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Extreme drought boosts CO_2 and CH_4 emissions from reservoir drawdown areas

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Extreme drought boosts CO_2 and CH_4 emissions from reservoir drawdown areas

Abstract

While previous studies suggest that greenhouse gas (GHG) emissions from reservoir sediment exposed to the atmosphere during drought may be substantial, this has not been rigorously quantified. Here, we determined carbon dioxide (CO_2) and methane (CH_4) emissions from sediment cores exposed to a drying and rewetting cycle. We found a strong temporal variation in GHG emissions with peaks when the sediment was drained (emissions from permanently wet sediment and drained sediments were respectively 251 and 1646 mg C m^{-2} d^{-1} for CO_2 and 0.8 and 547.4 mg C m^{-2} d^{-1} for CH_4) and then again during rewetting (emissions from permanently wet sediment and rewetted sediments were respectively 456 and 1725 mg C m^{-2} d^{-1} for CO_2 and 1.3 and 3.1 mg C m^{-2} d^{-1} for CH_4). To obtain insight into the importance of these emissions at a regional scale, we used Landsat satellite imagery to upscale our results to all Brazilian reservoirs. We found that during the extreme drought of 2014/2015 an additional 1299 km^2 of sediment was exposed, resulting in an estimated emission of $8.5x10^{11}$ g CO_2-eq during the first 15 days after the overlying water disappeared and in the first 33 days after rewetting, which is of the same order of magnitude as the year-round GHG emissions of large (~mean surface water area 454 km^2) Brazilian reservoirs excluding the emissions from the draw-down zone. Our estimate, however, has high uncertainty, with actual emissions likely to be higher. We therefore argue that the effects of drought on reservoir GHG emissions merits further study, especially since climate models indicate an increase in the frequency of severe droughts in the future. We recommend incorporation of emissions during drying and rewetting into GHG budgets of reservoirs to improve regional GHG emission estimates and to enable comparison between GHG emissions from hydroelectric and other electricity sources. We also highlight that in order to make reliable emission estimates, emphasis should be given to quantify peak emissions occurring at the onset of drought and the later rewetting.

Keywords: Reservoirs; sediment; drought; rewetting; emission peaks; greenhouse gases

Introduction

Hydroelectric reservoirs are subject to an ongoing debate regarding their net effect on atmospheric greenhouse gas (GHG) concentrations (Arvizu et al. 2011) as they are generally sites of intense GHG emissions (eg. Louis et al. 2000; Giles 2006; Barros et al. 2011; Deemer et al. 2016) as well as strong carbon sinks due to carbon burial (Mendonça et al. 2012). The debate continues largely because of the difficulties of consistent and systematic monitoring of hydroelectric reservoir emissions. Therefore, considerable efforts are currently being undertaken to better quantify methane (CH_4) emission through the major emission pathways, which generally are ebullition from the reservoir surface as well as emissions downstream from the dam (Fearnside 2015; Prairie et al. 2017). A critically overlooked potential source of reservoir GHG emissions however, comes from bottom sediments that are exposed to the atmosphere. While previous studies suggest that GHG emissions from sediment going through a drought and rewetting cycle may be substantial (eg. von Schiller et al. 2014; Gómez-Gener et al. 2016; Jin et al. 2016), such effects have not been rigorously quantified.

Reservoirs generally experience seasonal water level fluctuations, exposing marginal sediments to the air. This regular exposure – in combination with sediment focusing – may prevent the build-up of organic matter in these marginal sediments (Mendonça et al. 2014). In areas of deeper water, however, considerable amounts of organic matter can accumulate (Mendonça et al. 2014). Annual global carbon burial in inland water sediments has recently been estimated to be 0.15 Pg C, of which 40% is stored in reservoirs, even though these systems represent <10% of the total inland water area (Mendonça et al. 2017). Organic carbon burial efficiency estimates – i.e. the percentage of the carbon that remains in the sediment and is not re-mineralized – range from 9% to 94%, with the highest percentages found in deepest parts of the reservoir

78 (Kunz et al. 2011; Sobek et al. 2012; Mendonça et al. 2016). Still, sediment
79 accumulated at the reservoir bottom is not inert and may to some extent be
80 remineralized, particularly when the water level drops and the sediment is exposed to
81 air. The few existing drought studies describing carbon loss in sediments (e.g. De Groot
82 and Van Wijck 1993; Gómez et al. 2012; Skinner et al. 2014) suggest 40% to 79% of
83 the carbon accumulated in the top sediment layer may be lost when it dries out.
84 Though extended droughts are expected to occur, with higher frequency in many
85 parts of the world (IPCC 2014), little is known about how the increasing duration and
86 intensity of droughts will affect global surface water dynamics (Pekel et al. 2016),
87 aquatic sediments and the regional carbon flux. Part of the carbon present in reservoir
88 sediments will be emitted to the atmosphere as CO_2 and CH_4. Additionally, elevated
89 release rates of dissolved organic or inorganic carbon (DOC and DIC) from the
90 sediment to the water layer may occur after re-wetting and can lead to increased GHG
91 emissions over an expanded spatial extent.
92 Although previous studies have shown that GHG emissions strongly fluctuate
93 during a drying and rewetting cycle (e.g. Yang et al. 2012; Gallo et al. 2014; Serça et al.
94 2016), most assessments are based on infrequent measurements, varying from once a
95 year along a transect (Serça et al. 2016) to twice a month at specific locations (Yang et
96 al. 2012). As pulsed fluxes may be critical for the total GHG emissions, especially
97 during a period of rewetting (Gallo et al. 2014), infrequent measurements are likely to
98 result in an underestimation of overall emissions. Additionally, drawdown GHG
99 assessments so far have focused principally on areas that experience recurring drought,
100 while emissions may be greatest during and after a first-time drying and rewetting event
101 (Yu et al. 2014). Here, we investigated the importance of drought and rewetting for
102 reservoir sediment GHG emissions based on measurements of GHG emissions three-

103 times-a-week during an experimental drying and rewetting cycle using sediment from a
104 single reservoir. Reservoir sediment characteristics vary greatly among (Jorcin and
105 Nogueira 2005; Cardoso et al. 2014) and within reservoirs (Bini et al. 1999; Cardoso et
106 al. 2013), implying there are no representative sediments to study carbon emissions
107 during drought and re-wetting. Carbon emissions from drying sediments tend to
108 increase with organic carbon (OC) content (Gallo et al. 2014). As the organic matter
109 content in Brazilian reservoirs ranges from <1 to 21% (Jorcin and Nogueira 2005;
110 Cardoso et al. 2013), we chose the oligotrophic Chapéu D'Uvas reservoir with low
111 sediment OC content (<1.3%) to obtain a conservative estimate of potential sediment
112 carbon emissions. To obtain insight into the importance of the extreme drought-induced
113 GHG emissions on a regional scale, we combined our sediment carbon emissions with
114 satellite-derived estimates of the area of sediments in Brazilian reservoirs that are
115 generally inundated but that were exposed during Brazil's 2014/2015 extreme drought.

116 **Materials and methods**

117 ***Sediment carbon emissions***

118 *Study site*

119 The Chapéu D'Uvas dam (21º 33'S - 43º 35'W) was constructed in the
120 Paraibuna River - Minas Gerais, Brazil. Its catchment is situated in the Atlantic Forest
121 biome (Ibge 2012), with a warm temperate climate (Alvares et al. 2013), characterized
122 by warm and rainy summers and dry winter. The annual means of rainfall and
123 temperature are 1,600 mm and 18 – 20 ºC respectively (Alvares et al. 2013). The dam
124 became operational in December 1994 and the reservoir covers 14.6 km of the
125 Paraibuna River course, with 41 m maximum depth at the dam (mean depth: 19 m). The
126 average surface of the reservoir is 12 km^2.

Sampling and analyses

The effects of drought and rewetting on sediment carbon emissions were tested using undisturbed sediment cores sampled near the littoral zone of Chapéu D'Uvas reservoir below the average low-water-line. Eight sediment cores were taken in June 2015 with a gravitational sediment corer (Uwitec) at a permanently inundated site (water depth at time of sampling was 6 m). The upper 10 cm were transferred to transparent PVC incubation cores (5.4 cm inner diameter and 41.6 cm height) without visible disturbance of the sediment. Upon arrival in the laboratory, the water above the cores was carefully removed and substituted with distilled water lacking any dissolved organic carbon (DOC), so that all the respiration measured could be attributed to the sediment. Subsequently, the cores were kept at a temperature of 27°C (+/- 3°C) with a 12-h light/12-h dark cycle under well-ventilated conditions to enhance evaporation.

Twenty-four hours after the cores were placed under these climate conditions we started our first GHG measurements. These measurements were repeated three times a week (encompassing the inundated, drying, dry and re-wetting period; see below). To measure the GHG flux, the tops of the incubation cores were closed with a gastight expandable polyvinyl chloride (PVC) stopper fitted with double O-rings, leaving at least 10 cm of headspace air between the water or sediment surface and the stopper. The stopper had an inlet and outlet port, which was connected to an Ultraportable Greenhouse Gas Analyzer (UGGA, by Los Gatos Research Inc.). We determined diffusive CO_2 and CH_4 rates based on the linear increase in concentration of the gases over a period of three minutes taking the volume of the headspace into account (as in Almeida *et al.* (2016)). When a non-linear increase was observed, caused by ebullition, we repeated the measurement. This happened only a few times. The reported carbon

151 emissions to the headspace are conservative, as the gases might have dissolved in the
152 overlying water.
153 The water level was kept constant during the first week by adding distilled water
154 to compensate for loss due to evaporation. In the second week, we randomly assigned
155 four cores to a drought treatment (drought cores). From these cores, we removed 100
156 ml water each day until all overlying water was removed. This corresponds to a water
157 level drop of approximately 4.3 cm d^{-1} and resembles changes in water level during dry
158 periods observed in the reservoirs (observed water level drops in Três Marias and
159 Mascarenhas de Moraes, two different reservoirs located in Minas Gerais, were 2.6 cm
160 d^{-1} and 7.6 cm d^{-1} respectively). In the other four cores (permanently wet cores) the
161 water level was kept constant. After four weeks, water levels in the drought cores were
162 raised again to pre-drought levels by adding 100 ml distilled water every day for one
163 week. Although we did not measure moisture content of the sediment after all overlying
164 water was removed, we conducted a similar experiment later (sediment sampled at the
165 same location, same cores, same incubation conditions) which pointed out that the
166 gravimetric water content after 4 weeks of drought was approximately 28%.
167 After rewetting, GHG fluxes were measured for another four weeks. We
168 distinguish four different periods: The 'inundated period', which refers to the period all
169 sediments were inundated (days 0 – 11); the 'drying period' which refers to the period
170 from the moment all overlaying water was removed in the drought treatment until CO_2
171 and CH_4 emissions in the drought cores ceased to decline and stabilized (days 11 – 26);
172 the 'dry period' (days 26 – 40); and the 'rewetting period' from the moment when we
173 added water to the drought cores until the end of the incubation (days 40 – 73).
174 Arguably the exact delineation of the drying and dry period could have been chosen
175 differently as moisture content might have further declined during the dry period.

176 Nevertheless, we distinguished these two periods to avoid a possible increase in
177 emissions during the drying phase being masked by a decrease in emissions during the
178 drought period when we analyzed the four-week period in its entirety.
179 Total CO_2 and CH_4 emissions during the different periods were assessed by
180 calculating the area under the curve in the emission versus time plots. Average
181 emissions during the different periods were calculated by dividing the total emission
182 during the respective periods by the length of the period. CO_2 equivalents were
183 calculated by multiplying CH_4 emissions by 32, on the basis of CH_4 global warming
184 potential on a 100-year time horizon (Neubauer and Megonigal 2015).
185 In order to assess a possible DIC and DOC release from sediment to the
186 overlying water after rewetting, at the end of the incubation the water overlying the
187 sediment was carefully removed and subsamples were taken for total organic carbon
188 (TOC), dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC)
189 analyses. DOC samples were filtered through a 0.6 μm pore size filter (MN GF-3,
190 Macherey-Nagel) prior to analyses. TOC, DOC and DIC concentrations were analyzed
191 with an infrared gas analyzer (Shimadzu, model TOC-L) at a combustion temperature of
192 720°C. Sediment total carbon content was determined on dried sediments (dried at 105
193 ºC) using the Shimadzu TOC-L series, SSM50000A, in 50 mg of homogenized
194 subsamples at 900ºC. Inorganic carbon content was determined in 50 mg homogenized
195 subsamples using the same device at 200ºC and adding 0.3 mL of phosphoric acid (10
196 M). The difference between two values is the organic carbon in the sediment sample.

197 ***Areal extent of additional drawdown area***

198 We estimated the areal extent of the nation-wide additional drawdown area (ADDA)
199 during the drought of 2014/2015. This equals to the area of sediment that stayed
200 inundated during earlier (here 2011-2013) seasonal dry periods but was exposed during

the extreme drought of 2014/2015. We used the following approach: 1) Assess the ADDA of a selected set of reservoirs based on satellite image analysis (for details see "Satellite image-driven estimates of reservoir surface area dynamics"); 2) For each of these reservoirs, determine the proportion of the ADDA with respect to maximum reservoir area as derived from Lehner et al (2011) or from our satellite image analyses (further referred to as ADDA%); 3) Assess the difference in minimum water level between the periods 2011-2013 and 2014-2015 for 137 reservoirs from the Brazilian National Agency of Water (ANA 2016); 4a) Using the reservoirs with a known percentage of ADDA (assessed in step 2) and the difference in minimum water level (assessed in step 3) we constructed a regression model with the decrease in minimum water level as the explanatory variable and the percentage of ADDA as the dependent variable; 4b) We used this regression model to estimate the ADDA of the reservoirs that were not included in the satellite image analyses.

Satellite image-driven estimates of reservoir surface area dynamics

We processed all available (970 in total) surface reflectance-corrected 30 m spatial resolution satellite images from Landsat 5 (115 images), Landsat 7 (551 images), and Landsat 8 (304 images) collected over 34 reservoirs located throughout eastern Brazil (Fig. 3) for 2011-2014. Following Van Den Hoek et al. (in prep.), surface water, land, cloud, and cloud shadow pixels were identified using the Fmask product (see http://landsat.usgs.gov/documents/provisional_lasrc_product_guide.pdf), and 'missing' water pixels due to cloud or shadow contamination or data gaps were addressed by 'backfilling' water pixels from near-date (i.e. within 32 days) images. Of these 34 reservoirs, 17 had a lower minimum water level in 2014-2015 than in the preceding years (based on the water level data of ANA (2016)). The maximum water surface area for each of these 17 reservoirs was calculated, and each reservoir's boundary was

clipped at upstream and downstream (dam wall) locations based on visual interpretation of very high-resolution Google Maps-hosted satellite imagery. For each of the 17 reservoirs, we then determined the Landsat-derived surface area on the three dates closest to the minimum *in situ* water level date (for 2011-2013 and 2014). We visually inspected each candidate surface area and eliminated all with apparent cloud cover artefacts that reduce the surface area estimate. Of the remaining image dates, we selected those closest to the date of minimum *in situ* water level. The average temporal offset between the date of selected satellite-derived area and minimum *in situ* elevation was 22.7 days and 19.2 days for 2011-2013 and 2014, respectively. For further calculations, we only used areal estimates from within 20 days of the date of the lowest recorded water level.

Statistical analyses

Differences in total CO_2 and CH_4 emissions (area under the flux vs time curve) from the inundated and dry cores during the four different incubation periods were assessed with an unpaired t-test using SPSS (IBM).

Results

Sediment carbon emissions

Average sediment CO_2 and CH_4 emissions from the permanently wet cores over the entire incubation period were 412 (SD 139) mg C m^{-2} d^{-1} and 1.58 (SD 3.30) mg C m^{-2} d^{-1} respectively. Carbon emissions from the drought cores varied considerably over the incubation period (Table 1, Figs 1 and 2). During the drying period peak CO_2 emissions up to 6763 mg C m^{-2} d^{-1} were recorded. Total CO_2 emission during the drying period in the drought cores was 6.6 times higher than CO_2 emissions during the same time

interval in the wet cores (Table 1). CH_4 emissions reached even higher values, with maxima up to 9220 mg C m^{-2} d^{-1}. During the dry period, CO_2 emissions from the drought cores were considerably lower than during the drying period. The emission rates were significantly (on average 3.0 times) lower than the emission rates from the permanently wet cores. Average CH_4 emission from the drought cores during this period was not significantly different from emission from the permanently wet cores (Table 1).

Rewetting led to an instantaneous increase in CO_2 emission, which kept increasing until approximately 9 days after rewetting. The CO_2 emissions remained higher than those from the wet cores until the end of the assay (33 days after rewetting). Peak CO_2 emissions (max. 5976 mg C m^{-2} d^{-1}) were comparable to peak emissions during the drying period. Average CO_2 emissions during the rewetting period were significantly higher than emissions from the permanently wet cores (an average 3.6 fold increase). CH_4 emissions increased upon rewetting as well. CH_4 emissions from the drought cores were significantly higher (an average 2.1 fold increase) than emissions from the permanently wet cores during this rewetting period.

Upon rewetting DIC and DOC concentrations in the overlying water increased. DIC values in the overlying water differed significantly between the treatments ($p<0.001$) with concentrations of 5.1 mg L^{-1} and 0.7 mg L^{-1} in the drought and permanently wet cores, respectively. DOC concentrations at the end of the incubation were on average 49.5 mg L^{-1} in the drought cores and 8.4 mg L^{-1} in the permanently wet cores (which significantly differed; $p<0.001$), implying an additional sediment carbon loss of 12600 mg C m^{-2} as a consequence of drying and rewetting.

Areal extent additional drawdown area

Images of 10 reservoirs fulfilled our requisites, i.e. we could determine their surface

274 water area and their ADDA within 20 days of the date of their lowest recorded water
275 level. The largest 2014 ADDA occurred in the following reservoirs: Três Marias,
276 Mascarenhas de Moraes and Emborcação (Table 3). The total ADDA of the 10
277 reservoirs was 380 km^2 in 2014. The maximum ADDA accounted for up to 29% of the
278 reservoirs' surface area (Table 3). On average the ADDA comprised 10% of the
279 reservoirs' surface area.

280 Forty-eight percent of the 137 reservoirs analyzed had a lower water level in
281 2014-2015 than in the years before. In 24% percent of the reservoirs, the minimum
282 water level did not differ more than 10 cm between periods, and in 28% of the
283 reservoirs the minimum water level was lower in 2011-2013 than in 2014-2015 (Fig. 3).
284 The differences among the reservoirs are due to differences in regional precipitation
285 patterns and river network locations. Many rivers contain several dams, leading to a
286 cascade of reservoirs where during drought the water level of a specific reservoir can be
287 maintained at the expense of other(s).

288 The relationship between ADDA% and the difference in minimum water level
289 between the two periods studied could be described by the model:

290 ADDA% = 7.61 x ln(decrease in min. water level) + 7.46

291 (R^2=0.78, p=0.001, n=10) (Fig. 4).

292 As the intercept with the x-axis occurred at a minimum water level drop of 38 cm, only
293 reservoirs with a water level drop >38 cm were included in the subsequent analysis.

294 We used this regression model to estimate the ADDA% and the absolute ADDA
295 for the additional reservoirs in the ANA dataset. This led to an additional reservoir
296 drawdown area of 919 km^2, and an overall estimate (satellite-derived and extrapolated)
297 of 1299 km^2.

Discussion

Our drought and rewetting experiment indicates a strong impact of water level fluctuation on sediment GHG emissions. We estimate that an area of 1299 km^2 of Brazilian reservoir sediments that stayed submerged during previous dry periods were exposed to the atmosphere at some point during the drought of 2014/2015. The exact time of occurrence of the minimum water level varied among reservoirs with some reaching their lowest levels as early as February 2014 with others as late as December 2015. Extrapolating the experimentally derived sediment carbon emissions to the areal extent leads to an estimated emission of $3.2x10^{10}$ g C in the form of CO_2 and $1.1x10^{10}$ g C in the form of CH_4 during the first 15 days of drought. Subsequent rewetting leads to estimated CO_2 and CH_4 emissions of approximately $7.3x10^{10}$ g C in the form of CO_2 and $1.3x10^{8}$ g C in the form of CH_4 during the first month after rewetting. This adds up to a total estimated emission of $8.4x10^{11}$ g CO_2-eq at the onset of the drought and the later rewetting (considering a period of 15 days of drought and 33 days of rewetting). This is likely an underestimate because of several reasons, which we discuss below.

The intensity of the carbon emissions, i.e. the emission rate, varies strongly over the drying and rewetting cycling. We observed the first peak of CO_2 and CH_4 emissions when all overlying water was gone (Figs 1 and 2). As diffusion in air is > 10,000 times faster than in water (Haynes and Lide 2012) the intrusion of air into the sediment upon disappearance of the overlying water may strongly increase the gas exchange between the sediment and the atmosphere. The resulting increase in oxygen in the sediment likely increases organic matter degradation and potentially leads to high CO_2 emissions as we have observed in our experiment.

Although we cannot substantiate that it occurred during our assay – due to a lack of pore water pH and $CaCO_3$ measurements – peaks in CO_2 emission may also be due to

323 the dissolution of carbonates. When the sediment water content decreases,
324 mineralization of organic matter may lead to a decrease in pore water pH, triggering
325 dissolution (Skinner et al. 2014). When the water content in the sediment further
326 decreases, microbial activity declines (Jin et al. 2016) resulting in reduced GHG
327 emissions as observed in our experiment (Figs 1 and 2) as well as *in situ* in dry
328 streambeds (Gómez-Gener et al. 2015).
329 Although methanogenesis has been found to occur under oxic conditions
330 (Bogard et al. 2014; Tang et al. 2016) an increase in oxygen availability in drying
331 sediment tends to decrease rather than increase CH_4 production (Segers 1998;
332 Koschorreck 2000). Nonetheless, methanogenesis may persevere in anoxic micro sites
333 in the upper – largely oxic – sediment layers (Jørgensen and Revsbech 1985) as well as
334 in deeper – still anoxic – sediment layers. At the same time, CH_4 oxidation is likely to
335 increase due to the increase in oxygen availability in the sediment (Koschorreck 2000).
336 During the initial drying phase, CH_4 production may still be higher than CH_4 oxidation,
337 resulting in a net-CH_4 emission (Koschorreck 2000).
338 In addition, an increase in CH_4 emission may occur initially when gases that
339 were stored in deeper sediment layers are vented. Gas venting from drying sediments
340 may be an important pathway, especially for CH_4 which, due to its low solubility in
341 water, forms gas bubbles in the sediment. During gas venting, an air-filled pathway
342 (consisting of pores or cracks) connects gas bubbles to the sediment surface, the trapped
343 gas may move upwards first by convection and, when the pressure is equilibrated, move
344 further upward by molecular diffusion (Rosenberry et al. 2006). The processes may
345 differ from ebullition, i.e. the release of gas bubbles from the sediment and their rise
346 through the water column, with respect to the time span during which the gas bubble
347 reaches the atmosphere. Venting is a more gradual process as it depends partially on

348 diffusion whereas ebullition events lead to short-term peaks in emission when the
349 bubbles reach the water's surface. On a daily time frame, however, the CH_4 peaks we
350 observed during the drying phase were similar to reported ebullitive fluxes in different
351 water systems (Aben et al. 2017). The exact timing of a venting event will vary between
352 sites, which likely explains the large variation in the peak emissions we observed. This
353 calls for frequent measurements of GHG emission during the drying period, to ensure
354 accurate estimates.

355 Our assay shows fairly constant GHG emissions during the dry period with low
356 sediment CH_4 and CO_2 emissions compared with permanently wet sediments (Table 1).
357 The low emissions are likely due to desiccation of the microbial community (Borken
358 and Matzner 2009).

359 Rewetting increased CH_4 emissions (Table 1). This finding corroborates
360 numerous other studies – e.g. *in situ* measurements in Amazonian lakes by Conrad et al.
361 (2014); and laboratory incubations by Kannenberg et al. (2015), but also see Gallo et al.
362 (2014), who found no significant increase after re-wetting (see Table 2) which is likely
363 linked to the re-establishment of anoxic conditions in the sediment and the switch back
364 to anaerobic metabolism. Concurrently, rewetting has been shown to lead to an increase
365 in microbial biomass and a shift in community composition (eg. Evans and Wallenstein
366 2012; Conrad et al. 2014). In our assay, CH_4 emission during the rewetting phase did
367 not seem to differ from that during the earlier inundated phase (Table 1). Nevertheless,
368 methanogenesis rates after rewetting have been found to exceed those of the pre-
369 drought situation in a previous study (Kannenberg et al. 2015). The authors of that study
370 argued that rewetting may release nutrients from rewetted sediments due to microbial
371 lysis and disruption of soil aggregates which liberates different compounds that
372 stimulate the microbial community and their mineralization activity . However, physical

373 drivers of gas emissions play a role as well. Instantaneous CO_2 emissions upon
374 rewetting of up to 38 g C m^{-2} d^{-1} have been reported, which are argued to be indicative
375 of displacement of gases accumulated in the pores during the dry period (Gallo et al.
376 2014). The peak emissions upon rewetting again call for measurements during reservoir
377 refilling.
378 We likely underestimated the emissions that actually occurred during the
379 2014/2015 drought because of several reasons. Firstly, we likely underestimated the
380 total areal extent of the sediments exposed to the atmosphere due to the severe
381 2014/2015 drought because we only included reservoirs in the ANA database with daily
382 water level data. Secondly, our sediment-core-based estimation of GHG emission
383 intensity due to drought and rewetting is likely to be modest. Specifically, ebullition
384 was not captured by our measurements, yet it may contribute substantially to the total
385 flux (Aben et al. 2017) when the sediments are inundated, especially when the water
386 level drops (Maeck et al. 2014; Harrison et al. 2017). Although we rarely observed
387 bubbles, they may have occurred, leading to an underestimation of the CH_4 emission.
388 Additionally, our estimate does not include the 11.4 g C m^{-2} of carbon that was emitted
389 from the sediment in the form of DOC after rewetting. In the water column, DOC may
390 be partially mineralized through photo-oxidation, thereby enhancing reservoir carbon
391 emissions (Peter et al. 2016). Our experiment was conducted indoors at considerably
392 lower light intensities than outside and hence we likely underestimate DOC
393 mineralization by photo-oxidation. Additionally, we also may have underestimated
394 possible CO_2 production by photo-oxidation of the dry sediment (Rutledge et al. 2010).
395 Arguably, the most important factor pointing to a strong underestimation of the
396 actual fluxes is the fact that our estimates are based on measurements conducted on
397 sediments containing little organic matter. Besides nitrogen content, sediment particle

size and temperature, sediment GHG emissions are known to depend on organic matter content and reactivity (Gudasz et al. 2010; Gallo et al. 2014; Gómez-Gener et al. 2016). A comparison between sediments with organic matter contents of 3.0% and ~5.4% revealed a 1.7-fold increase in CO_2 emissions upon rewetting in the more organic sediment (Gallo et al. 2014). The sediments we used for our estimate had an organic matter content of 1.3% whereas organic matter contents in a range of Brazilian reservoirs have been found to be up to a factor 10 times higher (Bini et al. 1999; Jorcin and Nogueira 2005; Mariani and Pompêo 2008; Cardoso et al. 2013). In addition, redistribution of sediment and organic matter can lead to strong gradients in sediment organic matter content within an individual reservoir (Cardoso et al. 2013; Mendonça et al. 2016). The exposed sediment will therefore vary in organic matter content and likely in GHG emissions. This has to be taken into account in future work when comparing across reservoirs with different levels of drawdown and bathymetry. At this point, we can only speculate on how much higher the drought-induced carbon emissions from these more organic rich sediments may be, but we expect the increase will be considerable. Comparisons of our emission intensities with those reported in the few studies on GHG emissions from dry sediments confirm this: our dry sediment emissions are considerably lower than earlier reports (Table 2). Still, our dry sediment cores emitted CH_4, whereas some dry sediments may consume CH_4 (Koschorreck 2000; Juutinen et al. 2001; Yang et al. 2012; Jin et al. 2016). Additionally, the rewetting induced peak emissions may depend on the duration and severity of the dry period. When sediments do not dry out completely and aerobic mineralization continues during the dry period, organic matter availability may be limiting upon rewetting, which may result in an increase in the CO_2:CH_4 emission ratio over the whole drying and rewetting cycle. In short there are many different variables that influence GHG emissions during a

drying and rewetting cycle and we therefore highlight that the uncertainty regarding the GHG emissions due to drought and rewetting is high and our estimate is but a first step in quantifying the effect of extreme drought on Brazilian reservoir GHG emissions.

Even without taking the likely underestimation of our emission estimate into account, our analyses show that the single extreme drought event in 2014/2015 and the subsequent rewetting led to a higher total GHG emission than during an entire year by large Brazilian reservoirs (based on a comparison with the eight reservoirs (mean surface water area 454 km^2) described by Ometto et al. (2013)). In one of the reservoirs (Mascarenhas de Moraes) GHG emission was estimated to be $4.1x10^{10}$ g CO_2-eq in the drawdown area during the first 15 days of drought and the first 33 days after rewetting. This is a 33% addition to the $1.25x10^{11}$ g CO_2-eq emitted from the reservoir water surface area on a yearly basis (Ometto et al. 2013).

Conclusion

Our combined estimate of the Brazilian reservoir drawdown area during the 2014-2015 drought and the effect of drying and rewetting on GHG emissions from reservoir sediment highlights the potential importance of drought and rewetting cycles for reservoir GHG-budgets. It also indicates that interpreting sediment carbon burial as a long-term carbon sink (Mendonça et al. 2012) should be done with care as disturbances such as drought may liberate large parts of this carbon stock. This applies to sediment desiccation after the decommissioning of dams as well. The number of dams that will be decommissioned will increase over the years to come and our findings are indicative of the consequent potential carbon emissions. We argue, contributing to the current IPCC discussion, that the effect of drought events on sediment GHG emissions should be incorporated in hydroelectric reservoir GHG budgets to enable a valid comparison with the greenhouse gas emissions of other electricity sources. Furthermore, as inland waters

are often hotspots of carbon emissions in terrestrial landscapes (Kosten et al. 2010; Raymond et al. 2013) substantial improvement of regional GHG emission estimates may be made when drought-induced sediment carbon emissions are taken into account. This is particularly important as severe droughts are likely to occur more frequently in the future. More work is needed to estimate these emissions accurately with special attention to peak emissions occurring at the onset of drought and at the time of rewetting as our results suggest that these peaks make up the largest part of the total emission.

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638

639

640 Table 1. Average and total sediment CO_2 and CH_4 emissions from permanently wet
641 sediments ("wet") and sediments that were subjected to drought and subsequent
642 rewetting ("drought"; SD in between parentheses, n=4). p-value represents significant
643 difference between treatments based on t-test. Significant differences are presented in
644 bold.

	CO_2 emissions					**CH_4 emissions**				
	Flux [mg C m^{-2} d^{-1}]		**Total emission** [mg C m^{-2}]			**Flux** [mg C m^{-2} d^{-1}]		**Total emission** [mg C m^{-2}]		
	Wet	Drought	Wet	Drought	p	Wet	Drought	Wet	Drought	p
Inundated period	443 (35)	402 (56)	5010 (392)	4546 (632)	0.266	1.9 (0.9)	8.1 (11.0)	21.8 (10.3)	91.9 (124.0)	0.303
Drying period	**251 (82)**	**1646 (392)**	**3718 (1220)**	**24356 (5797)**	**<0.0001**	0.8 (0.9)	547.4 (688.8)	12.1 (13.8)	8102.2 (10194)	0.164
Dry period	**449 (99)**	**148 (147)**	**6335 (1394)**	**2091 (2078)**	**0.018**	2.8 (3.1)	2.2 (0.5)	39.5 (44.3)	30.6 (6.5)	0.705
Re-wetting period	**456 (62)**	**1725 (181)**	**14973 (2035)**	**56569 (5941)**	**<0.0001**	**1.3 (0.3)**	**3.1 (0.3)**	**41.8 (10.9)**	**100.8 (10.8)**	**<0.0001**
Total period			**30037 (2625)**	**87561 (8899)**	**<0.0001**			**115.2 (48.6)**	**8325.5 (10324.1)**	0.210

645
646

647 Table 2: CO_2 and CH_4 emissions from temporarily exposed and inundated sediments in
648 different water systems

Location	**System type**	**Measurement frequency**	**Condition**	**Mean flux (**mg C m^{-2} d^{-1}**)**		**Reference**
				CO_2-C	CH_4-C	
Brazil	river	7-9 times over a period of 2 months in 1996 and 1997	Initial phase of dry period		11.5 ±8.6	Kosschoreck (2000)
			After approx. 2 months		-0.84 ±0.34	
Finland	lake	1 or 3 times a week along transects for 4 to 6 months during water level lowering	Dry - permanently wet with emergent plants		-3.6 - 255.6	Juutinen et al. (2001)
China	reservoir	once or twice a month in fallow, crop and deforested land in drawdown zone	Dry		-0.144 ±0.63 (SE)	Yang et al. (2012)
			Wet (before and after drought)		3.96 ± 4.68 (SE)	
Arizona, USA	urban stream	1 hour before rewetting, immediately after and 0.5, 2 and 6 hours after rewetting	Dry	526 ± 101 (SE)	0.41±0.12 (SE)	Gallo et al. (2014)
			Re-wetted	5760 ± 816 (SE)	not diff. from dry	
			Instantaneous after re-wetting	10013 ±2530 (SE)	not diff. from dry	
Spain	temporary stream	2 times, once during dry period, once during wet	Dry	9377 ±4682(SD)		Gomez et al. (2016)
			Flowing streambed	3667 ±2473(SD)		
Laos	reservoir	transect in 2010 and 2011 in drawdown zone	Dry (soil moister 8-40%)		0.72± 2.4	Serça et al. (2016)
			Wet (soil moister>40%)		276±348	
South Korea	reservoir	once along a transect	50 m from waterline	12000 ± 2500 (SE)		Jin et al. (2016)
			140 m from waterline	3000 ± 900 (SE)		

649

650

651 Table 3. Minimum water surface area (derived from Landsat images) of 17 Brazilian
652 reservoirs with lower minimum water levels in 2014 than during the 3 preceding years.
653 For the 11 reservoirs for which we had areal estimates within a time span of 20 days
654 from the date (mm-dd-yy) the lowest water level was recorded, we also calculated the
655 additional draw down area (ADDA) and the percentage of ADDA of the total reservoir
656 area.

reservoir/dam name	2011-2013			2014			comparison between periods		
reservoir name	date of lowest water level	min. water surface area [km^2]	time span [days]	date of lowest water level	min. water surface area [km^2]	time span [days]	difference in min. water level [m]	additional draw down area [km^2]	ADDA of total reservoir area [%]
Três Marias	26-11-2013	494	6	14-11-2014	353	7	6.30	140	18
Mascarenhas de Moraes	3-1-2013	212	16	11-12-2014	150	5	8.14	63	25
Emborcação	1-1-2011	215	12	27-11-2014	154	6	5.67	61	29
Sao Simão	11-11-2012	516	13	28-10-2014	479	17	0.96	38	6
Itaipú	27-12-2013	1191	2	11-2-2014	1160	0	0.62	32	3
Barra Bonita	28-12-2011	213	12	12-12-2014	191	4	0.92	23	11
Chavantes	2-2-2013	307	9	19-12-2014	298	4	0.85	9	3
Serra de Mesa	16-12-2013	799	20	12-12-2014	790	13	1.252	9	1
Marimbondo	13-12-2012	196	20	27-11-2014	192	10	0.19	4	1
Nova Avanhandava	5-12-2013	173	2	8-5-2014	173	4	0.54	1	0.3
Sobradinho	4-12-2013	2465	35	4-12-2014	1990	34	0.92		
Ilha Solteira	2-1-2013	1124	65	17-11-2014	962	61	6.18		
Furnas	14-12-2012	1000	67	13-11-2014	825	38	0.21		
Promissão	24-12-2011	531	33	26-2-2014	529	20	0.43		
Capivara	14-12-2012	490	62	13-12-2014	492	47	1.42		
Nova Ponte	11-1-2013	224	8	27-11-2014	196	37	8.87		
Estreito (L.C.B. de Carvalho)	4-9-2013	60	4	9-4-2014*	44	19	0.21		

657

658 * This image and the subsequent image taken on 17-4-2014 had high cloud
659 contamination and were therefore not included in the ADDA analysis.

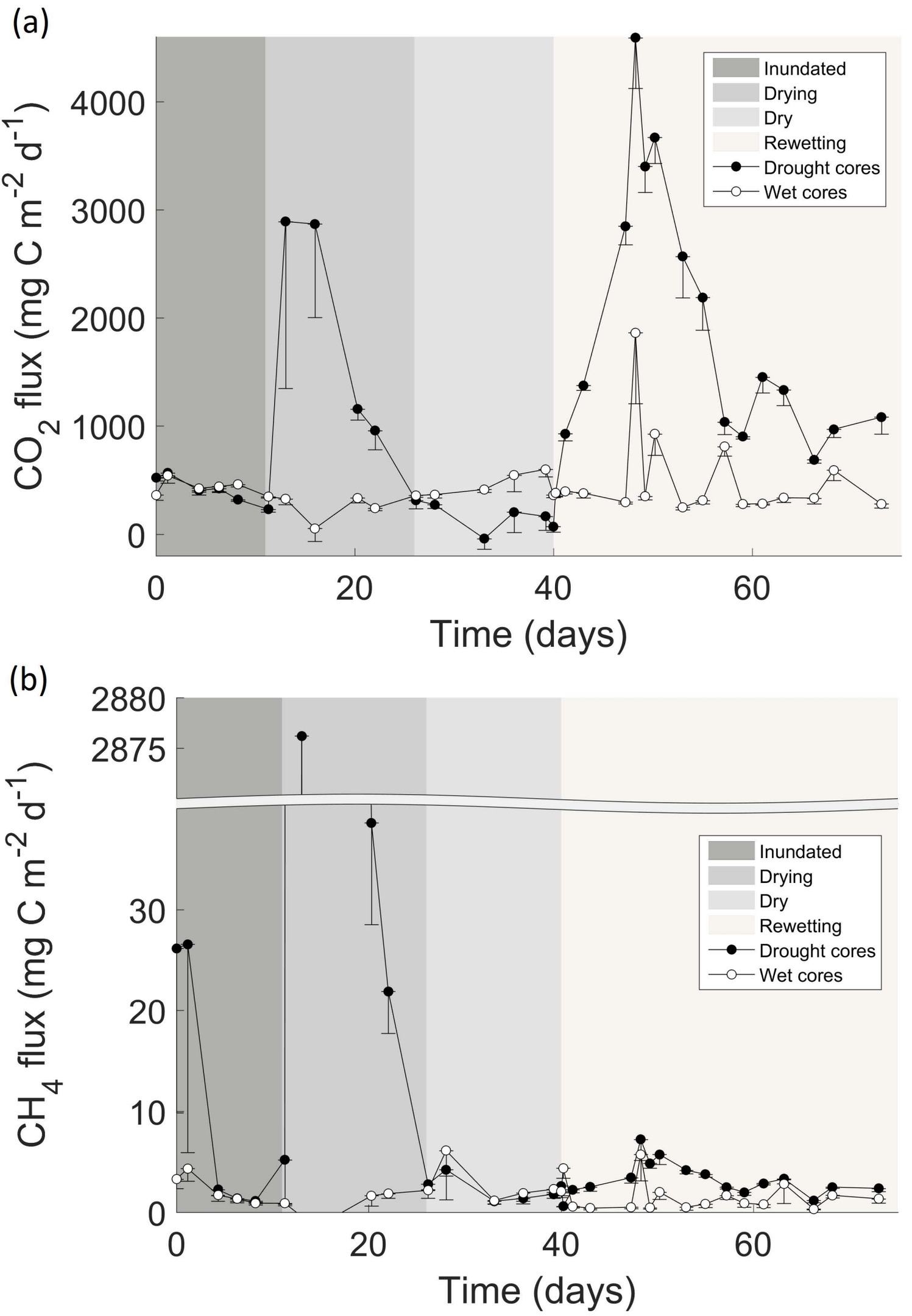
660

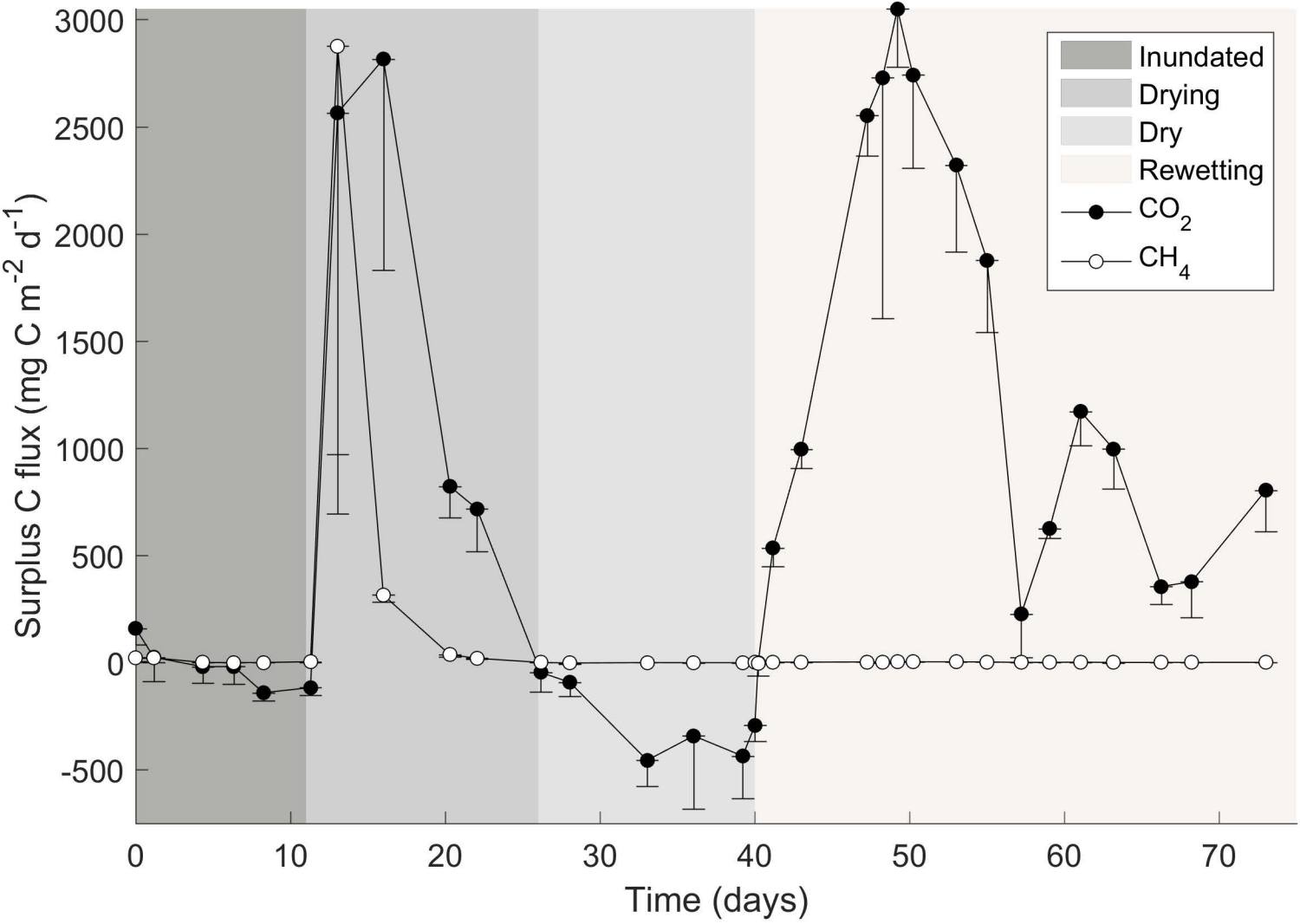
Figure 1. CO_2 (a) and CH_4 (b) emissions (average and SEM) from sediments that were continuously inundated (wet cores) and sediments that were exposed to drying and subsequent rewetting (drought cores).

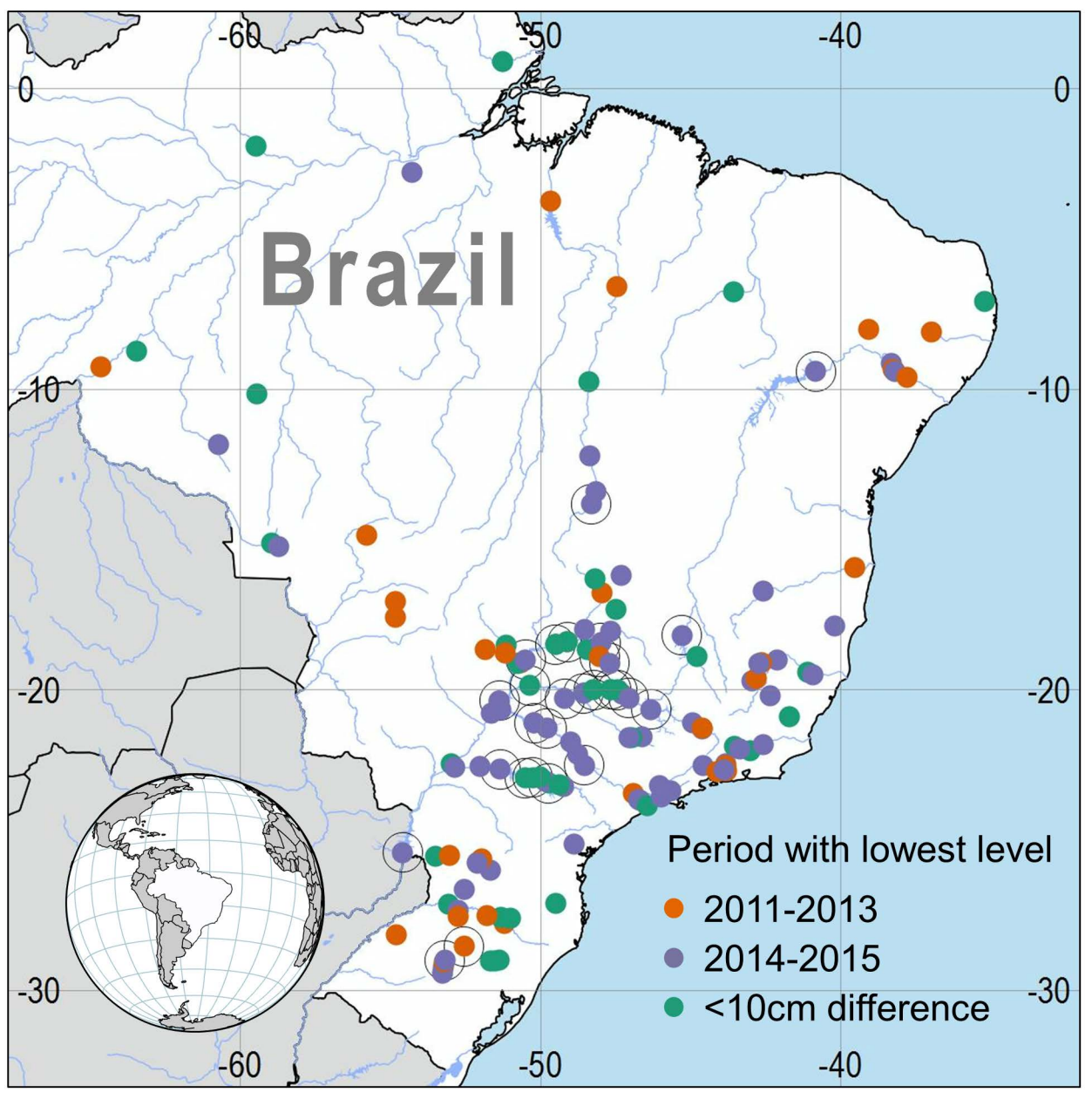
Figure 2. Difference between the CO_2 and CH_4 emissions from sediments that were exposed to drying and subsequent rewetting (drought cores) and from sediments that remained wet for the entire incubation period (permanently wet cores). Positive values (surplus) signify higher emissions from the drought cores than from the wet cores.

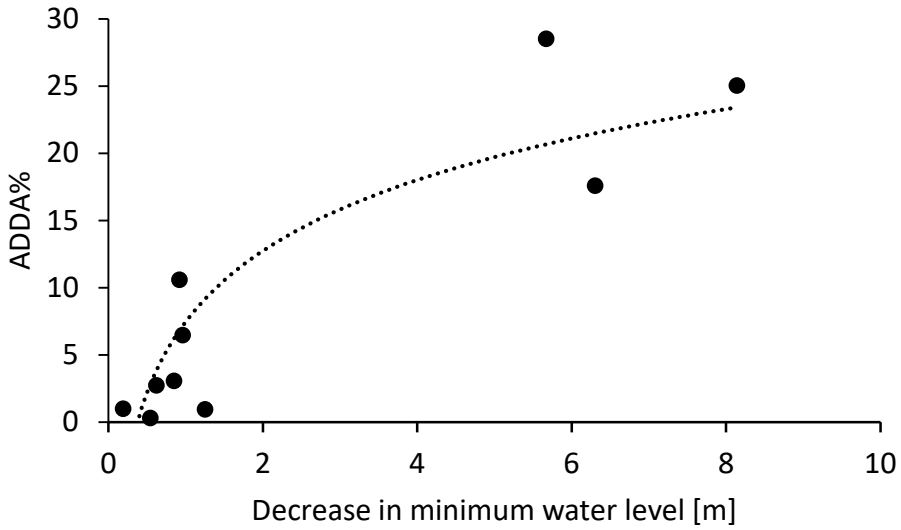
Figure 3. Comparison of minimum water levels in 137 reservoirs. Black circles signify reservoirs with satellite-derived estimates of the 2014 additional drawdown area.

Figure 4. Relation between the percentage of additional drawdown area (ADDA%) and the decrease in minimum water level between the periods 2011-2013 and 2014-2015. The dotted line depict the regression line ADDA%=7.61 x ln(decrease in min. water level)+7.46


(a)
CO_2 flux (mg C m^{-2} d^{-1})
4000
3000
2000
1000
0
0
20
40
60
Time (days)
Inundated
Drying
Dry
Rewetting
Drought cores
Wet cores
(b)
CH_4 flux (mg C m^{-2} d^{-1})
2880
2875
30
20
10
0
0
20
40
60
Time (days)
Inundated
Drying
Dry
Rewetting
Drought cores
Wet cores


Inundated
Drying
Dry
Rewetting
CO2
CH4
Surplus C flux (mg C m-2 d-1)
Time (days)
3000
2500
2000
1500
1000
500
0
-500
0
10
20
30
40
50
60
70


Brazil
-60
-50
-40
0
-10
-20
-30
Period with lowest level
2011-2013
2014-2015
<10cm difference


30
25
20
15
10
5
0
ADDA%
0
2
4
6
8
10
Decrease in minimum water level [m]