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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Emission and Sink of Greenhouse Gases in the Grassland Ecosystem of Southern Taiga of Western Siberia: Estimates of the Contribution of Soil Flux Component from Observations of 2023

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Abstract—Modern changes in the global climate are accompanied by rising air and soil temperatures. How do they affect soil respiration and should we expect a change in greenhouse gas emissions? These questions cannot be answered without studying the soil–air gas exchange. In this work, we analyze greenhouse gas fluxes at the soil–air interface measured at the Fonovaya Observatory in 2023 with the use of three chambers, transparent and opaque chambers on soil areas with vegetation and a transparent chamber on soil without vegetation. A stable CO_2 and CH_4 sink throughout the growing season is shown. For carbon dioxide, on the contrary, a weak positive flux was observed. A steady sink of N_2O from the atmosphere occurred from May to mid-August; its value attained −600 mg m^{-2} h^{-1} in June and July; the methane flux (sink) attained −0.08 mg m^{-2} h^{-1}. The nitrous oxide flux fluctuated about zero with the daily average within ± 0.02 mg m^{-2} h^{-1}. For CO_2, a nonlinear positive relationship between the increase in vegetation respiration and soil temperature is revealed. Linear temperature dependence is found for methane fluxes in all three chambers, that is, an increase in soil temperature enhances CH_4 absorption. N_2O fluxes show very weak positive dependence on the soil temperature in both transparent chambers (with and without vegetation). The estimates of the contribution of CO_2 fluxes from the soil show that microbial respiration can contribute from 46.7 to 77.9% to the total grassland ecosystem respiration during nighttime. The daily average share of methane absorption by soil due to diffusion and oxidation by methanotrophs not associated with plants varies from 5.3 to 48.3%; it becomes smaller during the daytime and increases at night. The contribution of soil without vegetation to the total N_2O flux can attain 92.3%. The results expand knowledge about the soil–air gas exchange under changing climate conditions.

Keywords: atmosphere, air, methane, nitrous oxide, flux, carbon dioxide, emission
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INTRODUCTION

One of the main problems facing humanity in past decades is the ongoing global warming [1]. According to the IPCC, this process is due to increasing atmospheric concentrations of greenhouse gases and the additional heat flux into the atmosphere caused by them [2]. This primarily concerns concentration of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [3–5]. The accurate assessment of greenhouse gas emissions and their redistribution between the atmosphere, ocean, and terrestrial biosphere under the changing climate conditions is critical for better understanding of this process, development of climate policy, and prediction of future changes. Despite great progress in the study of the global spatiotemporal variability of these gases, significant uncertainties still remain in the estimates of their balance [2]. This means that there are sources of greenhouse gas emissions and sink processes which are incorrectly taken into account.

In the total balance of carbon dioxide, methane, and nitrous oxide in the air, the soil–air exchange plays a key role [6]. Moreover, the soil can be both a source and a sink for these air components. To determine the emission or sink capacity under natural conditions, measurements are carried out in remote (background) areas where anthropogenic impact on them is minimal. For this purpose, eddy covariance (or turbulent pulsation) technique [7], as well as gradient or chamber [8] methods are usually used. The eddy covariance technique is considered the most accurate and is used as reference when comparing measurement data [9]. The comparison between the techniques showed that they give similar results. Thus, work [10] has shown that the eddy covariance technique overestimates the net ecosystem production (NEP) of forests by 25% and underestimates the ecosystem respiration (ER) by 10%.

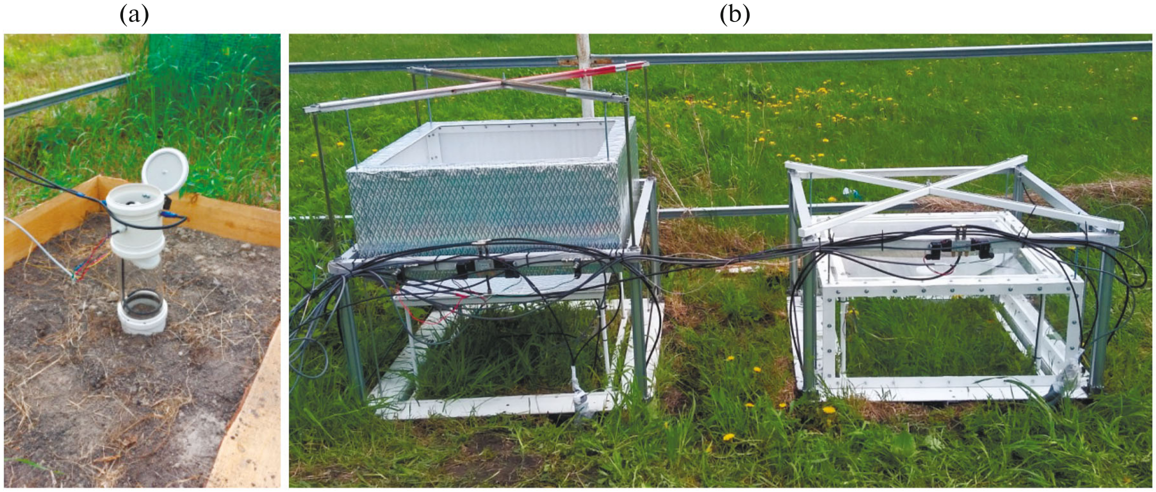

Fig. 1. (a) Small transparent chamber installed on a soil area without vegetation; (b) opaque and transparent chambers in the area with vegetation.

This paper analyzes greenhouse gas fluxes measured with by the static-pressure chamber method. The measurement procedure is well described in the literature and have already been brought to the level of instructions [11–14]. Hundreds of experiments have been conducted in various geographical regions of the planet and under different hydrometeorological conditions, which has made it possible to generalize the main processes of CO_2, CH_4, and N_2O gas exchange between the soil and the atmosphere (e.g., [15]). It should be emphasized that the chamber method, unlike others, provides a possibility of separating the components of the total flux of greenhouse gases at the soil–air interface [11–14]. However, this advantage was rarely used in the analysis of the results in the above publications.

The aim of this work is to study CO_2, CH_4, and N_2O fluxes and to estimate their components in one of the background areas of the Tomsk region.

1. MEASUREMENT SITE AND METHODS

Greenhouse gas fluxes were measured in a meadow ecosystem area on the territory of the Fonovaya Observatory located on the eastern bank of the Ob River 60 km west of Tomsk (56°25′07″ N, 84°04′27″ E) at an altitude of 139 m above sea level. The biogeocenosis type at the measurement site is a grass meadow (never flooded), the soil is alluvial gray-humus (turf) gley (AYg–G–CG~~ according to the 2004 classification). The grass canopy is mainly represented by narrow-leaved meadow-grass (*Poa angustifolia* L., ~50%) and awnless brome (*Bromopsis inermis* (Leyss.) Holub., ~30%), as well as couch grass (*Agropyron repens*), reed canary grass (*Phalaris arundinacea* L.), cow vetch (*Vicia cracca*), common dandelion (*Taraxacum officinale*), and others.

The observatory is surrounded by mixed forests typical of the southern taiga of Western Siberia. There are no large industrial facilities near the observatory. The measuring complex of the observatory is described in [16].

To measure greenhouse gas fluxes between the soil and the atmosphere during a growing season, we used a complex developed at V.E. Zuev Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences (IAO SB RAS), which consists of a Picarro G2508 $N_2O/CH_4/CO_2/NH_3/H_2O$ gas analyzer and automatic system of static-pressure chambers (opaque and transparent, Fig. 1b) [17]. The G2508 analyzer operates in recirculation mode using a Picarro A0702 vacuum pump. Chambers of 0.324 m^3 in volume are opened and closed by means of an automated pneumatic control system in the following sequence: (1) the opaque chamber is closed and the transparent chamber is open (5 min); (2) vice versa (8 min); (3) both chambers are open (7 min) for ventilation in order to maintain the natural ecosystem conditions, etc. (a total of three cycles per hour).

The vegetation cover of terrestrial ecosystems assimilates carbon during photosynthesis [13], which forms the gross primary production of vegetation (GPP). About 50–60% of the carbon absorbed by plants returns to the atmosphere due to the ecosystem respiration (ER), which consists of the above phytomass respiration (APR) and the soil respiration (SR). The latter, is divided into two main components: (1) the root respiration (RR) with the associated rhizomicrobial respiration (RMR) and (2) respiration of soil microorganisms (microbial respiration, MR), which decompose soil organic matter [13]. An indicator of the intensity of atmospheric carbon accumulation by vegetation cover is the net primary production (NPP) defined as [13]:

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{AR}, \qquad (1)$$

where AR = APR + RR + RMR is the total intensity of plant respiration (autotrophic respiration).

A transparent chamber (T) installed on soil with vegetation enables measuring the specific flux, which represents the net ecosystem exchange (NEE) [13]:

$$\begin{aligned}[F_{CO_2}]_T &= \mathrm{NEE}_{CO_2} = \mathrm{ER} - \mathrm{GPP} \\ &= \mathrm{APR} + \mathrm{SR} - \mathrm{GPP} \qquad (2) \\ &= \mathrm{APR} + \mathrm{RR} + \mathrm{RMR} + \mathrm{MR} - \mathrm{GPP}.\end{aligned}$$

Using an opaque chamber (O), we measured the specific CO_2 flux, which characterizes the total ecosystem respiration:

$$\begin{aligned}[F_{CO_2}]_O &= \mathrm{ER} = \mathrm{APR} + \mathrm{SR} \\ &= \mathrm{APR} + \mathrm{RR} + \mathrm{RMR} + \mathrm{MR}.\end{aligned} \qquad (3)$$

Therefore, when analyzing NEE and ER, it is impossible to distinguish the contributions of such carbon balance components as autotrophic and microbial respiration.

To solve this problem, the second transparent chamber was additionally installed at the Fonovaya Observatory on a 1-m^2 plot of soil, from which all vegetation had been previously removed, in August 2023 (Fig. 1a). Unlike previously installed chambers, the new one was compact, its inner diameter was 104 mm, the height of the measuring part (from the soil surface to the top) was 350 mm. The new chamber was integrated into the existing greenhouse gas flux measurement complex so as during the ventilation mode of the first two chambers (7 min), its tubes (supplying and outlet) were purging during the first 3 min and measurements were performed during the remaining 4 min. The previously developed software, which control the general process and data recording, has been modified. This made it possible to measure only microbial respiration (CO_2 emission).

The specific methane flux measured by the chambers at the soil–air interface is determined by natural processes [15, 18–23], which can be written in a simplified form as

$$F_{CH_4} = \mathrm{MG} + \mathrm{PMT} \pm \mathrm{PME} + \mathrm{ME} \pm \mathrm{MD} - \mathrm{MO}, \qquad (4)$$

where MG is the methanogenesis of CH_4; PMT is the plant-mediated transport of methane; PME is plant-mediated exchange of methane via methanogens (+) and methanotrophs (–) associated with shoots and roots; ME is the methane ebullition; MD is the methane diffusion into/from the soil, the sign of which depends on the CH_4 concentration gradient between the atmosphere and the soil; MO is the methane oxidation by methanotrophic and autotrophic ammonium-oxidizing bacteria.

Natural meadows are known to be site for methane sink from the atmosphere [18]. The rate of its absorption from the atmosphere by soil is determined by diffusion [22], which, in turn, serves the main limiting factor of methanotrophs oxidation of CH_4 in most soil types [24]. Diffusion, in turn, depends on soil moisture. It is lower in wetlands due to a decrease in the number of pores filled with air [18]. Though heavy precipitation creates favorable conditions for methanogenesis, which increases the CH_4 concentration in soil [25], emission of methane from meadow ecosystems is negligible due to diffusion weakening [26]. Methane ebullition is characteristic of aquatic ecosystems [19]. Therefore, equation (4) for the specific flux measured with the transparent chamber on a soil area without vegetation (S – soil) can be written in a simplified form as

$$[F_{CH_4}]_S = -\mathrm{MD} - \mathrm{MO}; \qquad (5)$$

and for transparent and dark chambers with vegetation,

$$\begin{aligned}[F_{CH_4}]_T &= \mathrm{PMT} - \mathrm{PME} + [F_{CH_4}]_S, \\ [F_{CO_2}]_O &= \mathrm{PMT} - \mathrm{PME} + [F_{CH_4}]_S.\end{aligned} \qquad (6)$$

Thus, the combination of three chambers made it possible to estimate individual components of the carbon cycle.

As for nitrous oxide fluxes, there are significant uncertainties in their measurement. Most of the currently available data are obtained by the chamber method and indicate N_2O absorption by soil. However, many authors attribute this to technical limitations, i.e., the detection limit and N_2O concentration measurement accuracy [27]. Some studies with other methods show that N_2O absorption is mainly possible during the daytime [28, 29]. A nitrous oxide flux at the soil–air interface is determined by the following processes [15, 27, 30]:

$$F_{N_2O} = \mathrm{NA} + \mathrm{DN} \pm \mathrm{NOD}, \qquad (7)$$

where NA and DN are the nitrification of ammonium (NH_4^+) and denitrification of nitrate (NO_3^-) by soil microorganisms, respectively; NOD is the nitrous oxide diffusion into/from soil (nitrous oxide diffusion), the sign of which depends on the N_2O concentration gradient between the atmosphere and the soil. In wetlands, the denitrification mechanism of nitrous oxide generation predominates, while in dryer soils, the nitrification mechanism predominates [15].

2. RESULTS AND DISCUSSION

2.1. Daily Average Fluxes

Monitoring of gas fluxes began at the Fonovaya Observatory in early May 2023 and was completed in mid-October. Figure 2 shows the specific fluxes of carbon dioxide, methane, and nitrous measured with the use of three chambers.

According to Fig. 2a, a steady sink of carbon dioxide from the atmosphere was observed from May to mid-August; its attained −600 mg m^{-2} h^{-1} in June and

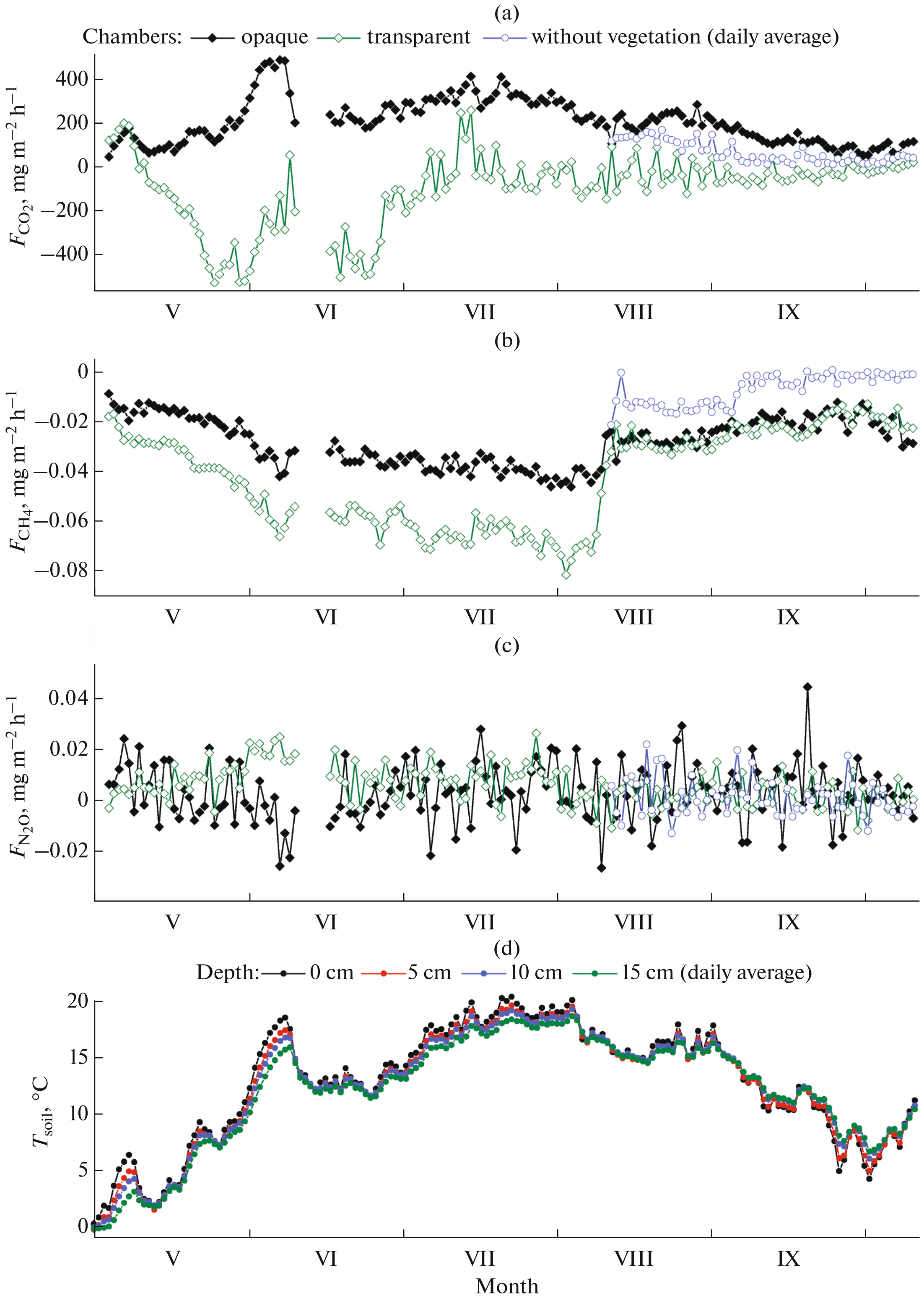

Fig. 2. Daily average specific fluxes of (a) CO_2, (b) CH_4, and (c) N_2O and (d) the soil temperature in 2023.

July. During that period, ecosystem respiration (ER) increased to 500 mg m^{-2} h^{-1}, as can be seen from the opaque chamber data. Since mid-August, the vegetation activity began to fade, which was reflected in the magnitude of the fluxes in the transparent and opaque chambers. The fluxes in the chamber installed on soil without vegetation were intermediate. This means that soil respiration makes a part of the total CO_2 gas exchange. The comparison between the dynamics of CO_2 flux and soil temperature (Figs. 2a and 2d) shows their long-term variations to be correlated. This is especially noticeable in the data from the opaque chamber.

The meadow area of the soil of the Fonovaya Observatory is also a place where methane sinks from the atmosphere (Fig. 2b). The sink rate can attain -0.08 mg m^{-2} h^{-1}. Its main period coincides with sink of CO_2. One can note differences in sink of CO_2 and CH_4. The comparison between Figs. 2b and 2d shows a monotone increase in the methane sink intensity, which weakly depends on soil temperature at first glance. It is likely that methanotrophs play a significant role in the sink of methane from the atmosphere in the presence of vegetation [23, 31], since the flux rate approaches zero in the chamber without vegetation after the decrease in the vegetation activity (mid-August) (Fig. 2b).

Work [31] have shown that an increase in the autotrophic respiration (CO_2 emissions) linearly increases the specific consumption of methane($R^2 = 0.81$). They suggested the quantitative theoretical explanation for this effect. According to their findings, the contribution of plant root-associated methanotrophy to the total methane consumption by soil of the grass-moss layer in forest ecosystems of southern taiga of Western Siberia is significant and should be taken into account when calculating the methane balance, since calculations of methane fluxes taking into account this mechanism of CH_4 absorption and free (not associated with plants) methanotrophy well agree with experimental data [31].

Nitrous oxide flux fluctuates about zero, and its daily average variations are within the range ± 0.02 mg m^{-2} h^{-1} (Fig. 2c). The fluctuations of N_2O have a higher frequency and are weakly related to soil temperature (Fig. 2a). Work [15] associates the pronounced pulsating nature of the N_2O flux with variations in humidity and temperature, which promote the "release" of nitrous oxide from soil solution.

2.2. Daytime and Nigh Fluxes

Since photosynthesis significantly influences the soil–air gas exchange, we separately consider it for daytime and nighttime conditions. Our analysis revealed significant differences in CO_2 and CH_4 fluxes at midday and at night. For N_2O, no significant difference was found against the background of low and variable flux values.

Figure 3 shows daytime (10:00–14:00 local time) and nighttime (22:00–02:00) average CO_2 fluxes. According to Fig. 3a, the daytime average CO_2 flux attain a minimum (sink) of ~–2000 mg m^{-2} h^{-1} in June, when the vegetation activity is maximal. Moreover, despite its sharp decrease by mid-August, F_{CO_2} values remain negative until mid-October. This witnesses that CO_2 absorption by plants continues. ER and MR (chamber without vegetation) are positive during this period, which means CO_2 emission into the atmosphere.

Before analyzing Fig. 3b, we should note that the opaque and transparent chambers installed on soil areas with vegetation are equal in geometric dimensions and located next to each other. Their bases were cut into the soil back in 2016. Vegetation inside them is similar. Measurements are carried out using the same gas analyzer.

The daily average specific CO_2 fluxes for these chambers (Fig. 3b*)* should also be close in value, since only the ecosystem respiration is measured at night using both chambers. The flux values evidently coincide only at the beginning and end of the growing season, while they differ by almost two times during the period of maximal vegetation activity. This difference is due to the suppression of vegetation in the opaque chamber because it is closed for 15 min each hour and, as a result, it receives 25% less solar radiation than the transparent chamber. This fact is pointed out by many authors, e.g., [9].

There are also daytime and nighttime differences in the daily average methane fluxes (Fig. 4). First, the fluxes measured in the transparent and opaque chambers significantly differ both during the day and at night in the period of active vegetation (Fig. 4), and the differences are leveled out when the vegetation activity decreases. This, in our opinion, suggests that the contribution of vegetation-associated methanotrophy to CH_4 sink in the opaque chamber is lower than in the transparent one due to the smaller number of methane oxidizing microorganisms in the former. Second, daytime methane fluxes are 20–30% greater than night fluxes during the growing season. It is difficult to connect this fact with any process.

2.3. Daily Variations

Let us consider to the daily variations in greenhouse gas fluxes measured with the use of three chambers (Fig. 5).

2.3.1. Carbon dioxide

The daily cycle of CO_2 fluxes averaged over different months of the growing season of 2023 measured in a transparent chamber is shown in Fig. 5a. It did not qualitatively change compared to previous years [32], the carbon dioxide absorption was maximal in June. Figure 5b shows the behavior of CO_2 fluxes in the opaque chamber throughout the growing season. A morning minimum around 06:00–08:00 and a broad daytime maximum from 10:00 to 20:00 are pronounced. The seasonal variation is also noticeable. The flux is maximal in June and July and minimal in

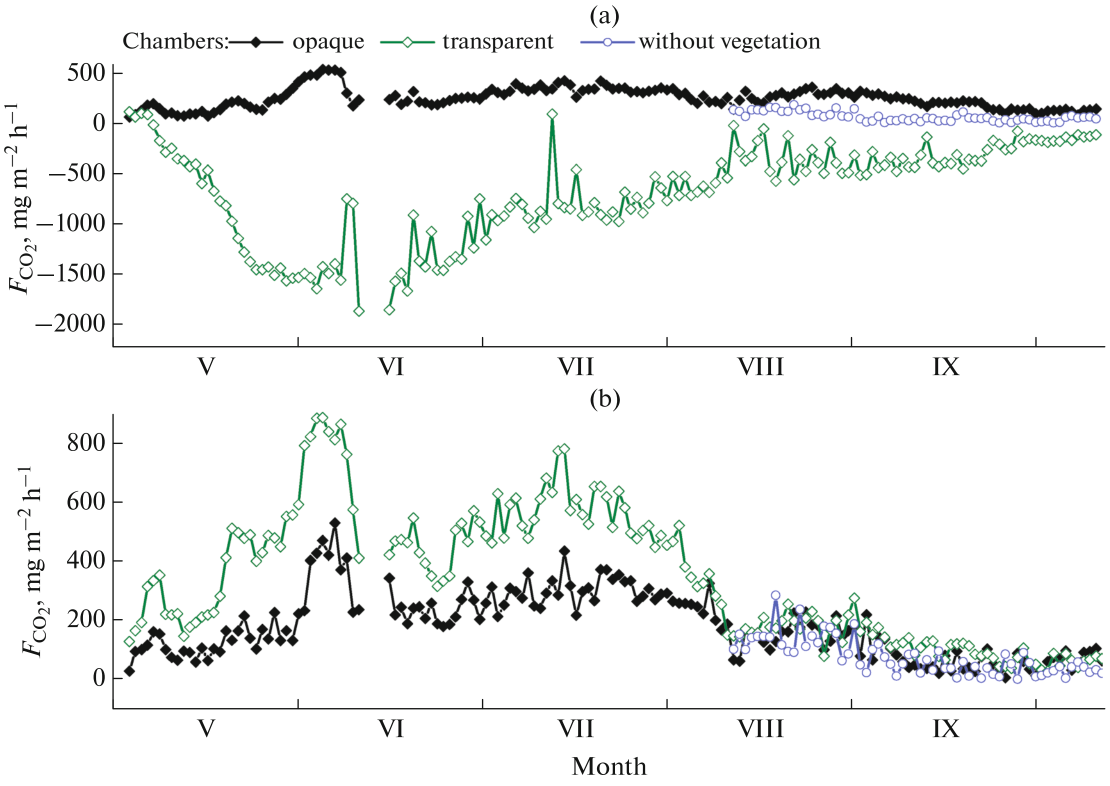

Fig. 3. (a) Daytime (10:00–14:00) and (b) nighttime (22:00–02:00) average specific CO_2 fluxes in 2023.

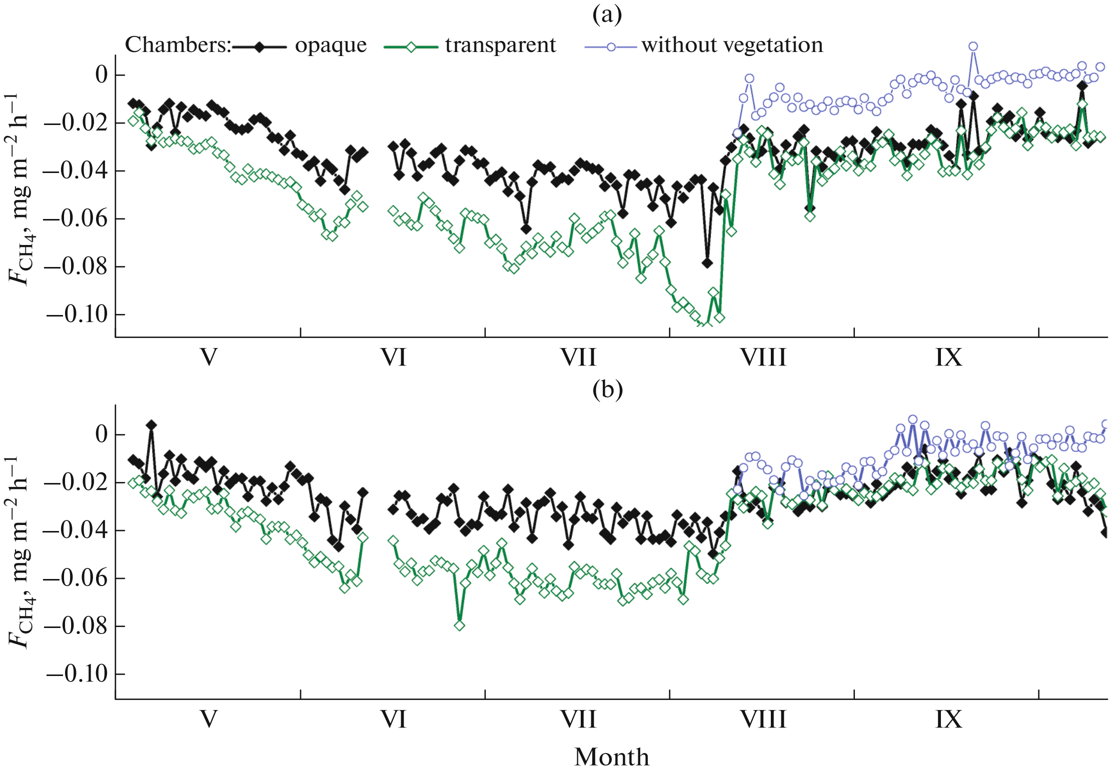

Fig. 4. (a) Daytime (10:00–14:00) and (b) nighttime (22:00–02:00) average specific CH_4 fluxes in 2023.

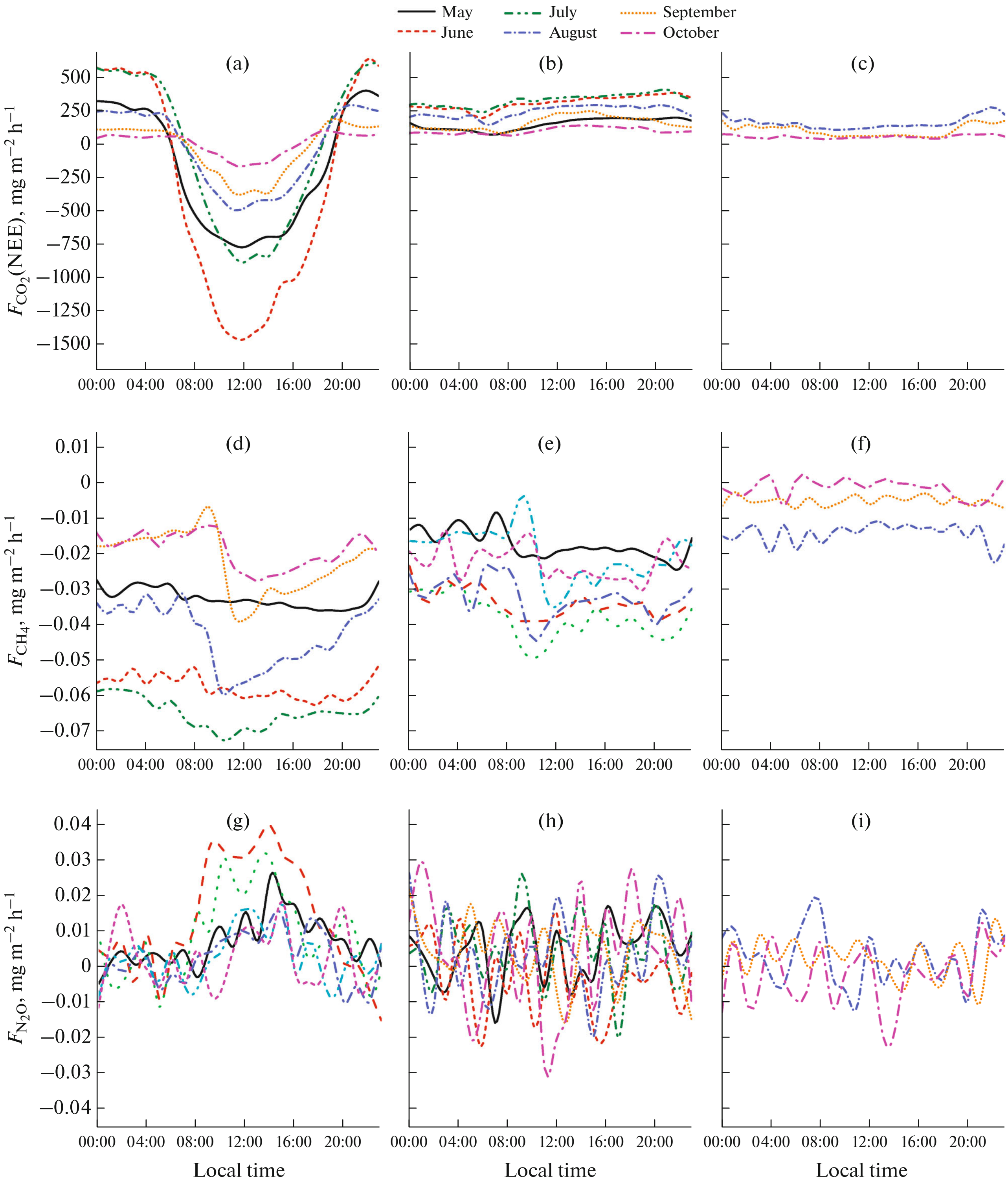

Fig. 5. Daily variations in specific CO_2, CH_4, and N_2O fluxes measured with (a, d, g) the transparent and (b, e, h) opaque chambers with vegetation and (c, f, i) the transparent chamber without vegetation in 2023.

May and October. Since we are talking about ER, this variation apparently reflects the daily variation in the soil temperature. We return to this issue in the next section.

For MR, an evening or night maximum and a daytime minimum are unexpectedly detected (Fig. 5c). The MR was maximal in August (the beginning of measurements) and decreased in October. It is difficult to explain this daily cycle.

2.3.2. Methane

Methane fluxes measured in the transparent and opaque chambers with vegetation (Figs. 5d and 5e) show similar daily variations with a daytime absorption maximum from June to October. Since the activity of methane oxidizing microorganisms strongly depends on the degree of soil warming, the daily cycle is less pronounced in May. The differences in the absolute values of the fluxes can be explained by the fact that the vegetation is less developed in the opaque chamber and, hence, the part of CH_4 oxidation by methanotrophs associated with shoots and roots is lower than in the transparent chamber.

The daily variations in the CH_4 fluxes measured in the chamber without vegetation are insignificant during August, September and October (Fig. 5f). The methane absorption by soil was maximal in August and decreased to zero in October. This can be explained by the influence of soil temperature on free methanotrophy processes.

2.3.3. Nitrous oxide

The measurements of N_2O fluxes show their daily variations to be the most pronounced, with a daily maximum, in the area with vegetation, where a transparent chamber was installed (Fig. 5g). The daily N_2O emission was maximal in June and July due to the activation of soil microorganisms involved in the biochemical processes of nitrification and denitrification in that period. Daily variations in N_2O fluxes measured in both the opaque chamber with vegetation (Fig. 5h) and the transparent chamber without it (Fig. 5i) are random in character, which is most likely determined by N_2O diffusion into/from the soil.

2.4. Seasonal Variations

Let us analyze the seasonal dynamics of greenhouse gas fluxes in 2023 based on their monthly average values (Fig. 6). Data from previous years has also been added to Fig. 6 for comparison. During the measurement season in 2023, carbon dioxide sink from the atmosphere was observed at the Fonovaya Observatory (Fig. 6a). It was maximal in June, then sharply decreased to near zero and remained at that level until the end of the growing season. A similar seasonal trend was also observed in 2020. The comparison between Figs. 2a and 6a shows that the decrease in the carbon dioxide absorption intensity starts earlier than the decrease in vegetation activity. Compared to previous years, 2023 is an intermediate year in terms of CO_2 exchange between the atmosphere and the soil (NEE). Methane is also characterized by sink throughout the growing season (Fig. 6b). Moreover, it was the highest in 2023 compared to previous years. Like for CO_2, the sink of methane started earlier than the decrease in vegetation activity (Figs. 2b and Fig. 6b). The behavior of N_2O fluxes was opposite (Fig. 6c). Although the fluxes were small in magnitude, they increased to their maxima in June and then slowly decreased until the end of the growing season. Compared to previous years, the values of N_2O fluxes were slightly below the long-term average in 2023, probably due to less precipitation (Fig. 6d).

Thus, the seasonal variations in greenhouse gas fluxes had several anomalies in 2023 compared to previous years [32].

2.5. Fluxes Versus Soil Temperature

Since the dependence of variations in greenhouse gas fluxes on the soil temperature is noted several times in the previous sections, we can assumed similar dependencies on the solar radiation intensity and air temperature. It is known that the atmosphere is heated due to solar radiation absorption.

Figure 7 shows the curves of CO_2 fluxes versus the soil temperature separately for the transparent and opaque chambers with vegetation and the transparent chamber without it, since the dependences of the fluxes on soil temperature significantly differ in these three cases. For the transparent chamber, a trend towards an increase in CO_2 sink with the temperature during the daytime is seen (Fig. 7a); nonlinear positive relationships can be traced between night values of ER and MR in this chamber and between their daily average values in the other two chambers (Fig. 7b).

For CH_4 fluxes, negative linear temperature dependences were obtained for all three chambers (Fig. 7a), i.e., methane absorption by the grassland ecosystem increases with the soil temperature.

Finally, very weak positive trends in N_2O fluxes can be seen for the transparent chambers with and without vegetation (Fig. 7a), i.e., N_2O emission from the soil surface slightly increases with the soil temperature. In the opaque chamber, the behavior of N_2O fluxes is neutral.

Since the dependence of the daytime CO_2 fluxes on the soil temperature is weak in the transparent chamber ($R = -0.30$; see Fig. 7a), the diurnal NEE is obviously primarily determined by the amount of solar radiation which reaches the Earth's surface. Figure 8 shows the dependence of the daily average NEE on the

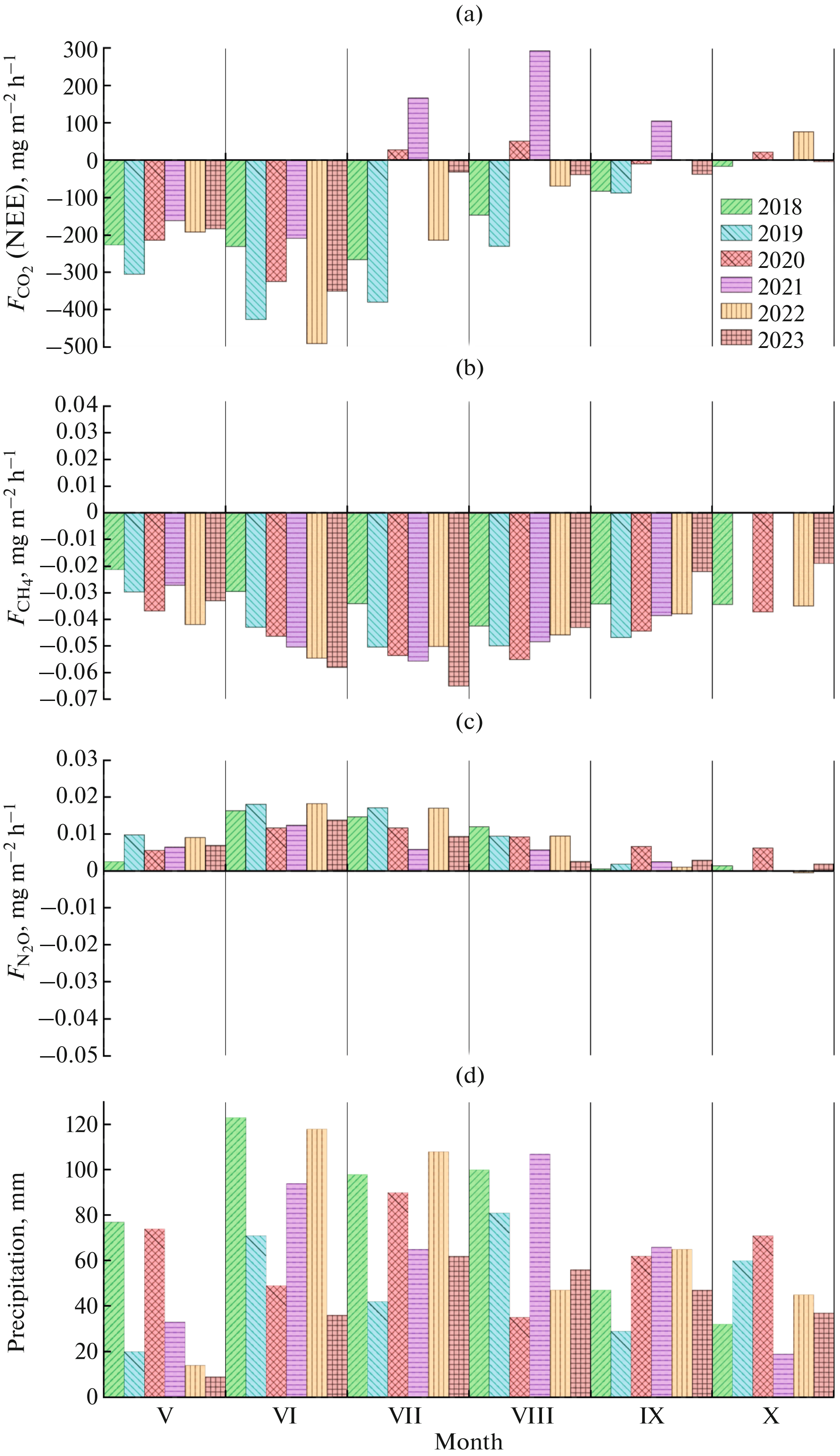

Fig. 6. Monthly average specific greenhouse gas fluxes measured with (a–c) the transparent chamber with vegetation; (d) monthly precipitation.

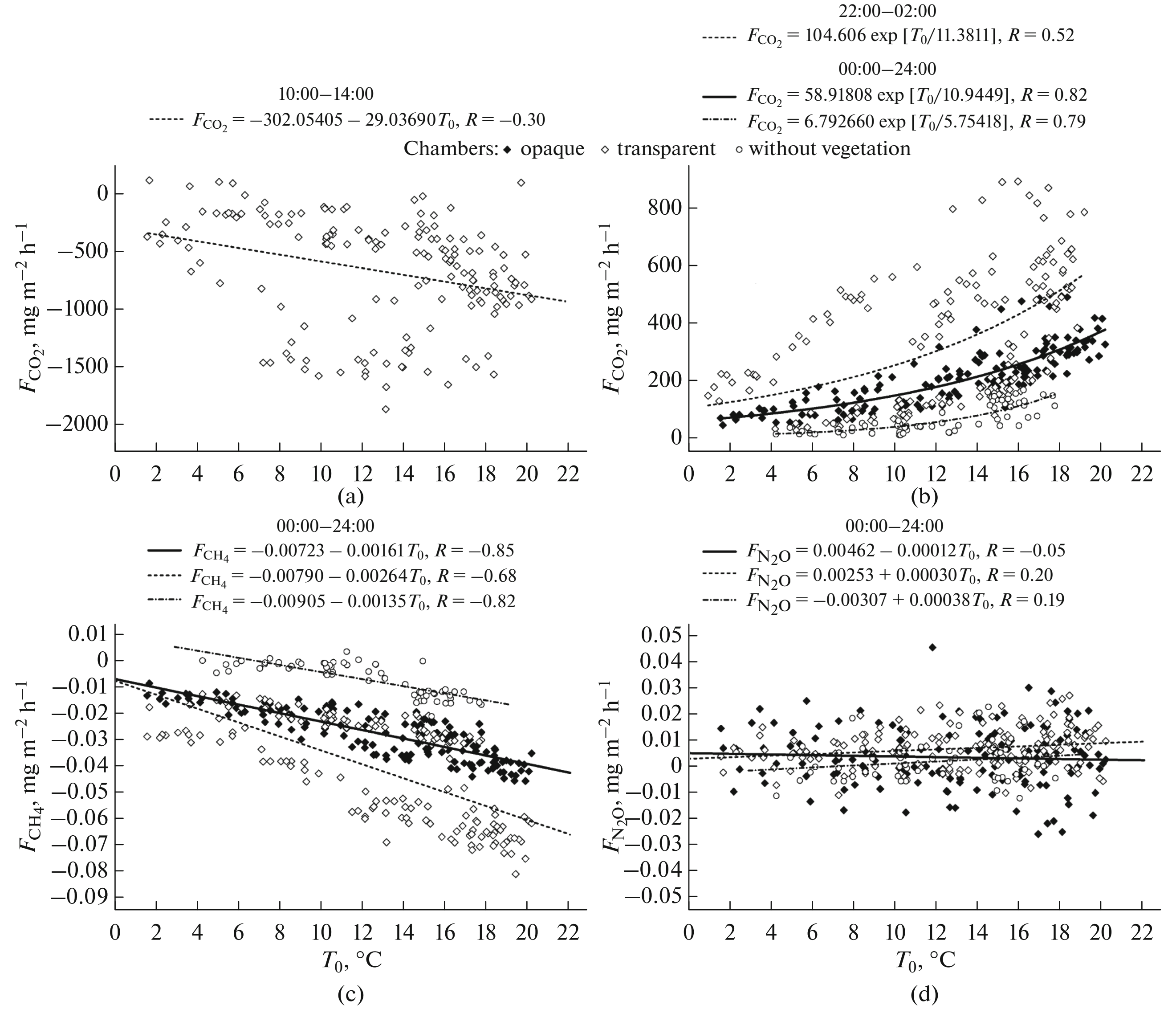

Fig. 7. Daily average specific (a, b) CO_2, (c) CH_4 and (d) N_2O fluxes as functions of the daily average soil surface temperature (T_0).

photosynthetically active radiation (PAR, 400 nm $< \lambda < 700$ nm) flux density measured with a PQS1 sensor (Kipp & Zonen BV, Netherlands). A significant negative linear relationship is seen from June to September inclusive. Since intensive growth of biomass begins with the spring resumption of photosynthesis and the total surface area of CO_2 absorbing plants rapidly changes, May is characterized by a steeper slope of the linear regression against the background of a greater spread of the flux values. In October, the photosynthesis efficiency drops to near zero and the dependence of daily NEE values on PAR becomes less significant.

Thus, when greenhouse gas fluxes are generated at the soil–atmosphere interface, they depend on the soil temperature, with the exception of daytime NEE, which is primarily determined by photosynthetic photon flux density.

2.6. Flux Ratios

2.6.1. Carbon dioxide

When analyzing greenhouse gas fluxes, we have noted suppression of vegetation on the soil area where the opaque chamber is mounted because of the disruption of natural biological cycles due to artificial creation of night conditions in the chamber three times per hour. Therefore, it would be incorrect to use the data obtained from this area to estimate the contribution of MR. Hence, this estimate can only be made using night-time data (22:00–02:00) from the transparent chambers with and without vegetation. The first of them enables recording ER = APR + SR =

APR + RR + RMR + MR, and the second records only MR. Hence, these measurements make it possible to estimate the contribution of MR to ER. Table 1 presents the estimates made in the period of CO_2 measurements with the simultaneous use of these chambers. One can see that on average, the soil microbial respiration (MR) can make up from 46.7 to 77.9% of the total meadow ecosystem respiration (ER) at night. The MR contribution smoothly changes as the temperature decreases.

2.6.2. Methane

According to Eqs. (5) and (6), the specific methane fluxes measured by the chambers in a soil area without vegetation $[F_{CH_4}]_S$ are determined by the processes of diffusion and free methanotrophy (MD and MO), while in the areas with vegetation $[F_{CH_4}]_T$ and $[F_{CH_4}]_O$ are also depends on the methane transport by vascular plants from the soil to the atmosphere and the exchange connected with shoots and roots associated methanotrophs. Therefore, it is possible to estimate the contribution of methane absorption by soil due to diffusion and free methanotrophy (Table 2). However, this estimation is more accurate if using data from two transparent chambers for the reason stated in the previous section. It changes from 5.3 to 48.3% per day on average. The contribution becomes smaller during the day and increases at night.

2.6.3. Nitrous oxide

As mentioned above, the soil–atmosphere exchange of N_2O is determined by nitrification and denitrification processes in soil and N_2O emission from the soil or sink from the atmosphere due to diffusion. According to Table 3, the contribution of soil without vegetation to the total N_2O emission was 92.3 and 82.8% in August and September, respectively. In October, N_2O diffusion from the atmosphere into the soil predominated on the soil area without vegetation. Unfortunately, we could not estimate the dynamics of N_2O fluxes during the day and night, since the flux values were very small, which resulted in a large spread in $[F_{N_2O}]_S/[F_{N_2O}]_T$ values.

In conclusion of this section, it is important to emphasize that the presented data should be considered preliminary, as they do not cover the entire season from May to October and have been received for the only year.

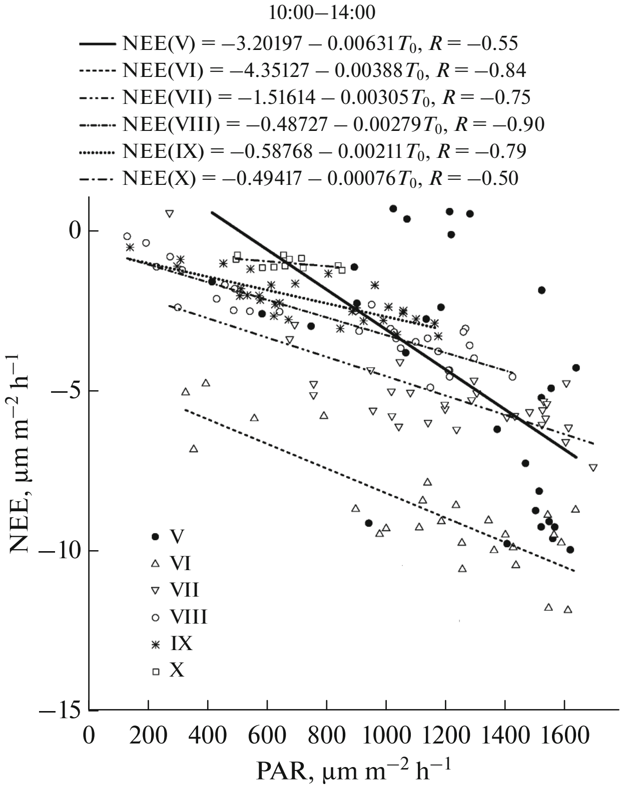

Fig. 8. Daytime average (10:00–14:00) specific CO_2 fluxes in the transparent chamber with vegetation as functions of the daytime average (10:00–14:00) photosynthetically active radiation flux density.

3. COMPARISON WITH LITERATURE DATA

In Siberia or adjacent areas, carbon dioxide fluxes were mainly measured in wetland [33–35]. The results of works [31, 36] for boreal forest or [37] for a meadow are the closest to our estimates in terms of the flux magnitudes and seasonal variations. They are significantly higher than the flux values for this region in [38]. Such differences might well be due to the more northern location of the area we have studied in this work.

Quite a lot of work has been devoted to methane fluxes from swamps or lakes [39–43]. Key forest areas

Table 1. Estimates of the contribution of heterotrophic respiration to total natural meadow ecosystem respiration at night (22:00–02:00)

Specific CO_2 flux, mg m^{-2} h^{-1}	VIII	IX	X
Transparent chamber with vegetation (ER)	179.8 ± 39.6	111.5 ± 50.1	59.5 ± 20.4
Transparent chamber without vegetation (MR)	140.1 ± 52.4	53.1 ± 41.6	27.8 ± 16.3
MR/ER, %	77.9	47.6	46.7

Table 2. Estimates of the contribution of diffusion and free methanotrophy to the total methane exchange in a natural meadow ecosystem during daytime and at night

Specific CH_4 flux, mg m^{-2} h^{-1}	VIII	IX	X
Daily Average			
Transparent chamber with vegetation $[F_{CH_4}]_T$	−0.029 ± 0.003	−0.022 ± 0.004	−0.019 ± 0.004
Transparent chamber without vegetation $[F_{CH_4}]_S$	−0.014 ± 0.004	−0.005 ± 0.005	−0.001 ± 0.001
$[F_{CH_4}]_S/[F_{CH_4}]_T$, %	48.3	22.7	5.3
Daytime (10:00–14:00)			
Transparent chamber with vegetation $[F_{CH_4}]_T$	−0.036 ± 0.008	−0.031 ± 0.008	−0.023 ± 0.004
Transparent chamber without vegetation $[F_{CH_4}]_S$	−0.012 ± 0.005	−0.004 ± 0.005	0.000 ± 0.002
$[F_{CH_4}]_S/[F_{CH_4}]_T$, %	33.3	12.9	0
Night (22:00–02:00)			
Transparent chamber with vegetation $[F_{CH_4}]_T$	−0.025 ± 0.004	−0.018 ± 0.005	−0.019 ± 0.006
Transparent chamber without vegetation $[F_{CH_4}]_S$	−0.016 ± 0.005	−0.005 ± 0.006	−0.001 ± 0.006
$[F_{CH_4}]_S/[F_{CH_4}]_T$, %	64.0	27.8	5.3

Table 3. Estimates of the contribution of N_2O emissions from soil without vegetation to the total N_2O exchange between the meadow ecosystem and the atmosphere

Specific N_2O flux, mg m^{-2} h^{-1}	VIII	IX	X
Daily average			
Transparent chamber with vegetation $[F_{N_2O}]_T$	0.0026 ± 0.0052	0.0029 ± 0.0064	0.0015 ± 0.0046
Transparent chamber without vegetation $[F_{N_2O}]_S$	0.0024 ± 0.0095	0.0024 ± 0.0066	−0.0026 ± 0.0052
$[F_{N_2O}]_S/[F_{N_2O}]_T$, %	92.3	82.8	But

of the southern taiga of Western Siberia were studied in detail in [31]. We have previously compared of CO_2 and CH_4 fluxes measured at the Fonovaya Observatory [44] and at a site of the Vasyugan swamp [33, 34]. We have shown that the swamp is a source of methane throughout the season, while methane sink is observed at the Fonovaya Observatory on average.

The values of nitrous oxide fluxes in [45–47] are very close to our estimates. Daily and seasonal variations also coincide. Moreover, small N_2O fluxes recorded in many background areas enables the authors of [48] to conclude that it is necessary to increase the number of chambers for measuring N_2O fluxes in order to make representative regional assessments.

Some studies have analyzed changes in greenhouse gas fluxes depending on the soil temperature. Thus, [49, 50] have found that the CO_2 flux nonlinearly increases with the soil temperature. A linear relationship between an increase in the methane sink and the increase in the soil temperature was revealed in [51]. In [45], a very weak linear relationship between nitrous oxide fluxes and soil temperature was derived. Hence, the relationships we have derived are confirmed by other authors.

Work [52] analyzes soil respiration measurements on a global scale. It has been established that soil respiration can contribute from 1.8 to 89.3% to the total respiration of the soil–atmosphere system. Our estimates fall within this range. Work [53] has shown an increase in the contribution of soil respiration at night and a decrease in daytime, which confirms the above made conclusions. The highest emission from the soil is recorded for carbon dioxide, and the lowest, for nitrous oxide [54]. This is also evident from the comparison of the data in Tables 1–3.

CONCLUSIONS

The analysis of greenhouse gas fluxes at the Fonovaya Observatory in 2023 showed several anomalies in their dynamics compared to previous years. The sink of carbon dioxide and methane from the atmosphere continued. The CO_2 sink was maximal in June and then it sharply decreased to near zero. This value maintained until the end of the growing season. Moreover, the reduction in the carbon dioxide and methane absorption began earlier than the decrease in vegetation activity. Negative methane fluxes (sink) in 2023 were the largest in absolute value compared to previous years. N_2O fluxes were small in magnitude, they maximized in June and then slowly decreased until the end of the growing season. Compared to previous years, they were slightly lower than the long-term average.

Daily averages showed a steady sink of carbon dioxide from the atmosphere between May and mid-August. During that period, the meadow ecosystem respiration also increased. The main period of methane sink was the same. The N_2O flux fluctuated near zero, and its daily average variations were within the limits of about ± 0.02 mg m^{-2} h^{-1}.

In 2023, peculiarities were also identified in the daily variations in greenhouse gas fluxes. Thus, a morning minimum around 06:00–08:00 and a broad daytime maximum from 10:00 to 20:00 were characteristic of CO_2 flux in the opaque chamber, throughout the growing season. During the daytime, methane emissions increased. Nitrous oxide flux randomly varied throughout the day. An evening or nighttime maximum and a daytime minimum were unexpectedly detected for carbon dioxide in the soil microbial respiration. It is still difficult to explain this daily cycle. No pronounced daily variation in CH_4 and N_2O fluxes was observed for a soil area without vegetation.

The analysis of the relationship between the specific greenhouse gas fluxes and the soil temperature showed a slight trend towards an increase in CO_2 sink with the temperature in the transparent chamber with vegetation. A nonlinear positive relationship is observed between the meadow ecosystem respiration and the soil microbial respiration. For methane, negative linear dependences were found for all three chambers, i.e., methane absorption by the meadow ecosystem increases with the soil temperature. A very weak positive dependence was found for N_2O in transparent chambers with and without vegetation, i.e., nitrous oxide emission from the soil surface slightly increased with the soil temperature. The daily average variations in N_2O fluxes measured with both the opaque chamber with vegetation and a transparent chamber without it, rather reflect the predominance of the diffusion mechanism of gas exchange between the soil and the atmosphere over the biochemical mechanism.

Estimates of CO_2 emission contributions into the total ecosystem respiration show that soil microbial respiration can contribute from 46.7 to 77.9% at night. The daily contribution of the methane absorption by soil due to diffusion and free methanotrophy varies from 5.3 to 48.3% on average. This magnitude becomes smaller during the daytime and increases at night. Contribution of soil without vegetation to total N_2O emissions can attain 92.3%. It is important to emphasize that the data presented here should be considered preliminary. They do not cover the entire season and are received for the only year.

Measurements of fluxes in the opaque chamber have shown that its long-term use on the same soil area leads to vegetation suppression because of the disruption of natural biological cycles due to the artificial creation of night conditions three times per hour. In this regard, we plan convert the opaque chamber into transparent in order to assess the effect of meadow ecosystem inhomogeneity on greenhouse gas fluxes in general and their measurements with the use of an eddy covariance system, which is planned to be mounted in 2024.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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