ISSN 1024-8560, Atmospheric and Oceanic Optics, 2024, Vol. 37, No. 2, pp. 236–243. © Pleiades Publishing, Ltd., 2024.
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ATMOSPHERIC RADIATION, OPTICAL WEATHER, AND CLIMATE

Carbon Dioxide Emissions from Freshwater Systems in Western Siberia

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Received October 19, 2023; revised November 20, 2023; accepted November 21, 2023

Abstract—One of the possible sources of carbon dioxide emission into the atmosphere can be river ecosystems. The paper presents the results of measuring CO_2 fluxes from the surface of several rivers and lakes in Tomsk Region. In the experimental period, average carbon dioxide fluxes were 143.7 ± 21.7 (August 13–14, 2023), 53.3 ± 21.2 (August 19), and 80.4 ± 59.9 mgC m^{-2} h^{-1} for the Ob River; 66.1 ± 17.3 mgC m^{-2} h^{-1} for the Ket River; 33.3 ± 17.3 mgC m^{-2} h^{-1} for the swamp Karasevoye Lake, 50.2 ± 23.0 mgC m^{-2} h^{-1} for the Suiga River, and 81.9 ± 11.5 mgC m^{-2} h^{-1} for the Iksa River. The flux magnitudes significantly depended not only on the object of the study, but also on hydrometeorological conditions.

Keywords: atmosphere, air, flux, river, carbon dioxide, emission

DOI: 10.1134/S1024856024700386

INTRODUCTION

One of the main problems of concern to all of humanity is the global warming [1]. According to the IPCC, this process is due to an increase in the concentration of greenhouse gases in the atmosphere and the additional heat flux into the atmosphere caused by them [2]. This primarily concerns carbon dioxide (CO_2), the content of which in the air continues to increase [3]. Accurate assessment of CO_2 emissions and its redistribution between the atmosphere, ocean, and the terrestrial biosphere under the changing climate is critical for better understanding the global carbon cycle, developing climate policy, and predicting future changes in this cycle [2].

Despite great progress in the study of spatiotemporal variability of CO_2 on the planet, there is still uncertainty in its budget, estimated at 1 GtC (gigaton of carbon (12/44 for CO_2 and 12/16 for CH_4) [4]. This means that not all sources of CO_2 emission into the atmosphere are correctly taken into account.

River systems can be among these sources; they transfer carbon from terrestrial ecosystems to the open ocean [5]. This major transfer is complemented by two shorter branches: from terrestrial ecosystems to inland waters and from tidal wetland systems to the ocean. Estimates of global carbon emissions from rivers show fluxes ranging from 0.6 to 1.8 PgC year^{-1} (petagram of carbon) [6–8]. The carbon budget significantly differs in different river basins. Dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (DIC) are also important for estimating the contribution of total organic carbon (TOC) into the ocean and its sediment accumulation in the global carbon cycle. Based on the collected data for 27 river basins in various ecosystems of the Earth, the average flux of TOC, DOC, POC, and DIC into the World ocean and CO_2 emissions from the water masses on the way to it were determined in [9, 10]. As a result, horizontal carbon transfer was estimated (export from land to inland waters at 2.01 ± 1.98 and flow into the ocean at 1.13 ± 0.50 PgC yr^{-1}), as well as its vertical fluxes (degassing at 0.79 ± 0.38 and deposition of sediments at 0.20 ± 0.09 PgC yr^{-1}). Significant uncertainties in these estimates require clarification based on experimental data.

Carbon fluxes from river surfaces in Europe and North America are quite well studied [11–16]. A few studies concerning Siberia have been published only recently [17–20], but they obviously are insufficient for such a huge region as Siberia.

To expand knowledge about the dynamics of carbon dioxide fluxes from the surfaces of Siberian rivers, measurements were carried out in August–early September 2023 in the middle stream of the Ob River (Kireevsk village, Tomsk Oblast), at the Ket River (Bely Yar village, Tomsk Oblast), and at small taiga rivers and swamp lakes. The purpose of this work is to estimate carbon dioxide fluxes from river and swamp lake surfaces.

MATERIALS AND METHODS

To measure CO_2 fluxes a floating chamber of 0.4 × 0.4 × 0.4 m in size was manufactured from transparent

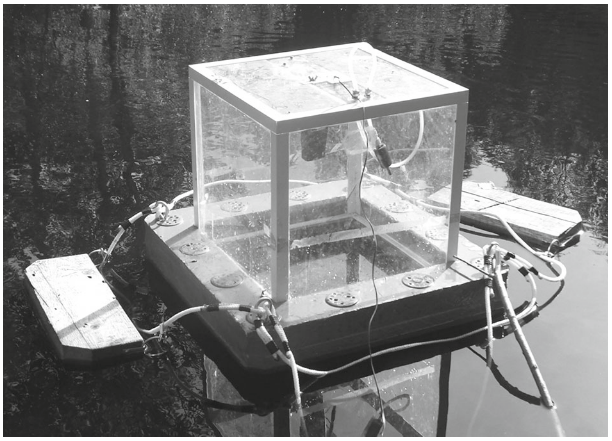

Fig. 1. Floating chamber in exposure mode on water surface.

plexiglass (Fig. 1). Positive buoyancy of the chamber is ensured by a base made of foam plastic. The small size and weight of the chamber made it possible to measure at hard-to-reach sites.

The chamber technique for measuring gas fluxes is widely known in the scientific community and is quite well developed [21–26]. It is used on open soils, various plant covers, and even trees. The idea of the technique is to record changes in gas concentrations in a volume isolated from the atmosphere. The air can be sampled from a chamber either into separate minicontainers for subsequent laboratory analysis or directly into a portable gas analyzer during in situ measurements. This technique suggests both one-time measurements at individual points for greater coverage of an area under study and continuous measurements at the same site to determine the seasonal/daily variation in gas fluxes or clarify their values.

We performed one-time and serial in situ measurements at water bodies during our study. Before each exposure of the chamber (in closed operation mode), it was aired and then closed for approximately 5 min. CO_2 fluxes were determined by the least-squares method from changes in the concentrations over known time periods.

The concentration was measured using an NDIR gas analyzer (Senseair AB, Sweden) with a snail-type optical cell; the range of CO_2 concentrations is 0–6000 ppm with uncertainty of ± 3%. When the working volume is ventilated with an air flow of 0.2 L/min, the optimal response time of the device is 15 s. The built-in ABC (Automatic Background Calibration) procedure enables gas analyzer baseline drift correction. The device logger stores up to 900 measurements with a specified time step, which are read through the interface by software. The device run time is determined by a built-in battery and is about 12 h.

The chamber size made it possible to place the sensor inside it. To finally check the device operation, intercalibration was carried out with a portable Picarro G4301 gas analyzer ($CH_4 + N_2 + H_2O$) (U.S.), with a CO_2 concentration uncertainty of no more than 0.4 ppm. Figure 2 shows a series of simultaneous measurements performed by both gas analyzers in a darkened chamber installed on grass. Segments of the rise of concentration correspond to the chamber exposure time intervals, from which CO_2 fluxes were calculated at the interface between the media.

According to Fig. 2, the response time of the Picarro gas analyzer was significantly shorter than that of the Senseair sensor. The average ratio between the concentrations measured by the instruments with different measurement principles was 1.15, which is insignificant within the differential flux recording technique.

In addition to CO_2 concentrations, to measure fluxes at the water surface–air interface, it is necessary to control the ambient temperature, including of water. The Senseair gas analyzer supports monitoring of the working volume temperature, which coincides with the air temperature (T_{air}) during ventilation. The water temperature (T_{water}) was measured using a small-size Thermochron iBotton DS1921L at depths of 10–20 cm.

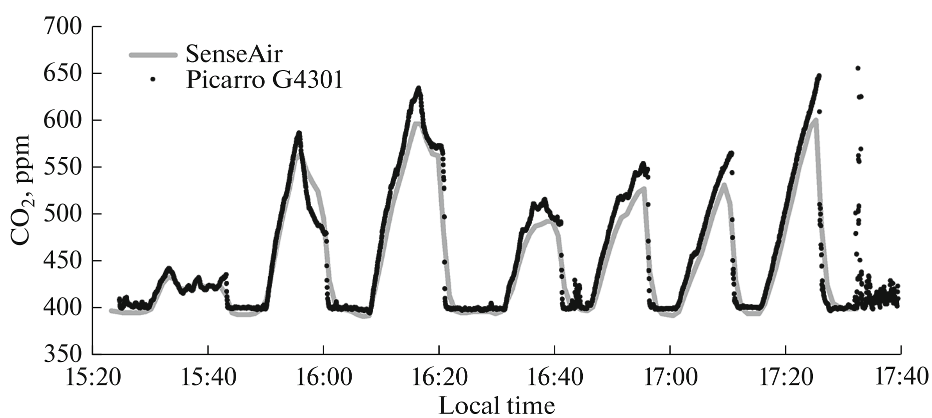

Fig. 2. Time variation in the CO_2 concentration measured with Senseair and Picarro G4301 gas analyzers (August 18, 2023).

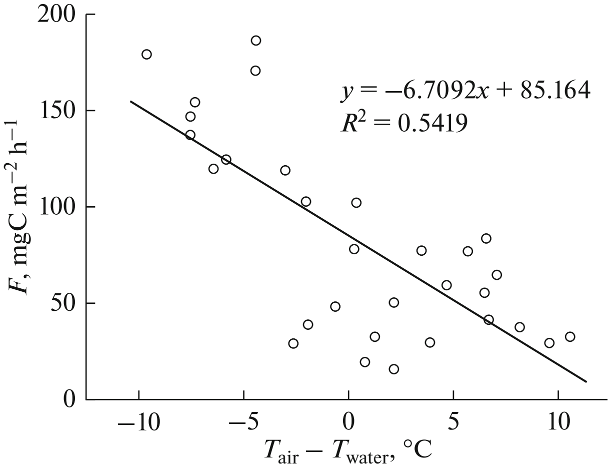

Fig. 3. Linearization of the dependence of measured CO_2 flux values on the temperature difference $T_{air} - T_{water}$ (Ob River).

RESULTS AND DISCUSSION

The 2023 measurement campaign consisted of several stages. During the first stage, we examined the area of the Ob River near the village of Kireevsk (Tomsk region), adjacent to the Fonovaya Observatory of IAO SB RAS (56.4185° N; 84.0740° E). The measurements were performed in various areas of the shallow main stream of the river and in adjacent branches. The river bottom is sandy and gravel here; it is patched with a layer of silt with a near-total absence of algae. The water color was light yellow during the campaign, with admixted suspended matter. The first series of measurements on August 13–14, 2023, was performed at different times of the day in relatively cool weather, when T_{water} exceeded T_{air} by 6–10°C. During the second episode on August 19–20, 2023, under the sunny weather, on the contrary, T_{air} exceeded T_{water} by 2–10°C, with the exception of the morning hours (Table 1).

Table 1 shows that the average CO_2 fluxes were higher during the first series of measurements (143.7 ± 21.7 mgC m^{-2} h^{-1}) than during the second episode (53.3 ± 21.2 and 80.4 ± 59.9 mgC m^{-2} h^{-1}), excluding cases of artifacts (bolded hereinafter). The most pronounced trend in changes in the CO_2 fluxes was observed on August 19, 2023, when the difference ($T_{air} - T_{water}$) changed from negative to positive values.

Figure 3 shows the derived dependence of the flux magnitude on the difference ($T_{air} - T_{water}$). Given the general linearity of the parameter, one can note an area of increased uncertainty within $-3°C < T_{air} - T_{water} < +3°C$, apparently associated with transient thermodynamic processes in the open "water–air" system. It should be noted that during chamber exposure, T_{air} in the closed volume usually noticeably changes towards the measured T_{water} values.

The above-mentioned deviations from the main set of measurements were associated with a short-term release of bottom gas bubbles into the isolated volume of the chamber (measurement no. 4 on August 19, 2023, and no. 12 on August 20, 2023), which almost an order of magnitude increased the CO_2 flux (>800 mgC m^{-2} h^{-1}). The exception is the negative flux value (measurement no. 11 on August 20), which was recorded during the chamber exposure over a water area with vegetation and caused by CO_2 absorption during photosynthesis. Although all chamber measurement instructions advise avoiding such events [27], the negative value we measured confirms a possibility of using the selected gas analyzer in our studies.

During the second stage of the campaign, the measurements were performed at water bodies in the middle taiga zone. The experiments were carried out on August 30–31, 2023, near Bely Yar village, Tomsk Oblast (58.4500° N; 85.0310° E.) at the Ket River, which is a large right-bank tributary on the Ob River. In addition, a series of measurements of CO_2 fluxes were carried out at the swamp Karasevoye Lake and the Suiga River near Nibega village (same area of the Tomsk region, 58.2840° N; 84.8850° E). All water bodies in this region are enriched with dissolved organic matter (DOC and POC) and are dark brown. The bottom of small rivers and lakes are often peat deposits without algae and with outcrops of underlying sandy rocks. The measurement results are given in Table 2.

All measurements presented in Table 2 were serial because of to time constraints. The observed values of T_{air} always exceeded T_{water}. It should be noted that the water in the swamp lake well warmed up by the late summer (T_{water} = 18°C). Lower T_{water} values in the Suiga River, which originates from the same swamps, witness to a slow penetration of heat into the peat deposit. The average CO_2 fluxes in the Karasevoye Lake (33.3 ± 17.3 mgC m^{-2} h^{-1}) were lower than in the Ket and Suiga Rivers (66.1 ± 17.3 and 50.2 ± 23.0 mgC m^{-2} h^{-1}, respectively). That might well be due to not only the large difference $T_{air} - T_{water}$, but also the lack of active mixing of water layers. An important role of the mixing in gas fluxes at the water–air interface is confirmed by the high value recorded in the Ket River, when the floating chamber during exposure entered the fast flow and CO_2 flux values noticeably increased (measurement no. 6 on August 31, 2023). This value is excluded from the general consideration.

During the third and final stage of the measurement campaign (Table 3), short-term measurements of CO_2 fluxes were made at the Iksa River near Plotnikovo village, Tomsk Oblast (56.8548° N; 83.0750° E) in the evening. This river flows from the Great Vasyugan Swamp. It is sluggish; the banks of this taiga river

Table 1. CO_2 flux measurement results at the Ob River (Kireevsk village) (RB (LB) means right (left) bank)

No.	Time	Measuring point	T_{air}, °C	T_{water}, °C	CO_2 flux, mgC m^{-2} h^{-1}
August 13–14, 2023					
1	17:35 (Aug. 13)	Main stream. PB	15.4 ± 0.2	21.3	124.5
2	18:16 (Aug. 13)	Main stream. PB	13.8 ± 0.2	21.3	147.0
3	07:13 (Aug. 14)	Main stream. PB	11.8 ± 0.4	21.5	179.1
4	07:49 (Aug. 14)	Main stream. LB	13.9 ± 0.1	21.5	137.4
5	10:27 (Aug. 14)	Main stream. LB	14.2 ± 0.1	21.5	154.5
6	11:01 (Aug. 14)	Main stream. PB	15.0 ± 0.1	21.5	119.8
	Average				143.7 ± 21.7
August 19, 2023					
1	09:29	Main stream. PB	17.3 ± 0.3	20	28.8
2	10:01	Main stream. LB	23.9 ± 0.5	20	29.7
3	10:59	Main stream. LB	26.6 ± 0.6	20	83.5
4	**11:17**	**Main stream. PB**	**25.8 ± 0.3**	**20**	**825.7**
5	12:17	Branch. Point 1	26.4 ± 0.5	20	55.3
6	12:33	Branch. Point 2	28.2 ± 0.3	20	37.4
7	12:43	Branch. Point 3	29.6 ± 0.3	20	29.1
8	12:54	Branch. Point 4	27.0 ± 0.2	20	64.5
9	13:06	Branch. Point 5	30.6 ± 0.2	20	32.5
10	13:25	Branch. Point 6	25.7 ± 0.4	20	76.6
11	13:39	Branch. Point 7	23.5 ± 0.2	20	77.2
12	13:52	Branch. Point 8	26.7 ± 0.5	20	41.1
13	17:01	Main stream. LB	24.7 ± 0.3	20	59.2
14	17:33	Main stream. PB	20.3 ± 0.1	20	78.0
	Average				53.3 ± 21.2
August 20, 2023					
1	08:10	Main stream. PB	15.9 ± 0.1	20.3	186.5
2	08:22	Main stream. LB	15.9 ± 0.1	20.3	170.6
3	08:48	Main stream. LB	17.3 ± 0.1	20.3	118.9
4	09:22	Islands. Point 1	18.3 ± 0.1	20.3	102.8
5	09:41	Islands. Point 2	18.4 ± 0.1	20.3	38.7
6	10:15	Islands. Point 3	19.8 ± 0.0	20.3	48.1
7	10:29	Islands. Point 4	20.7 ± 0.1	20.3	101.9
8	10:44	Islands. Point 5	21.0 ± 0.3	20.3	19.2
9	11:02	Islands. Point 6	21.5 ± 0.2	20.3	32.3
10	11:23	Main stream. LB	22.4 ± 0.3	20.3	50.1
11	**11:36**	**Main stream. LB**	**22.4 ± 0.1**	**20.3**	**−134.1**
12	**12:00**	**Main stream. PB**	**22.2 ± 0.1**	**20.3**	**855.3**
13	12:15	Main stream. PB	22.4 ± 0.2	20.3	15.5
	Average				80.4 ± 59.9

Table 2. CO_2 flux measurements at water bodies (tributaries of the Ob River)

No.	Time	Measurement point/series	T_{air}, °C	T_{water}, °C	CO_2 flow, mgC m^{-2} h^{-1}
Karasevoye Lake, Nibega village (August 30, 2023)					
1	14:15	1/1	28.0 ± 1.4	18.5	73.7
2	14:25	1/2	25.3 ± 0.5	18.5	29.5
3	14:35	1/3	25.5 ± 0.3	18.5	27.1
4	14:46	1/4	27.8 ± 0.9	18.5	29.3
5	15:04	2/1	28.9 ± 0.6	18.5	27.5
6	15:15	2/2	28.7 ± 0.3	18.5	10.2
7	15:25	2/3	29.9 ± 0.6	18.5	29.1
8	15:33	2/4	29.1 ± 0.3	18.5	52.4
9	15:46	2/5	29.3 ± 0.5	18.5	30.5
10	15:57	3/1	28.7 ± 0.7	18.5	16.3
11	16:07	3/2	29.5 ± 1.0	18.5	21.2
12	16:16	3/3	29.7 ± 0.3	18.5	23.3
13	16:26	3/4	28.3 ± 0.4	18.5	28.1
14	16:36	3/5	28.1 ± 0.4	18.5	40.9
15	16:51	4/1	28.1 ± 0.4	18.5	23.4
16	17:07	4/2	25.5 ± 0.2	18.5	33.0
17	17:25	4/3	24.5 ± 0.2	18.5	71.0
	Average				33.3 ± 17.3
Ket River, Bely Yar village (August 31, 2023)					
1	07:11	1/1	17.7 ± 0.2	17	59.3
2	07:24	1/2	17.5 ± 0.3	17	53.3
3	07:32	1/3	17.7 ± 0.3	17	56.5
4	07:43	2/1	20.4 ± 1.4	17	96.1
5	07:55	2/2	23.9 ± 0.6	17	65.2
6	**08:06**	**2/3**	**24.9 ± 1.3**	**17**	**251.6**
	Average				66.1 ± 17.3
Suiga River, Nibega village (August 31, 2023)					
1	10:37	1/1	22.7 ± 0.2	13.5	48.8
2	10:46	1/2	25.9 ± 1.5	13.5	85.6
3	11:01	1/3	26.1 ± 1.0	13.5	22.0
4	11:11	1/4	26.7 ± 1.5	13.5	27.1
5	11:27	2/1	23.6 ± 0.7	13.5	36.8
6	11:39	2/2	21.5 ± 0.7	13.5	40.6
7	11:51	2/3	20.5 ± 0.5	13.5	87.2
8	12:03	2/4	20.1 ± 0.7	13.5	54.0
9	12:15	2/5	18.9 ± 0.4	13.5	50.1
	Average				50.2 ± 23.0

Table 3. CO_2 flux measurement results at the Iksa River (September 6, 2023)

No.	Time	Measurement point/series	T_{air}, °C	T_{water}, °C	CO_2 flux, mgC m^{-2} h^{-1}
1	17:33	1/1	15.0 ± 0.4	14.5	61.1
2	17:46	1/2	13.5 ± 0.1	14.5	77.6
3	17:56	1/3	13.0 ± 0.0	14.5	74.2
4	18:05	1/4	12.8 ± 0.1	14.5	68.6
5	18:16	1/5	12.7 ± 0.0	14.5	82.6
6	18:29	2/1	12.5 ± 0.1	14.5	86.4
7	18:39	2/2	12.3 ± 0.1	14.5	88.4
8	18:50	2/3	12.1 ± 0.0	14.5	88.2
9	19:00	2/4	11.8 ± 0.1	14.5	97.9
10	19:11	2/5	11.7 ± 0.1	14.5	93.8
	Average				81.9 ± 11.5

are rich in aquatic vegetation; the bottom is mostly muddy, more like floodplain lakes. However, its dark brown marsh waters are rich in dissolved organic matter (DOC and POC), and T_{water} is low (14.5°C) like in the Suiga River.

The recorded average CO_2 flux was 81.9 ± 11.5 mgC m^{-2} h^{-1} here, with a trend towards an increase with a decrease in the difference $T_{air} - T_{water}$ (Fig. 4).

In contrast to a similar pattern we identified for the Ob River (Fig. 3), the small width of the Iksa River could have caused lower flux values due to the significant, on its scale, CO_2 absorption by aquatic vegetation. The time of serial measurements here coincided with the transition of the aquatic ecosystem from partial CO_2 absorption to its emission.

The data obtained and the results of the study of carbon dioxide fluxes from the Ob and Ket Rivers [28, 29] are in good agreement, if we take into account the seasonal variation we recorded. However, work [30] showed that the Lena River delta turned out to be a significant absorber of atmospheric CO_2 (−119 g/m^2) in summer, with estimated annual carbon exchange of 71 g/m^2. In [30], measurements were carried out by the eddy covariance method, and the contribution of vegetation apparently affected the result. Long-term measurements at Lake Baikal have shown that the total carbon dioxide flux is directed from the atmosphere into the lake during the period of open water and amounts to 6.5–7.0 g/m^2 per year [31–35].

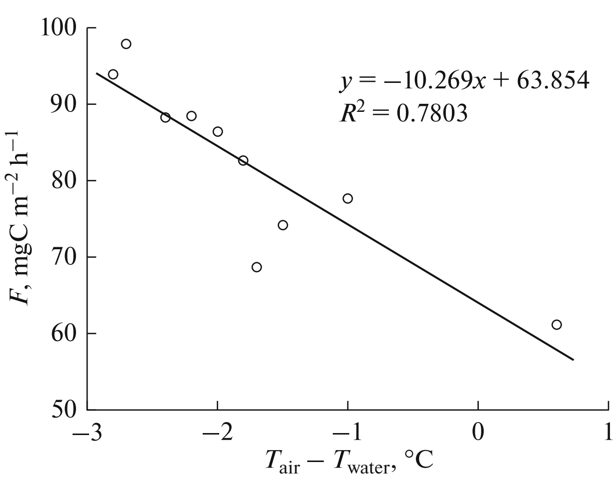

Fig. 4. Linearization of the dependence of measured CO_2 flux values on the difference $T_{air} - T_{water}$ (Iksa River).

CONCLUSIONS

A floating chamber designed on the basis of a relatively simple carbon dioxide sensor, calibrated against a precision gas analyzer, turned out to be a very effective instrument of measuring CO_2 fluxes.

Measurements of CO_2 fluxes from water bodies of the Ob River basin and lakes and swamp systems of Western Siberia showed emission of dissolved carbon into the atmosphere always everywhere. This is somewhat different from the dynamics of CO_2 fluxes from other large freshwater bodies.

The measured carbon dioxide fluxes from the surface of water bodies range from 10 to 180 mgC m^{-2} h^{-1} neglecting deviations. The fluxes depend not only on the object of study, but also on hydrometeorological conditions, which should be taken into account when analyzing these data.

Future research in this field could fill existing gaps in related data and help to refine model calculations and identify sources/sinks of atmospheric carbon on the global scale.

FUNDING

The work was supported by the Ministry of Science and Higher Education of the Russian Federation within the innovative project of national importance "Development of a System for Ground-based and Remote Monitoring of Carbon Pools and Greenhouse Gas Fluxes on the Territory of the Russian Federation, Creation of a System for Estimating Fluxes of Climate Agents and Carbon Budget in Forests and Other Terrestrial Ecosystems" (agreement VIP-GZ/23-14).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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