dispersive X-ray spectroscopy (SEM–EDX) analysis of biochar. Magnification of (**a**) *Saccharina japonica* and (**b**) algae mixture.

The pH values and biochar yield of the obtained biochars are shown in Table 10.

Table 10. Some parameters of biochar from marine macrophytes.

	Saccharina Japonica	**Algae Mixture**
Pyrolysis temperature, °C	500	500
pH	10.38 ± 0.16	9.67 ± 0.1
Biochar yield, %	40 ± 2.0	46 ± 2.4

4. Discussion

Storms are the main reason for the appearance of the macrophyte beach wrack [39]. In the studied area of Kievka Bay, the appearance of macrophyte beach wrack depends on the number and intensity of wave and storm phenomena. Kievka Bay is located on the coast of the Sea of Japan (the northwestern part of the Pacific region), which is considered intense in terms of the number of storm events. The maximum number of storms in Kievka Bay is observed during the cold season, starting in November. In some years, their number per month reaches 7–8 with an average wind speed of 19–20 m/s, which generates active

wave activity. In summer (June–August), there are usually two (maximum four) storm events per month. The frequency of gale force winds with a speed of more than 16 m/s during the period December–February reaches 7–10%, and during the summer season it does not exceed 1–1.5%. In autumn, the wind speed can reach the hurricane category (≥40 m/s) [40].

The prevailing winds, combined with the relief of the bottom and the configuration of the coastline, caused the development of unrest. Wave heights of 0.5–1.0 m prevail throughout the year. The maximum value of wave heights is not seasonal and varies from 5 to 7.5 m in the open part of the bay.

The tides in Kievka Bay, as well as on the entire southern coast of Primorsky Krai, have an irregular semi-diurnal character [40].

Based on publicly available data from the portal of the Unified State Information System on the Situation in the Oceans, we calculated that only during the period from October–November 2022 and May–November 2023, about 40 storms with wind gusts from 16 to 30 m/s occurred in the Primorsky Territory. [41]. These storms can cause the release of large numbers of marine macrophytes on the coast, which are potential raw materials to produce biochar.

As an example, data from the MODIS Aqua satellite scanner (L2 level, spatial resolution of 300–750 m depending on the wavelength of the spectral channel, daily shooting) obtained before and after the passage of typhoon Khanun were analyzed. The peak of typhoon activity occurred on 29 August 2023 (Figure 6); therefore, the dates 26 August–28 August were chosen as "Before" and 30 August–2 September as "After".

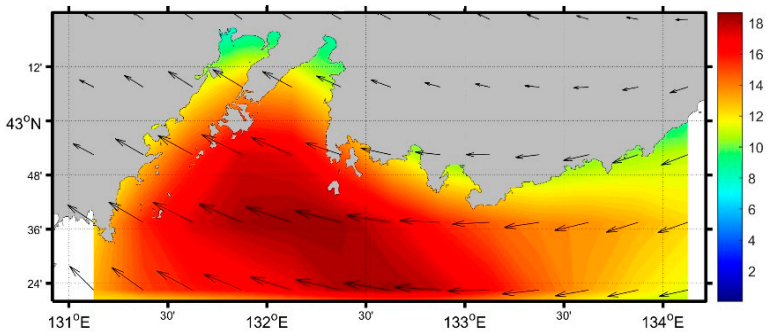


Figure 6. Wind speed (m/s) and direction during the peak of the typhoon's passage through the southern part of the Primorsky region (according to CCMP satellite reanalysis (https://www.remss.com/measurements/ccmp/ (accessed on 25 April 2025)). The arrows show the direction of movement of the air masses.

Based on the average values of chlorophyll-a fluorescence intensity (Figure 7b) and NDVI index (Figure 7d) after the passage of typhoon Khanun, it is possible to identify an area where both NFLH and NDVI increased simultaneously after the typhoon. This increase in indicators may indirectly indicate accumulations of various marine macrophytes on the sea surface. Unfortunately, we were unable to estimate the number of marine macrophyte accumulations on the water surface due to the quality of the images. Nevertheless, it is clear that the macrophyte accumulation zone is quite significant. Over time, these marine macrophytes may approach the shore and become macrophyte beach wrack.

Thus, we see that the result of storm events in the Sea of Japan may be an active removal of coastal macrophytes, which can be tracked using satellite data. The amount of macrophyte beach wrack will depend on the biodiversity in the bays being studied. The coastal marine ecosystems of the sublittoral of Kievka Bay are represented by 14 macrophyte communities, which are represented by 152 species, including 24 species of green algae, 39 species of brown algae, 85 species of red algae, and 4 species of seagrasses [31]. The most

developed macrophyte community near the coast area under study are *Saccharina japonica*, *Phyllospadix iwatensis* + *Saccharina Intermedius* + *Costaria costata*, and *Zostera marina* [31]. At the same time, the biomass of *Zostera marina* alone was 6204.8 ± 47.9 g/m^2, and the projective coverage was 92.2 ± 5.7% [31]. Therefore, the share of this macrophyte in storm emissions is quite significant. The average biomass of Saccharina japonica is 524.85 g/m^2 [31]. *Phyllospadix iwatensis* occurs fragmentarily throughout the bay. The number of storm and wave events, as well as the constant and relatively dense growth of macrophytes, indicates the stable formation of the macrophyte beach wrack.

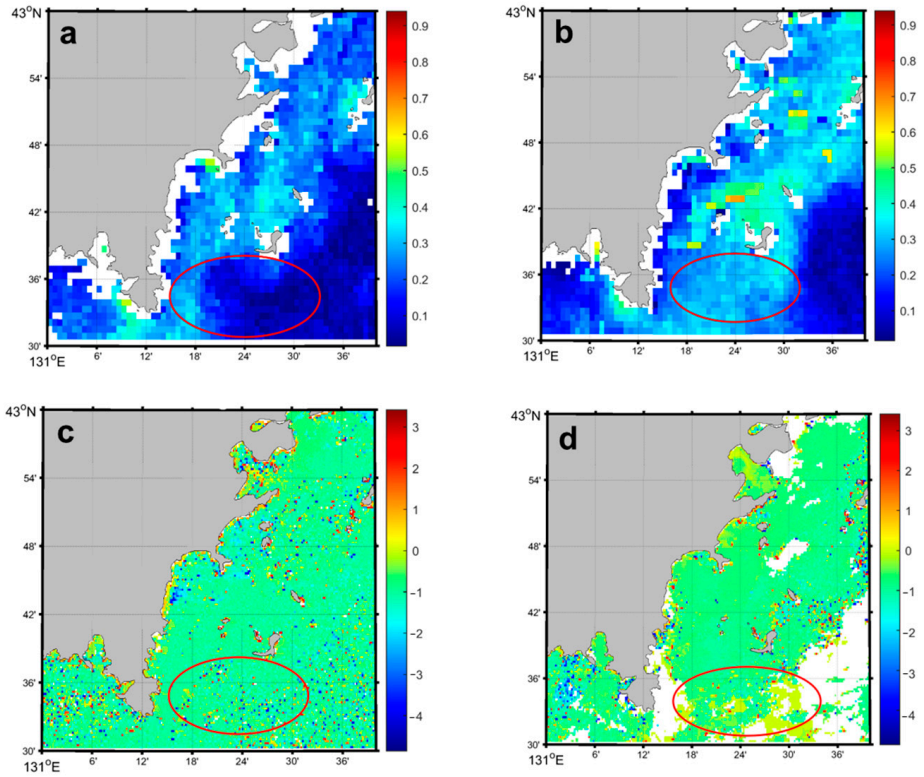


Figure 7. Average values of chlorophyll-a fluorescence (NFLH) intensity for the periods "Before" (**a**) and "After" (**b**) the typhoon Khanun. NDVI index values in the Primorsky Krai for the periods "Before" (**c**) and "After" (**d**) typhoon Khanun.

According to studies, the decomposition of macrophyte beach wrack results in the formation of CO_2 and CH_4 fluxes, which vary over a wide range due to the varying power, temperature, and humidity of macrophyte beach wrack [7,14].

This study showed that CO_2 is released during the decomposition of macrophyte beach wrack on the beach of Kievka Bay. Despite the fact that this study did not measure the humidity of the macrophyte beach wrack, its effect on the CO_2 flux was noted. The CO_2 flux from macrophyte beach wrack that was located near the water's edge was 20% lower compared to CO_2 fluxes from macrophyte beach wrack that was located higher above sea level and visually contained significantly less moisture. According to Liu et al. [13], the moderate moistening of macrophytes leads to increased microbiological processes and leaching of organic matter, which increases the flow of CO_2. In a study by Liu et al., during the 30-day laboratory incubation of the seagrass *Zostera nigricaulis* and *Amphibolis antarctica*, samples with constant moisture showed a 72% higher CO_2 flux value compared to samples without additional moisture [13].

The proximity of the macrophyte beach wrack to the water's edge probably slows down the development of aerobic decomposition, as this area is often flooded with water. Moving the macrophyte beach wrack further away from the water's edge minimizes cases

of flooding with water, which is favorable for the development of aerobic decomposition. As noted by studies in different regions, it is during the aerobic decomposition of macrophyte beach wrack that active processes of CO_2 and CH_4 release occur [4,13,14]. Thus, on beach plots, macrophyte beach wrack plots that remain on the beach for a relatively long time make a more significant contribution to the CO_2 flux.

The presence of a macrophyte beach wrack significantly increases the CO_2 flux compared to plots without a macrophyte beach wrack. On average, according to Coupland et al., in areas with macrophyte beach wrack, there are three times more active flows than in sandy areas [14]. The value of the CO_2 flux in an area with bare sand in the study by Coupland et al., which was conducted on the southwestern coast of Australia, was 350.01 ± 19.8 mg $(CO_2)/m^2$ h and, as can be seen from Figure 3 and Table 1, is close to the measured values of the flux in areas without macrophyte beach wrack. Thus, it is likely that gas flows in areas without macrophyte beach wrack are approximated in different natural and climatic conditions, and in decomposition conditions, the number and type of marine macrophytes contribute to the increase in gas flow in areas with macrophyte beach wrack.

Since we obtained a significant difference in CO_2 flux between the plots with and without macrophyte beach wrack, we assumed that the removal of macrophyte beach wrack would lead to a decrease in CO_2 flux. So, we measured the CO_2 flux before and immediately after the manual removal of the macrophyte beach wrack. Regardless of the degree of humidification of the macrophyte beach wrack, the CO_2 flux decreased significantly immediately after the removal of the macrophyte beach wrack from the deposit plot.

The observed effect of reducing the CO_2 flux when removing macrophyte beach wrack from the surface was noted in September, and we critically evaluated the result and understand that this effect may differ in other months and with other external environmental factors. To further confirm our hypothesis, long-term seasonal observations are needed, which are planned to be carried out in the future.

Reducing the CO_2 flux during cleaning of the macrophyte beach wrack can have a positive environmental effect for owners of recreational areas. In Russia, according to sanitary rules and regulations No. 2.1.3684-21, owners of recreational areas are required to clean the territories from macrophyte beach wrack. Today, the main management strategy of macrophyte beach wrack is its removal and disposal by incineration, which incurs certain financial costs and is environmentally irrational. A similar situation is observed on the Baltic Sea coast [7]. Björk et al. [5] indicate that macrophyte beach wracks are stored in heaps and rot during the summer period, and at the end of the season, they are dumped back into the sea. According to their study, stored marine macrophytes were isolated from 0 to 176 mg $(CH_4\text{-}C)/m^2$ day with an average value of 12.75 mg $(CH_4\text{-}C)/m^2$ day, while areas without marine macrophytes were isolated from 0.01 to 0.36 mg $(CH_4\text{-}C)/m^2$ day.

If the CO_2 flux after macrophyte beach wrack removal is considered as the baseline, then the amount of CO_2 flux reduction can be calculated. Macrophyte beach wrack removal with subsequent recycling into a useful product makes it possible to create climate projects and recalculate the resulting reduction into carbon credits. However, to improve the accuracy of the calculations, the following should be taken into account: (1) the volume of removed macrophyte beach wrack biomass; (2) the percentage of carbon contained in the removed biomass; (3) seasonal or annual greenhouse gas flux at macrophyte beach wrack removal plots; and (4) the frequency of weather conditions and events.

In different countries around the world, washed-up seaweed is processed into fertilizers, which contributes to sustainable development and a circular economy [42]. Also, one of the effective environmental strategies for managing macrophyte beach wrack can

be their processing into biochar. Biochar is a widely used carbon product that allows for long-term carbon storage.

The effectiveness of using biochar is noted on various soils. Biochar, when applied to the soil, can affect pH, EC, specific surface area, the volume density of the soil, water retention capacity, the availability of nutrients for plants, and the microbiological composition of the soil, as well as reduce greenhouse gas emissions [24,25,43–46].

Marine macrophytes are not a traditional raw material to produce biochar. Compared with biochar from land-based raw materials, biochar from marine macrophytes has higher pH values, ash content, nitrogen, phosphorus, and potassium but lower carbon content and surface area [21,22]. However, fresh storm emissions may contain chlorine and sodium, which may adversely affect the growth and development of plants, which means that the pretreatment of such raw materials is necessary, as was shown during our study. According to our SEM–EDX results (Figure 5), biochar from non-desalinated raw materials contains high concentrations of chlorine and sodium, which can be a problem when applied to the soil. Thus, we concluded that the biomass should be rinsed with fresh water before the pyrolysis of macrophyte beach wrack [47,48]. Prolonged exposure to storm surges ashore contributes to the gradual removal of chlorine and sodium from raw materials, which makes them more suitable for use as fertilizers.

If we consider another important parameter of biochar, pH, then due to the high pH value and the content of plant nutrients, biochar from marine macrophytes is likely to have a positive effect when used on acidic, depleted soils. The positive effect of applying biochar to acidic soils has been well studied for biochars from other raw materials [49]. No field experiments have been conducted to evaluate the effects of biochar from marine macrophytes.

The strategy of removing macrophyte beach wrack and converting it to biochar, along with the effect of reducing CO_2 flux and removing carbon from macrophyte beach wrack biomass, can bring such environmental benefits as long-term carbon storage and the reduction of CO_2 flux from soils (carbon sequestration) with the right technology for introducing biochar into the soil, considering natural and climatic conditions. Among the geographical features that affect the success of the climate project, one can single out the hydrological conditions of the territory, the frequency and intensity of the appearance of macrophyte beach wrack, and the amount of biomass of marine macrophytes in the coastal zone.

The main success of creating a climate project based on the processing of macrophyte beach wrack into biochar will depend on economic parameters such as the cost of pyrolysis equipment, energy costs for the collection and processing of raw materials, and transportation costs. Usually, the highest costs are necessary to transport raw materials to the place of production, that is, it is most profitable to process macrophyte beach wrack into biochar close to the place of its origin.

5. Conclusions

According to the results obtained, plots without macrophyte beach wrack had lower CO_2 fluxes compared to plots with macrophyte beach wrack. This effect was noted both during the natural distribution of macrophyte beach wrack on the coast and after their manual collection. On average, the CO_2 flux we measured in August at plots with macrophyte beach wrack (WM and DM) was an order of magnitude higher than at plots without macrophyte beach wrack, depending on the method of analyzing the actual data. In the areas after manual removal of the macrophyte beach wrack, on average, there was a 1.8-fold decrease in flow values compared to the areas with the macrophyte beach wrack.

Removing macrophyte beach wrack and converting it to biochar can be a good environmentally sound strategy because it has such benefits as the reduction of CO_2 flux

after removal of macrophyte beach wrack; the long-term conservation of biomass carbon without macrophyte beach wrack in the biochar structure; and the reduction of greenhouse gas fluxes with proper application of biochar in soils.

Since the study took place on the territory of Primorsky Krai, it can be concluded that Primorsky Krai (and similar territories) are promising for creating projects based on the processing of macrophyte beach wrack into biochar. This is primarily due to the large number of cyclones and storms, the presence of the macrophyte beach wrack, the long coastline, and the farmers' need for high-quality organic fertilizers. In recent years, the tourism industry has been actively developing in Primorsky Krai, and new beach areas have been developed. Like developed tourist and recreational areas, this makes the presence of the macrophyte beach wrack a problem. It is also worth noting that earlier in the Primorsky Territory, the use of charcoal had a positive effect on agricultural soils. In the conditions of vegetation field experience, the use of wood biochar on Luvic Anthrosols led to a decrease in CO_2 fluxes by 28.2% and 57.7% in the cultivation of cabbage and soybeans, respectively, in 2018 and 2019 [36].

This study was the initial stage of assessing the impact of macrophyte beach wrack on CO_2 flux and the possibility of creating a project based on the removal and transformation of macrophyte beach wrack into biochar, including in the Primorsky Territory. The resulting effect of reducing CO_2 flux after the manual removal of macrophyte beach wrack in September is reliable only for the territorial, weather, and climatic conditions of this study. It should be understood that the results may differ in other territorial, weather, and climatic conditions. We understand that for a complete quantitative and qualitative assessment, it is necessary to carry out regular measurements in seasonal dynamics. It is necessary to provide detailed characteristics of the properties of the obtained biochars in accordance with international standards.

For more reasonable conclusions about the economic efficiency of climate projects based on the processing of marine macrophytes into biochar, economic calculations of the entire production technology, risks, and footprint are necessary.

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