



Carbon dioxide emission from drawdown areas of a Brazilian reservoir is linked to surrounding land cover

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Abstract

Reservoir sediments exposed to air due to water level fluctuations are strong sources of atmospheric carbon dioxide (CO₂). The spatial variability of CO₂ fluxes from these drawdown areas are still poorly understood. In a reservoir in southeastern Brazil, we investigated whether CO₂ emissions from drawdown areas vary as a function of neighboring land cover types and assessed the magnitude of CO₂ fluxes from drawdown areas in relation to nearby water surface. Exposed sediments near forestland (average = 2733 mg C m⁻² day⁻¹) emitted more CO₂ than exposed sediments near grassland (average = 1261 mg C m⁻² day⁻¹), congruent with a difference in organic matter content between areas adjacent to forestland (average = 12.2%) and grassland (average = 10.9%). Moisture also had a significant effect on CO₂ emission, with dry exposed sediments (average water content: 13.7%) emitting on average 2.5 times more CO₂ than wet exposed sediments (average water content: 23.5%). We carried out a systematic comparison with data from the literature, which indicates that CO₂ efflux from drawdown areas globally is about an order of magnitude higher than CO₂ efflux from adjacent water surfaces, and within the range of CO₂ efflux from terrestrial soils. Our findings suggest that emissions from exposed sediments may vary substantially in space, possibly related to organic matter supply from uphill vegetation, and that drawdown areas play a disproportionately important role in total reservoir CO₂ emissions with respect to the area they cover.

Keywords Exposed sediment · Dry sediment · Carbon dioxide · Greenhouse gas · Dam

Introduction

Although reservoirs provide key services to humans, the construction of numerous dams worldwide has been resulting in a vast range of ecological and hydrological alterations (Nilsson et al. 2005). By the damming of rivers and

the resultant flooding of land, biogeochemical cycles in the original river and the flooded land areas are substantially altered (Friedl and Wüest 2002), which may result in increased greenhouse-gas emission (St. Louis et al. 2000). The most up-to-date review indicates that greenhouse-gas emission from reservoirs—predominantly as methane (CH₄) and carbon dioxide (CO₂)—is responsible for ~1.5% of the global anthropogenic CO₂-equivalent emissions (Deemer et al. 2016). The importance of understanding spatial and temporal variability in order to reliably assess total carbon emission from reservoirs is getting increasingly evident (Descloux et al. 2017; Paranaíba et al. 2018; Teodoru et al. 2012; Roland et al. 2010; Yang et al. 2013). Nevertheless, existing studies on reservoir emissions focus almost exclusively on emission from the water surface. Emissions from drawdown areas are largely neglected and these areas are considered blind spots in the global carbon cycle (Marcé et al. 2019).

Drawdown areas are referred to as the margins of reservoirs that are, due to seasonal hydrological cycles or dam

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operation, subject to water level fluctuation that causes periods of inundation and desiccation. The extent of these areas increases dramatically during periods of prolonged droughts. For instance, the extreme drought of 2014/2015 in Brazil has resulted in an additional exposure to air of $\sim 1300 \text{ km}^2$ of reservoir sediments throughout Brazil, which substantially enhanced carbon emission rates (Kosten et al. 2018). An increasing number of studies—all of them very recent—indicate that exposed aquatic sediments are relevant net sources of atmospheric CO_2 (Catalán et al. 2014; Hyojin et al. 2016; Marcé et al. 2019; Obrador et al. 2018; Schiller et al. 2014). An important factor supporting enhanced CO_2 emission rates from exposed sediments is the increased microbial metabolism (e.g., enhanced enzyme activity of phenol oxidases and hydrolases) as sediment dries out (Hyojin et al. 2016; Weise et al. 2016). The importance of exposed sediments to reservoir carbon processing is clearly illustrated by a study in a Southeast Asian reservoir, which demonstrates that drawdown areas may contribute up to 75% of total annual CO_2 emissions (Deshmukh et al. 2018). Globally, dry exposed sediments are estimated to emit $\sim 200 \text{ Tg}$ of carbon as CO_2 , which is equivalent to $\sim 10\%$ of global CO_2 emissions from inland waters (Marcé et al. 2019).

A more comprehensive understanding of carbon processing in drawdown areas is necessary for two principal reasons. First, there is growing evidence that exposed sediments are hotspots for carbon emission from freshwaters. Second, weather extremes can substantially affect CO_2 fluxes from freshwater systems (Almeida et al. 2017; Kosten et al. 2018), and the increased frequency of weather extremes associated with climate change is enhancing the desiccation of freshwater systems (Pekel et al. 2016) as well as the subsequent extent of drawdown areas (Kosten et al. 2018). Understanding the variability of CO_2 fluxes from drawdown areas over time and space is fundamental to support the definition of adequate sampling strategies and thus more realistic upscaling of CO_2 emissions from freshwater systems. While one study has reported limited spatial and annual variability in drawdown area CO_2 fluxes (Deshmukh et al. 2018), the scarcity of data makes it difficult to draw general conclusions about spatial or temporal variability of drawdown area CO_2 emission. Here we investigate the spatial variation in CO_2 fluxes from the drawdown areas of a reservoir in southeastern Brazil. More specifically, we studied whether emission varies as a function of neighboring land cover types (i.e., forestland and grassland), since drawdown areas are transitional zones between aquatic and terrestrial ecosystems and, as such, are presumably influenced by both adjacent ecosystems. We further gauged the relative importance of drawdown zone emissions by assessing the magnitude of CO_2 emission from the drawdown areas in relation to water surface emissions on a seasonal and interannual time scale. Lastly, we compared the measured drawdown CO_2 emission

with reported CO_2 fluxes from reservoir water surfaces and terrestrial soils worldwide, to understand whether exposed sediments align with terrestrial or aquatic ecosystems with respect to CO_2 emission.

Methods

Study area and quantification of drawdown areas

Chapéu D'Uvas (CDU) reservoir ($21^\circ 33'S$, $43^\circ 35'W$) is an oligotrophic water supply reservoir constructed in 1994 in the Paraibuna River, Minas Gerais state, southeastern Brazil. The land cover of the reservoir's watershed is composed of grassland ($\sim 66\%$), natural forest ($\sim 30\%$), and Eucalyptus plantation ($\sim 4\%$) (Machado 2012). To estimate the total reservoir area, we contoured the reservoir shape on Google Earth based on satellite images from four periods with different water levels and generated a regression between water level and flooded area (flooded area = $0.4117 \times$ water level $- 293.68$; $r^2 = 0.91$, $p < 0.05$, $n = 4$). We then used daily water level data to calculate daily flooded area. Between November 2014 and August 2017, the flooded area ranged between 7.0 and 10.6 km^2 . The difference between maximum and minimum flooded area was assumed to be the maximum drawdown area (i.e., 3.6 km^2), and the drawdown area was assumed to be zero at maximum flooded area. Daily drawdown area was then calculated by subtracting daily flooded area from the maximum flooded area.

CO_2 flux from water surface

We estimated CO_2 fluxes from open water surface during four sampling campaigns over hydrologically different seasons in 2015 and 2016. We used a combination of online equilibration system surveys and floating chamber measurements along the reservoir (see Paranaíba et al. 2018 for details on the approach). We performed continuous measurements (1-Hz frequency) of dissolved CO_2 concentrations in surface water using an open gas-flow equilibration system connected to an Ultra-portable Greenhouse Gas Analyzer (UGGA, Los Gatos Research, detection limit: $1.5 \times 10^{-7} \text{ mol L}^{-1}$). We attached the inlet of the online equilibration system to the boat at 0.5 m depth, so that water was continuously pumped into the system (3 L min^{-1}) while the boat navigated through the reservoir at $\sim 7 \text{ km h}^{-1}$. Each kilometer, the boat was stopped and the dissolved CO_2 measurements were interrupted for the measurements of the CO_2 gas exchange coefficient (described below).

We connected a transparent acrylic floating chamber (cylindrical, 17 L , 0.07 m^2) to the UGGA in a closed gas loop, and CO_2 concentration was monitored over 5-min intervals. Measurements were done in triplicates at each

sampling spot. At each spot, we also took discrete samples of surface water in triplicates for the determination of CO₂ surface water concentrations according to the headspace technique (Cole and Caraco 1998). From these discrete samples, we further computed the CO₂ gas exchange coefficient following the equation below:

$$k_{CO_2} = \frac{C_w - C_{eq}}{F_{CO_2}} \quad (1)$$

where k_{CO_2} (m day⁻¹) is the gas exchange coefficient for CO₂; C_w (mmol m⁻³) is the concentration of CO₂ in water and C_{eq} (mmol m⁻³) is the theoretical concentration of CO₂ in water if the water phase was in equilibrium with the atmosphere, both calculated from the discrete samples; and F_{CO_2} (mmol m⁻² day⁻¹) is the CO₂ flux at the air–water interface, calculated from the floating chambers measurements.

We then combined the CO₂ concentrations from the online equilibration system with k_{CO_2} to compute CO₂ emissions for the entire reservoir during each of the four campaigns. Specific details about the online equilibration system, floating chamber and discrete sample measurements, as well as flux calculation can be found in Paranaíba et al. 2018.

CO₂ flux from drawdown areas

We assessed the spatial variation of CO₂ fluxes from drawdown areas during the wet season in January 2018 (nine sites) and during the dry season in August 2018 (eight sites) using static chambers (cylindrical, 6.24 L, 0.07 m²). To capture potential spatial variation related to neighboring land cover, we sampled sites in the drawdown area adjacent to the two main land cover types of the CDU watershed (forestland and grassland), which correspond to ~95% of the land cover. These land cover types were heterogeneously distributed along the reservoir (Fig. 1). At each sampling site, we measured CO₂ flux in triplicates in three different areas: underwater shoreline (1–3 cm water depth), wet exposed sediments and dry exposed sediments (Fig. 2), totaling nine chamber measurements per sampling site. We made the distinction between wet and dry sediment visually (Fig. 2) and further confirmed that through moisture analysis in the laboratory—the average water contents of wet and dry exposed sediments were 24 ± 5% (± SD) and 13 ± 4% (± SD) of total weight, respectively. The triplicated chambers were deployed about 1 m apart from each other and connected to an Infrared Gas Analyzer (IRGA EGM-4 PP Systems) for five minutes to quantify changes in CO₂ concentration over

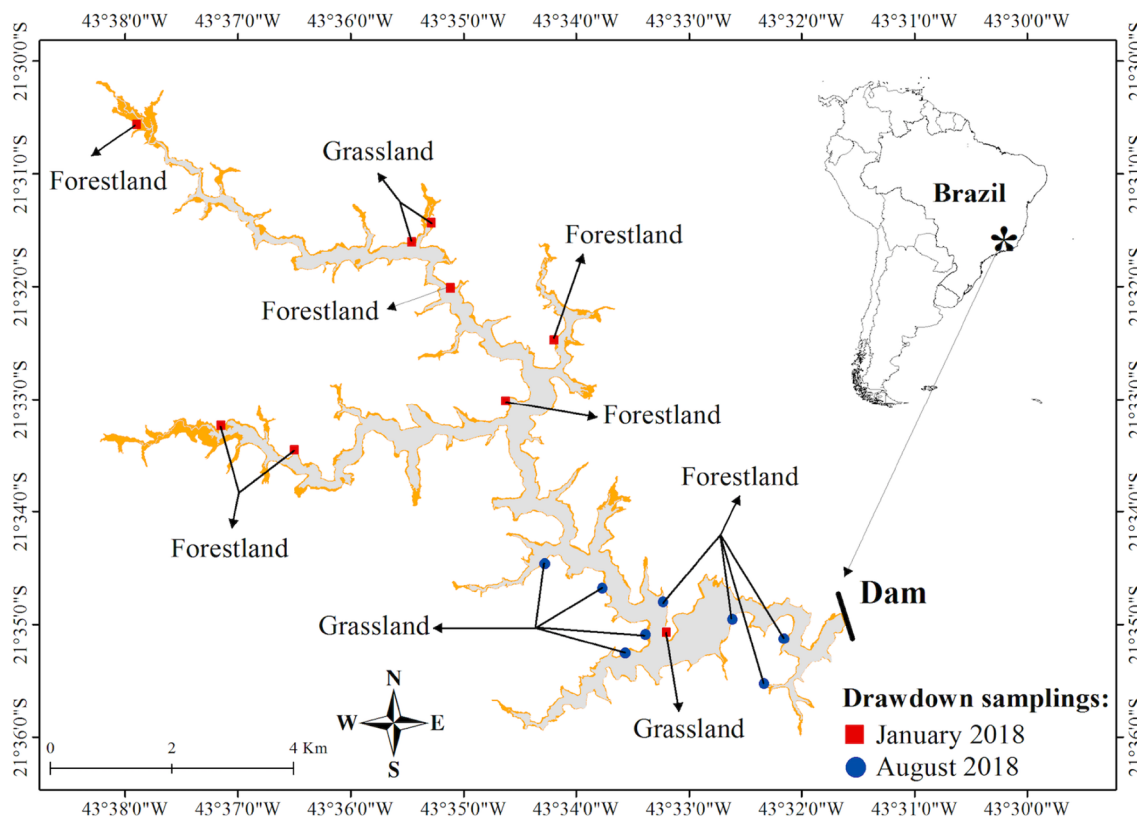
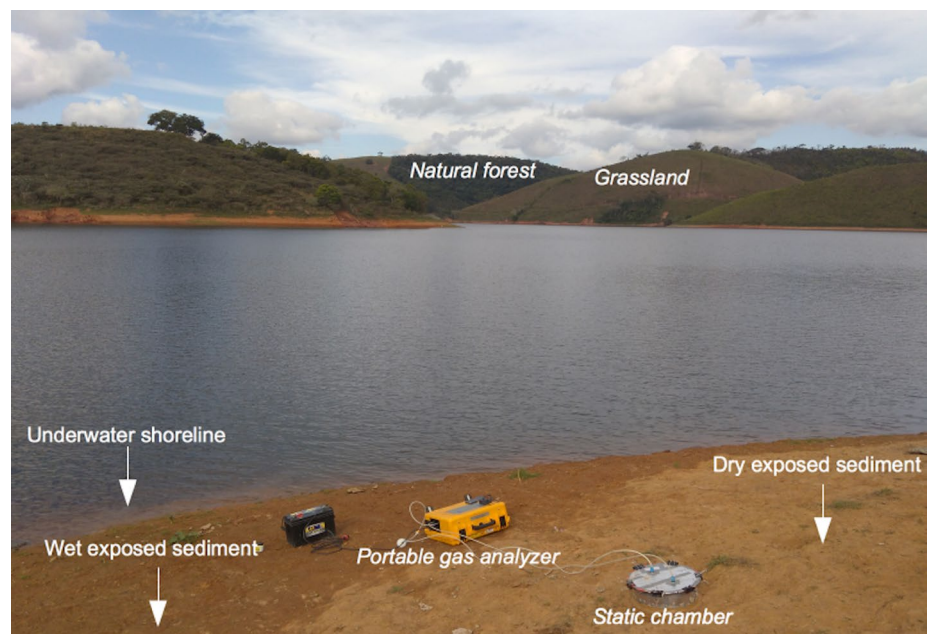


Fig. 1 Map of Chapéu D'Uvas (CDU) reservoir, with drawdown areas highlighted in orange. The sampling sites for static chambers deployed to measure CO₂ fluxes from drawdown areas are shown in the map

Fig. 2 Photograph taken in May 2017 depicting a typical drawdown area of Chapéu D'Uvas (CDU) reservoir. We deployed static chambers connected to a portable gas analyzer to measure CO₂ fluxes at the underwater shoreline, wet exposed sediment, and dry exposed sediment



time. The chambers were opaque to minimize temperature change. We used clay around the exterior of the chambers to avoid gas leakage (Lesmeister and Koschorreck 2017). Soil temperature and conductivity were determined using a conductivity meter (Akrom KR31). Surface soil samples of exposed sediments (wet and dry) were collected after each measurement and stored in coolers for laboratory analysis of moisture and organic matter content within 2 days. Moisture content was measured as the weight loss after drying 10 g of sediment sample at 105 °C for 2 h. The samples used for moisture analysis were further used to quantify the organic matter content, which was measured as loss on ignition (450 °C for 4 h).

We also performed measurements of CH₄ emission from drawdown areas at one grassland-neighbored site in May 2017, using static chambers connected to a UGGA. While CH₄ fluxes from exposed sediments can be important in some reservoir systems, these preliminary measurements indicated CH₄ uptake (4 mg CO₂eq m⁻² day⁻¹, 100-year global warming potential of 34; data not shown). The magnitude of that uptake is, however, negligible compared to the magnitude of CO₂ emissions measured over the same time period (1452 mg CO₂ m⁻² day⁻¹), and CH₄ uptake thus canceled less than 1% of CO₂ emissions. Our study therefore focuses exclusively on CO₂.

Data analysis

We used analyses of variance to evaluate the effects of season, moisture and neighboring land cover on CO₂ flux, as well as the interaction between these two predictors. We log-transformed the CO₂ fluxes to meet the assumptions of

normality and homoscedasticity and applied the *aov* function of R Statistical Software version 3.3.2 (R Development Core Team 2016).

We further compared CO₂ fluxes from exposed sediments of CDU reservoir with fluxes reported in the literature for exposed sediments of other freshwater systems, reservoir surfaces, and terrestrial soils. CO₂ fluxes from reservoir surfaces were taken from a recent compilation of CO₂ emissions from 228 reservoirs worldwide (Deemer et al. 2016). CO₂ fluxes from terrestrial soils were taken from a global database of soil respiration from all types of ecosystems worldwide (Bond-Lamberty and Thomson 2012).

Results and discussion

Extent of drawdown areas

The relative share of drawdown areas to the total area of CDU reservoir varies seasonally and interannually (Fig. 3). The share was smallest right after the rainy season (< 1% between March and May 2016) and largest right after the dry season (> 30% in November and December 2014). In 2015, drawdown areas accounted on average for 24% of the total reservoir area, whereas in 2016 they accounted for 7%. According to the Brazilian National Institute of Meteorology (INMET; <http://www.inmet.gov.br>), the average annual rainfall near CDU (Juiz de Fora station) is 1597 mm. The INMET reports that 2014 and 2015 were characterized by below-normal total rainfall (906 and 1251 mm, respectively), whereas 2016 had above-normal total rainfall (1705 mm). Interannual variation in rainfall thus explains the high

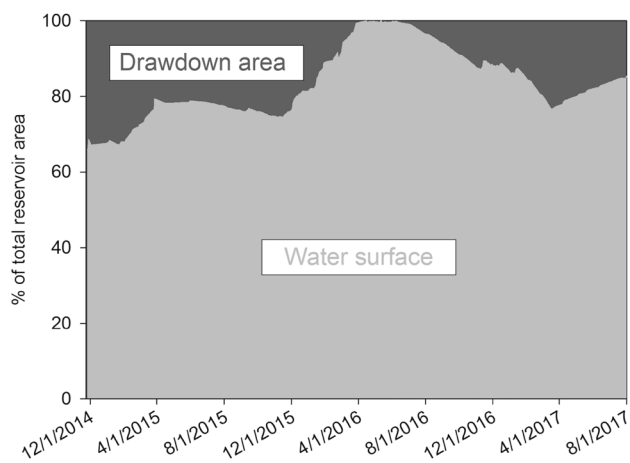


Fig. 3 Relative contribution of drawdown area (dark grey) and water surface area (light grey) to the total reservoir area of Chapéu D'Uvas (CDU) reservoir over time

interannual variation in the share of drawdown areas to the total reservoir area. On average, drawdown areas accounted for 17% of the total reservoir area between November 2014 and August 2017.

CO₂ fluxes in drawdown areas

The average CO₂ emission from exposed sediments in drawdown areas of CDU reservoir was 1855 mg C m⁻² day⁻¹ (range: 204–6425 mg C m⁻² day⁻¹, n=18) during the wet season in January 2018 and 2432 mg C m⁻² day⁻¹ (range 163–6857 mg C m⁻² day⁻¹, n=16) during the dry season in August 2018. The seasonal difference in CO₂ emission from exposed sediments was not significant (F=0.5, p=0.48, df=33). Underwater shoreline areas near exposed sediments had average emissions of 353 mg C m⁻² day⁻¹

(range: 130–776 mg C m⁻² day⁻¹, n=9) in January 2018 and 726 mg C m⁻² day⁻¹ (range 310–1330 mg C m⁻² day⁻¹, n=8) in August 2018. Notably, the rates of CO₂ efflux from the reservoir drawdown areas were on average 19 (January 2018) to 26 (August 2018) times higher than the average CO₂ efflux from the reservoir water surface (71 mg C m⁻² day⁻¹; Fig. 4a, b).

CO₂ emissions significantly differed between dry exposed sediments, wet exposed sediments, and neighboring underwater shoreline in both January 2018 (F=10.9, p<0.05, df=26) and August 2018 (F=11.8, p<0.05, df=23) (Fig. 4a). A Tukey post hoc test indicated higher emissions from dry exposed sediments than from wet exposed sediments (January: t=2.5, p<0.05; August: t=4.1, p<0.05) and underwater shoreline (January: t=4.7, p<0.05; August: t=4.3, p<0.05) in both seasons. In contrast, there was no difference between emissions from wet exposed sediments and underwater shoreline in either January (t=2.1, p=0.10) or August (t=0.2, p=0.98). Our results are in agreement with other recent studies reporting increasing CO₂ efflux as exposed sediments dry out (Gilbert et al. 2017; Weise et al. 2016). We did not measure how long it takes for exposed sediments to transition from wet to dry, and this merits further investigation. The transition time is likely variable and may be influenced by many factors including solar irradiance, wind conditions, precipitation, temperature, and slope of the exposed area.

Cycles of wetting-desiccation accelerate carbon losses from freshwater systems (Reverey et al. 2016). Indeed, a growing number of studies in different types of aquatic ecosystems (reservoirs, intermittent streams, temporary ponds) suggest that exposed sediments emit substantially more CO₂ than adjacent water surfaces (Catalán et al. 2014; Deshmukh et al. 2018; Gilbert et al. 2017; Gómez-Gener et al. 2015; Hyojin et al. 2016; Looman et al. 2017; Obrador

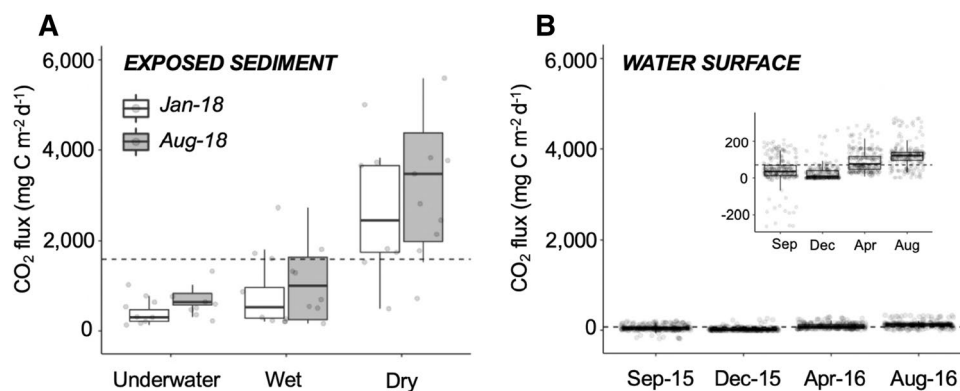


Fig. 4 CO₂ fluxes from (A) exposed sediment (underwater shoreline, wet exposed sediments, and dry exposed sediments) in January and August 2018, and (B) the water surface in September 2015, December 2015, April 2016 and August 2016 in Chapéu D'Uvas reservoir.

The inset figure in B shows the water surface results on a different scale for better visualization of the seasonal variability. The lines within the boxes indicate the median, the boxes delimit the 25th and 75th percentiles, and the whiskers delimit the 5th and 95th percentiles

et al. 2018; Schiller et al. 2014). Higher CO₂ emission from exposed sediments compared to nearby water surfaces have been attributed to enhanced microbial metabolism: sediment desiccation stimulates bacterial growth and enzyme activity, which in turn enhances CO₂ production and subsequent efflux (Fenner and Freeman 2011; Hyojin et al. 2016; Weise et al. 2016). The solubility of oxygen in water is low and its diffusivity slow (Furrer and Wehrli 1996), such that in water-logged sediments oxygen supply to microbes is probably slow, which limits degradation rates (Zehnder and Svensson 1986). Once the void pore space in the sediments fills with air when sediment dries out, it is likely that microbial degradation rates are enhanced, increasing CO₂ production. In combination with the higher diffusion rates, this may then lead to higher CO₂ emission rates.

In addition to being affected by moisture, CO₂ emission from exposed sediments was significantly different among sites grouped according to the predominant land cover adjacent to the sampling locations (Fig. 5). Exposed sediments near forestland exhibited significantly higher CO₂ emission rates than those near grassland in both January ($F = 7.8$, $p < 0.05$, $df = 17$) and August ($F = 5.6$, $p < 0.05$, $df = 15$). Unlike exposed sediments, CO₂ fluxes from underwater shoreline did not vary significantly among sites grouped according to the predominant adjacent land cover in either January ($F = 0.2$, $p = 0.68$, $df = 8$) or August ($F = 0.5$, $p = 0.49$, $df = 7$). Although thin (< 3 cm of depth), the layer of water above the sediment in underwater shoreline areas is still connected to pelagic water, such that CO₂ can be transported laterally, which may explain the more homogeneous spatial variability in these compartments compared to areas of exposed sediment.

We found that exposed sediments adjacent to forestland had higher organic matter concentrations (average = 14.9% of dry weight) than those next to grassland (average = 11.3% of dry weight) in August (one-tailed t test, $t = 1.9$, $p < 0.05$,

$df = 14$). In January, however, we could not detect a significant difference between the organic matter content of exposed sediments in forestland- (average = 10.4%) and grassland-neighborhood areas (average = 9.2%; one-tailed t test, $t = 0.9$, $p = 0.19$, $df = 15$) (Fig. 6). The substantial variability in organic matter content in exposed sediment within each group of adjacent land cover (Fig. 6) indicates that uphill forests may export more organic matter to neighboring exposed sediments than grassland areas, which may in part explain the higher CO₂ emission rates observed in drawdown areas adjacent to forestland.

Relative contribution of drawdown areas to total reservoir CO₂ emissions

To estimate the relative annual contribution of drawdown areas to total CO₂ emissions from CDU reservoir, we considered the average values of all water surface (September 2015, December 2015, April 2016 and August 2016)

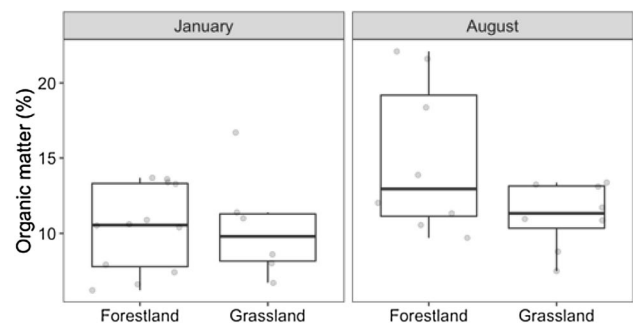
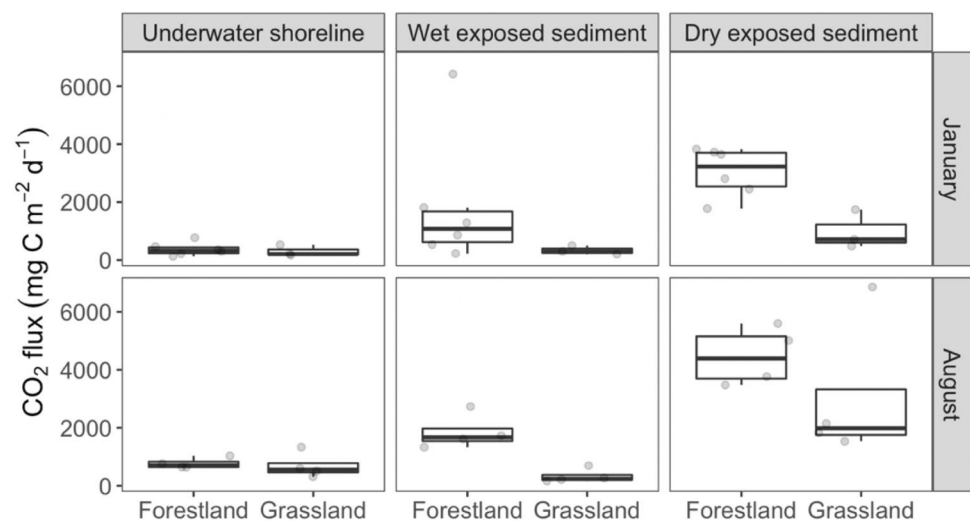


Fig. 6 Concentrations of organic matter (in percentage of dry weight) in exposed sediments of Chapéu D'Uvas reservoir in January and August 2018. The lines within the boxes indicate the median, the boxes delimit the 25th and 75th percentiles, and the whiskers delimit the 5th and 95th percentiles

Fig. 5 CO₂ fluxes from underwater shoreline, wet exposed sediment, and dry exposed sediment (left to right) in areas neighbored by forestland and grassland in Chapéu D'Uvas reservoir. The lines within the boxes indicate the median, the boxes delimit the 25th and 75th percentiles, and the whiskers delimit the 5th and 95th percentiles



and drawdown (January and August 2018) measurements. These calculations were made considering the average CDU basin land cover (~66% grassland and 34% forestland). The weighted average CO₂ emission from the CDU drawdown area was 1736 mg C m⁻² day⁻¹, and this gives a total CO₂ emission of 3038 kg C day⁻¹ for 1.75 km² of drawdown area (i.e., the average extent of the drawdown area over time). The average CO₂ emission from the CDU water surface was 71 mg C m⁻² day⁻¹, and this gives a total CO₂ emission of 628 kg C day⁻¹ for 8.85 km² of water surface area (i.e., the average extent of the reservoir water surface area over time). The drawdown area thus accounted for <20% of the total reservoir area but contributed to >80% of total reservoir CO₂ emissions upstream the dam. Our results are in line with a recent study conducted in a reservoir in Southeast Asia, which found that drawdown areas accounted for 50–75% of

total annual reservoir CO₂ emission (Deshmukh et al. 2018). Our findings indicate that drawdown areas are CO₂ emission hotspots in CDU reservoir, not only due to high emission rates in relation to reservoir water surface, but also because exposed sediments cover a large fraction of the total reservoir area over long periods of the year (Fig. 3).

CO₂ emission from drawdown zones and other freshwater systems worldwide

In order to quantitatively compare our findings, we compiled data from reservoir water surfaces and exposed sediments of freshwater systems worldwide (Fig. 7). The average flux from the drawdown zone of CDU reservoir (1736 mg C m⁻² day⁻¹) is close to the average flux from exposed sediments of reservoirs, intermittent streams, and temporary ponds worldwide (2145 ± 1637 mg C m⁻² day⁻¹, average ± standard deviation, Table 1). The average CO₂ flux from global exposed sediments is roughly one order of magnitude higher than the average CO₂ flux from global reservoir surfaces (332 mg C m⁻² day⁻¹) (Fig. 7), which is a similar pattern as observed in CDU reservoir data alone (Fig. 4). Although studies on CO₂ emissions from drawdown areas are scarce, existing data suggest that the range of CO₂ flux from drawdown zones resembles the range of CO₂ flux from terrestrial soils rather than from reservoir water surfaces (Fig. 7). This has also been suggested by two separate studies in Mediterranean ecosystems (Gómez-Gener et al. 2015; Schiller et al. 2014). Importantly, however, terrestrial soil respiration is often counteracted by primary production from overlying vegetation, which typically results in positive net ecosystem production (i.e., net CO₂ sinks) in terrestrial ecosystems. In terrestrial sites with reported measurements of both soil respiration and net ecosystem production in the global soil

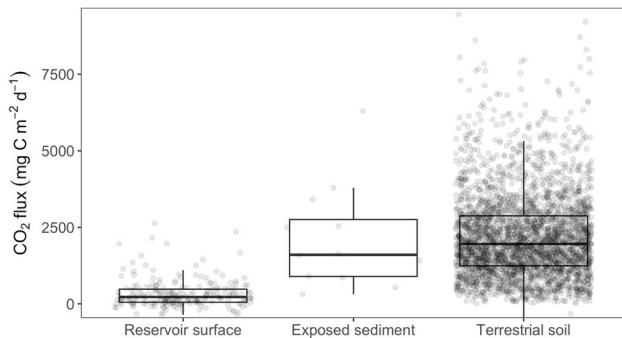


Fig. 7 CO₂ fluxes from exposed sediment of freshwater systems, reservoir surface and terrestrial soils worldwide. Data on exposed sediment were compiled from published literature and are shown as median or mean fluxes of each study (Table 1), data on reservoir surface were taken from (Deemer et al. 2016), and data on terrestrial soil were taken from (Bond-Lamberty and Thomson 2012)

Table 1 Mean fluxes of CO₂ from exposed sediments of different types of freshwater systems worldwide reported in literature

Site	Type	Country	CO ₂ flux (mg C m ⁻² day ⁻¹)	References
Nan Theum 2 Reservoir	Reservoir drawdown	Lao PDR	3414	Deshmukh et al. (2018)
Fluvià River	Dry streambed	Spain	2508	Gómez-Gener et al. (2015) and Schiller et al. (2014)
Lake Soyang	Reservoir drawdown	South Korea	6300	Hyojin et al. (2016)
River Po	Exposed river sediment	Italy	317	Bolpagni et al. (2017)
Temporary ponds on Menorca Island	Temporary pond	Spain	1576	Catalán et al. (2014) and Obrador et al. (2018)
Experimental temporary ponds	Temporary pond	England	3792	Gilbert et al. (2017)
Rappbode Reservoir	Reservoir drawdown	Germany	1620	Lesmeister and Koschorreck (2017)
Elbe River	Exposed river sediment	Germany	900	Lesmeister and Koschorreck (2017)
Jamison Creek	Dry streambed	Australia	864	Looman et al. (2017)
Urban temporary streams	Dry streambed	United States	528	Gallo et al. (2014)
Chinese hydropower reservoirs	Reservoir drawdown	China	2110	Li et al. (2015)
Chapéu D'Uvas Reservoir	Reservoir drawdown	Brazil	1736	This study

respiration database (Bond-Lamberty and Thomson 2012), although the average soil CO₂ efflux is high (2148 mg C m⁻² day⁻¹), the average net ecosystem production is positive (460 mg C m⁻² day⁻¹). This indicates that despite elevated soil respiration, these terrestrial sites are overall net CO₂ sinks when the primary production of overlying vegetation is taken into account. Our findings suggest that exposed aquatic sediments respire organic matter at a similar rate as terrestrial soils, but unlike terrestrial sites they end up functioning as strong CO₂ sources since they frequently lack primary producers to compensate for CO₂ production during microbial respiration.

Implications and future directions

Most studies focusing on CO₂ emissions from exposed sediment are fairly recent (Table 1), and this area of research has been receiving increasing attention in the scientific literature. To our knowledge, our study is the first to demonstrate that CO₂ fluxes from drawdown areas vary significantly in space, which is possibly related to the adjacent land cover. In addition to demonstrating the importance of spatial dynamics for a comprehensive understanding of CO₂ fluxes from drawdown areas, our study presents a systematic comparison of reservoir water surface, freshwater drawdown, and soil fluxes of CO₂. Even though we could not find significant seasonal variability in drawdown CO₂ fluxes, our study is based on only two points in time, and does not preclude the existence of temporal variation of CO₂ fluxes from drawdown areas.

The pattern observed in CDU reservoir, with CO₂ emissions from drawdown areas exceeding those from the water surface, concurs with other freshwater systems around the globe (Fig. 7). Globally, CO₂ emissions from exposed sediments in drawdown areas are about one order of magnitude higher than those from adjacent water surfaces. The current knowledge suggests that drawdown areas play a disproportionately important role in total CO₂ emissions with respect to the area they cover. The fact that drawdown zones of reservoirs are CO₂ emission hotspots has an important implication in light of a changing climate that may result in more frequent extended droughts throughout the world (Pachauri et al. 2014). Changing drawdown area extent may affect not only reservoir carbon emissions, but burial as well. Because submerged reservoir sediments typically act as carbon sinks and exposed sediments release a large fraction of organic carbon that would otherwise be buried for long timescales (Marcé et al. 2019), an increased drawdown area extent may reduce organic carbon burial efficiency on a reservoir scale. Finally, although we have not focused on methane emission, recent studies indicate that reservoir drawdown areas might be sites of intense methane release (Beaulieu et al. 2017;

Harrison et al. 2017; Yang et al. 2012), which is also temporally heterogeneous (Kosten et al. 2018). Carbon processing in drawdown areas deserves more attention to support better constrained upscaling of carbon emission from freshwaters.

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