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Carbon dioxide emission from drawdown areas of a Mediterranean reservoir

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ABSTRACT

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Sediment beds from drawdown areas of reservoirs constitute a relevant hotspot for carbon dioxide (CO_2) emission to the atmosphere. This CO_2 source is especially relevant in the case of Mediterranean reservoirs, where hydrological variability favors the exposure of large sediment areas to air. In spite of this, the role of dry sediments as CO_2 emitters has been typically neglected in lakes and reservoirs greenhouse gas emission assessments, and there is also a lack of research on the spatial variability of CO_2 fluxes from drawdown sediments. In this study we contribute to this knowledge by combining drone-based aero-photogrammetry techniques with *in situ* infrared gas analyzer measurements to assess the magnitude and spatial variability of CO_2 fluxes from the drawdown area of a Mediterranean reservoir (El Gergal, Southwestern Spain) during one dry season. Our results show that during survey dry sediments in El Gergal were a relevant net CO_2 source to the atmosphere, with a mean emission of 0.36 ± 0.38 g CO_2 m^{-2} h^{-1}. In addition, CO_2 fluxes from El Gergal drawdown depict a marked spatial variability, with maximum values measured in areas influenced by river or intermittent streams discharges. Distance to the shore, sediment particle size, pH and temperature also have a significant effect on CO_2 emissions from the reservoir dry banks. The expected strengthening of droughts intensity and frequency in the Mediterranean region could enhance the role of exposed sediments from the drawdown of reservoirs as CO_2 source to the atmosphere.

Key words: Exposed sediments, Carbon dioxide, Emissions, Mediterranean reservoirs, Drone-based aero-photogrammetry, IRGA, Hydrological change

RESUMEN

Emisiones de dióxido de carbono desde sedimentos expuestos de un embalse Mediterráneo

Los lechos sedimentarios expuestos al aire en las zonas litorales de los embalses constituyen un foco relevante de emisiones de dióxido de carbono (CO_2) a la atmósfera. Esta fuente de CO_2 puede ser especialmente relevante en el caso de los embalses mediterráneos, donde la variabilidad hidrológica favorece la exposición de grandes áreas de sedimentos al aire. A pesar de esto, el papel de los sedimentos secos como focos emisores de CO_2 ha recibido típicamente escasa atención en las evaluaciones de emisiones de gases de efecto invernadero de lagos y embalses. Además, existe poco conocimiento sobre la variabilidad espacial de los flujos de CO_2 de los sedimentos de embalses expuestos al aire. En este estudio combinamos técnicas de aero-fotogrametría basadas en drones con mediciones in situ *mediante analizadores de gases por infrarrojos para evaluar la* *magnitud y la variabilidad espacial de los flujos de CO_2 en los sedimentos litorales expuestos de un embalse mediterráneo (El Gergal, suroeste de España) durante una estación seca. Nuestros resultados muestran que los sedimentos secos en El Gergal son una importante fuente de CO_2 a la atmósfera, con una emisión media de 0.36 ± 0.38 g CO_2 m^{-2} h^{-1}. Además, las emisiones de CO_2 desde los lechos sedimentarios expuestos del embalse presentan una marcada variabilidad espacial, con valores máximos medidos en áreas influidas por la descarga de ríos o arroyos intermitentes. La distancia a la orilla, el tamaño de las partículas del sedimento, así como su pH y temperatura presentaron un efecto significativo sobre las emisiones de CO_2 desde los bancos sedimentarios secos del embalse. El incremento esperado en la intensidad y frecuencia de las sequías en la región mediterránea podría reforzar el papel de los sedimentos expuestos de los embalses como fuente de CO_2 a la atmósfera.*

Palabras clave: *Sedimentos expuestos, Dióxido de carbono, Emisiones, Embalses mediterráneos, Aero-fotogrametría basada en drones, IRGA, Cambio hidrológicoos*

INTRODUCTION

Reservoirs provide key ecosystem services to human societies, such as water supply, irrigation, hydrological regulation, and hydroelectric energy production. However, these man-made ecosystems are far from being carbon-neutral, and it has been demonstrated that they emit relevant amounts of greenhouse gases (predominantly as carbon dioxide CO_2 and methane CH_4) to the atmosphere (St. Louis et al., 2000; Deemer et al., 2016; Samiotis et al., 2018; León-Palmero et al., 2020). In this context, Deemer et al. (2016) estimated that reservoir emissions are responsible of around 1.5 % of the global anthropogenic CO_2-equivalent emissions. Nevertheless, most of the existing studies on reservoir greenhouse gas emissions focus on fluxes at the water surface, while the role of seasonally exposed sediment beds as CO_2 emitters to the atmosphere has been largely neglected (Almeida et al., 2016; Marcé et al., 2019).

In reservoir ecosystems, drawdown areas are formed by those shores that, as a consequence of hydrological changes or hydraulic management, are subject to significant water level variations causing flooding or desiccation (Almeida et al., 2019). Flooded reservoir sediments can constitute relevant organic carbon sinks, in which mineralization of large inputs of allochthonous and autochthonous organic matter is often limited by the low oxygen availability, thus remaining buried for long time. However, when hydrological conditions (i.e., droughts or recurrent low water level periods) promote sediments exposure to air, the aerobic respiration of organic matter release a fraction of the buried organic carbon as CO_2 emissions to the atmosphere, and the exposed sediment beds constitute relevant CO_2 sources (Tesi et al., 2016; Marcé et al., 2019), as previously described for peatlands (Freeman et al., 2001; Fenner & Freeman 2011). An increasing number of recent assessments suggests that exposed aquatic sediments are relevant sources of CO_2 to the atmosphere (Catalán et al., 2014; Gallo et al., 2014; Von Schiller et al., 2014; Jin et al., 2016; Obrador et al., 2018; Marcé et al., 2019; Mallast et al., 2020), contributing to total CO_2 emissions at greater rates that those typically measured from the water surface of inland aquatic ecosystems (Catalán et al., 2014; Deshmuk et al., 2018; Keller et al., 2020, Gómez-Gener et al. 2015, 2016).

Emissions from dry exposed sediments may be relevant at a global scale, and it has been estimated that dry sediments emit ~ 200 Tg of C per year as CO_2, which is equivalent to ~ 10 % of global CO_2 emissions from inland waters (Marcé et al., 2019). Notwithstanding, these emissions are excluded from terrestrial and inland waters carbon budgets, constituting a relevant potential blind spot in global carbon cycling estimates (Marcé et al., 2019). Keller et al. (2020) suggest that if CO_2 fluxes from dry sediment beds were included in the actual estimations of inland waters CO_2 emissions, they would be increased by a 0.4 to 10 % factor.

Hydrological extremes associated to climate change and increased water demand are together enhancing the extension of dry sediments exposed to the atmosphere (Pekel et al., 2016; Keller et al., 2020) and the subsequent growth of reservoir drawdown areas (Mallast et al., 2020) and CO_2 leakage (Jin et al., 2016). This process is especially relevant in the case of Mediterranean reservoirs, which are characterized by a highly dynamic and intermittent hydrological regime (Gómez-Gener et al., 2015) enhanced by water withdrawals to satisfy growing human demands, resulting in marked water shrinking during the dry period. Once the sediment is exposed to the atmosphere, several drivers have been proposed to control the CO_2 sediment-air emissions, including organic matter supply, and sediment temperature, moisture, pH, and texture (Keller et al., 2020). All these factors are liable to present a marked spatial heterogeneity in the drawdown areas of reservoirs.

A deeper knowledge on the spatial variability of CO_2 fluxes from the banks of the reservoirs and related drivers is required to achieve a more realistic image of this process, which becomes even more relevant in the context of hydrological change. With this aim, in this study we combine drone-based aero-photogrammetry and soil respiration chamber measurements to investigate the magnitude and spatial variability of CO_2 emissions from dry sediment beds in the drawdown area of a Mediterranean reservoir. We also explore potential relations between drawdown CO_2 fluxes and topographical and physico-chemical sediment features.

MATERIAL AND METHODS

Study site

El Gergal reservoir (37º 34’ 13’’ N, 6º 02’ 57’’ W) is located in the siliceous watershed of the Rivera de Huelva River (a tributary of Guadalquivir River) and constitutes part of a network of four reservoirs which supplies water to the city of Seville and its metropolitan area, in the southwestern margin of Spain (Fig. 1).

El Gergal is a medium-size (maximum surface area: 250 ha; maximum depth: 37 m; maximum water storage capacity: 35 hm^3), canyon-type reservoir. Maximum reservoir length is 7.75 km, and maximum shoreline length is 31.08 km. Shoreline development ratio (the ratio between the measured reservoir shoreline length and the shoreline length of an ideal perfectly circular reservoir; Wetzel, 2001) is 5.5, a characteristic value of branched reservoirs with irregular shorelines receiving several tributaries (Kalff, 2002).

Both the surface area and water volume in the reservoir undergo frequent and severe fluctuations as a result of hydrological changes (Cruz-Pizarro et al., 2005). Effective residence time in the reservoir is very variable and ranges from a minimum of 20 days to a maximum of 1 year during severe droughts (Moreno-Ostos et al., 2007).

The thermal regime of El Gergal is warm monomictic, and its trophic status has been previously classified as meso-eutrophic (Cruz-Pizarro et al., 2005). Research addressed on El Gergal reservoir includes general limnology and hydrology (Cruz-Pizarro et al., 2005), phytoplankton dynamics (Moreno-Ostos et al., 2008; Hoyer et al., 2009; Moreno-Ostos et al., 2009a; Moreno-Ostos et al., 2009b; Moreno-Ostos et al., 2012), sedimentary processes (De Vicente et al., 2005), physical-biological modelling (Moreno-Ostos et al., 2007; Vidal et al., 2010), and ecosystem metabolism (Moreno-Ostos et al., 2016; Gilling et al., 2017).

Survey

In this study we explore the magnitude and spatial variability in CO_2 fluxes from the drawdown areas of El Gergal reservoir through an intensive survey campaign conducted during a low water level episode on 26th and 27th September 2018.

Due to the high topographical heterogeneity in the reservoir drawdown areas, we selected four different study sites to measure CO_2 emission (Fig. 1): The riverine area (site 1), two littoral zones influenced by the presence of an intermittent stream tributary to the reservoir (site 2 and site 3), and a drawdown area close to the dam (site 4). Considered drawdown surface was 2.3 ha in site 1, 2.3 ha in site 2, 1.4 ha in site 3 and 0.36 ha in site 4.

At each one of these study sites, we performed a detailed drone-based aero-photogrammetric survey, followed by randomized georeferenced

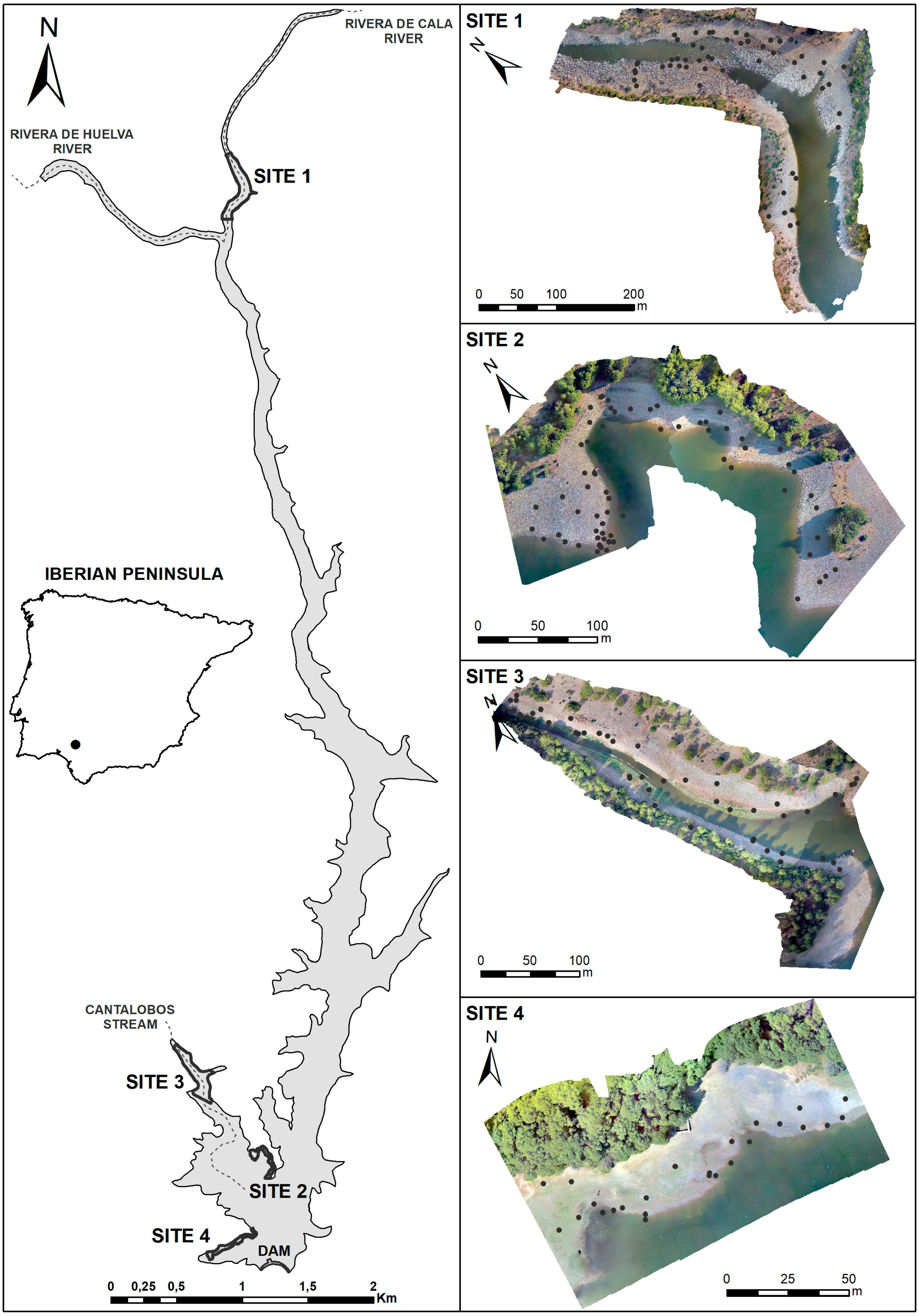

Figure 1. Map of El Gergal reservoir, with the four studied drawdown areas drone-based orthoimages. Dots depicts sampling stations where CO_2 fluxes where measured. *Mapa del embalse de El Gergal, con ortoimágenes de dron de las cuatro zonas de sedimentos expuestos estudiadas. Los puntos representan las estaciones de muestreo donde se midieron flujos de* CO_2.

measurements of CO_2 emissions at 57 sampling stations at site 1, 66 sampling stations at site 2, 49 sampling stations at site 3, and 25 sampling stations at site 4.

Dry sediments CO_2 emissions

At each sampling station direct measures of CO_2 sediment fluxes were performed *in situ* using an infrared gas analyser (IRGA EGM-5, PP-Systems, Amesbury, USA) attached to a soil respiration chamber SRC-2 (15 cm height, 10 cm diameter, 1171 ml volume, 78 cm^2 surface) in a closed system (Lesmeister & Koschorreck, 2017). The CO_2 concentration inside the soil respiration chamber was monitored every 5 s, with an accuracy of 1 %. The flux measurements lasted 120 s. Fluxes were determined by linear regression between the CO_2 concentration in the chamber and time ($R^2 > 0.9$), correcting for temperature and atmospheric pressure (Lambert & Fréchette, 2005). At each sampling site pH and sediment temperature were also measured using a Crison pH25+ probe fitted with a 50 54TC sediment penetration electrode.

CO_2 emission raster maps were interpolated from the sampled stations using the Inverse Distance Weighted (IDW) method (Fig. 2).

Drone-based aero-photogrammetry, topography and soil texture

In order to obtain accurate Digital Terrain Models (DTMs) of the reservoir dry margins, drone-based aero-photogrammetry has been performed throughout the shoreline of the four sites. A DJI Phantom 4 drone, equipped with a 12.4 MP sensor (20 mm equivalent focal length) photo camera, has been employed. The overall surveyed coast was segmented in a total of 12 smaller sub-regions, which have been covered with one single drone flight each (battery duration is the bottle-neck of the survey). Flight height was fixed to 45 m, in order to assure the optimal tradeoff between coverage and resolution. Averaged Ground Sampling Resolution (GSD) was 1.5 cm/pix (approximately 1000 points per square meter). Image overlapping was set to 85 % and 75 % for front and side superposition, respectively, and flight speed was fixed as slow as possible (~ 5 m/s) to improve accuracy. An average of ~ 200 images were collected for each single flight, with a total amount of more than 2400 pictures, all captured with zenithal orientation.

The images were processed with Pix4D photogrammetric suite, obtaining dense point clouds with more than 50 000 points in average for each flight. Point clouds were interpolated to obtain DTMs and RGB orthomosaics with a 5 cm cell resolution, for each sub-region (Fig. 1 and Fig. 2). One known issue of the aircraft used is about the vertical coordinate. It is very accurate (measured with the internal barometer), but poorly precise (GPS-based z-coordinate), with usually tens of meters of bias. In order to correct this bias, we precisely measured the height difference between the take-off altitude of the drone and the water level of the reservoir (at the time of the take-off), which was accurately reported by the Seville water supply company (EMASESA), and this value was applied to correct the height recorded by the drone on pictures metadata. Once applied this correction, the DTMs of the adjacent sub-regions matched with sub-centimetric accuracy.

Orthomosaics were used to vectorialize the water level contour at the survey time, and DTMs were applied to compute the distance of each CO_2 sampling station to the closest wet point. Shore slope was calculated from the DTMs mosaics obtained by merging the elevation models of each region. The slope rasters were used as input variables for the classification method used to determine the sediment granulometry of the margins. In particular, an Iterative Self-Organizing (ISO) clustering method was employed to obtain the statistical signature of three different granulometry classes based on the Udden-Wentworth scale (Wentworth, 1992): fine sand (0.25-0.50 mm diameter), coarse sand (0.51-2 mm diameter), and larger particles (> 2 mm diameter). Slope cells were classified based on an iterative computation of the cluster means (migrating means technique) up to converge to a statistically stable number of clusters (Ball & Hall, 1965). After a manual inspection of the output clusters, based on a visual comparison with the RGB orthomosaic and ground direct observations, three of them were selected as the most representative of the target granulometry classes. The statistical

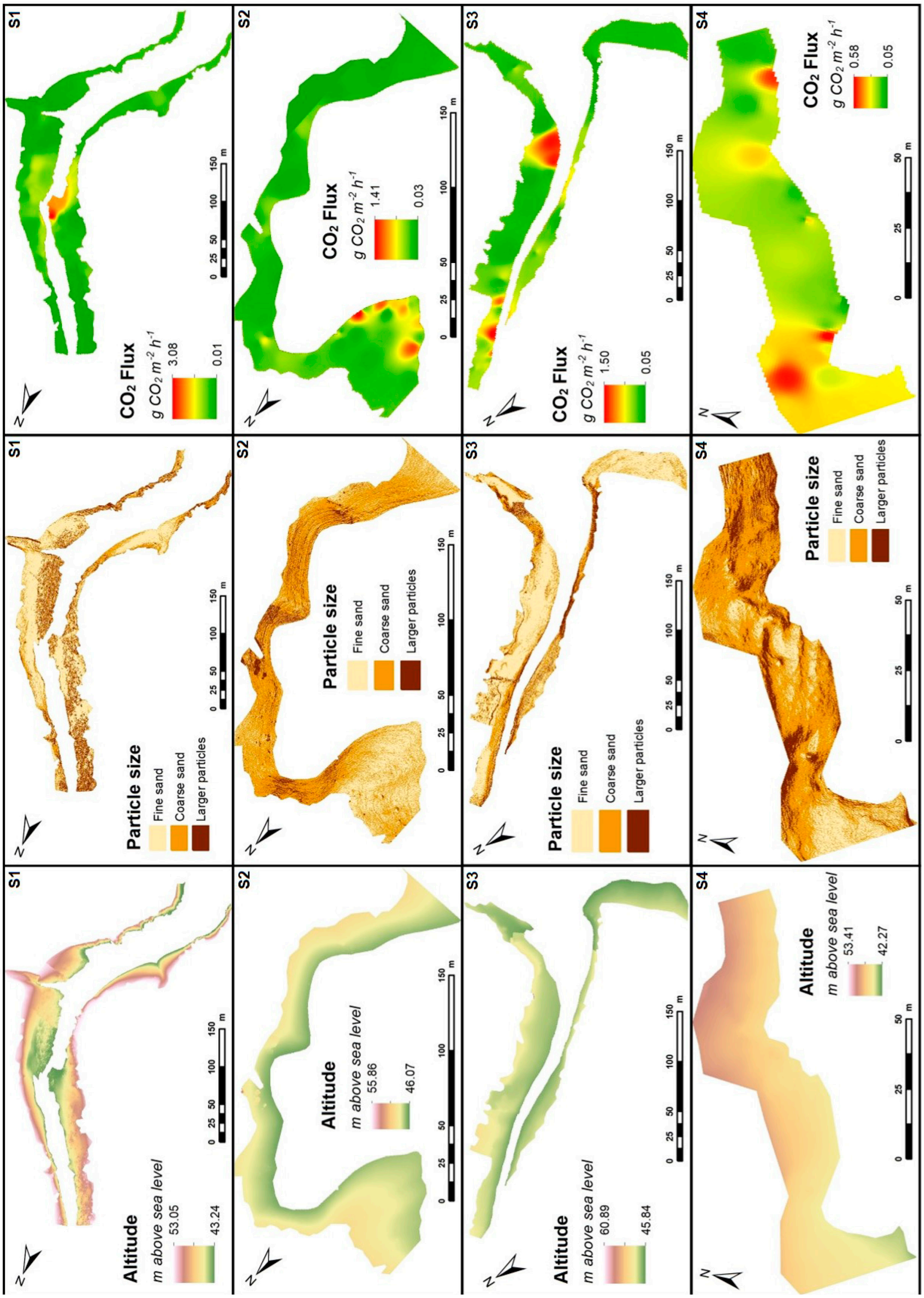

Figure 2. Digital Terrain Models, exposed sediment particle size, and CO_2 emission maps from the four studied drawdown sites. *Modelos Digitales de Terreno, tamaño de partícula sedimentaria, y mapas de emisión de CO_2 en las cuatro zonas de sedimentos expuestos estudiadas.*

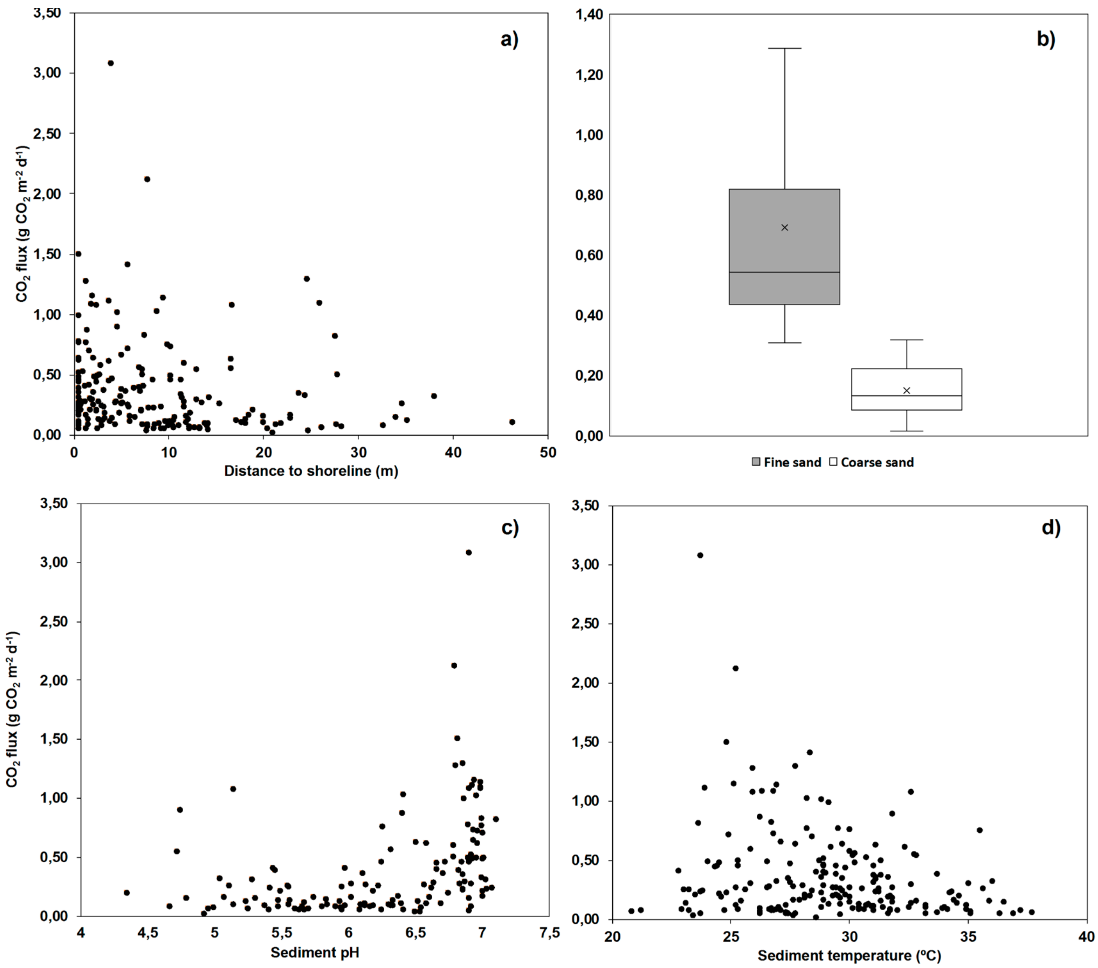

Figure 3. The influence of distance to the shoreline (a), sediment particle size (b), sediment pH (c) and sediment temperature (d) on CO_2 emissions from El Gergal drawdown exposed sediments. Correlation parameters in the text. In the box and whiskers plot (b), box represent first and third quartiles, whiskers are maximum and minimum values, horizontal line is median, and x is mean. *Influencia de la distancia a la orilla (a), tamaño de partícula sedimentaria (b), pH sedimentario (c) y temperatura del sedimento (d) sobre las emisiones de CO_2 en las zonas de sedimentos expuestos estudiadas. Parámetros de las correlaciones en el texto. En el gráfico de cajas y bigotes (b) Las cajas representan el primer y tercer cuartil, los bigotes los valores máximos y mínimos, la línea horizontal es la mediana, y x sitúa la media.*

signature of these clusters was used as input for a more sophisticated unsupervised classification method based on Maximum Likelihood (Ahmad & Quegan, 2012). The result was a set of classified rasters in which each pixel was assigned to one of the three granulometry classes, based on the highest probability of its membership (Fig. 2). Rasters processing and soil granulometry classification were implemented with ESRI ArcMap GIS software.

RESULTS AND DISCUSSION

The four studied drawdown sites of El Gergal reservoir were a net CO_2 source to the atmosphere during the studied dry season. Mean CO_2 emission for the surveyed reservoir drawdown areas was 0.36 ± 0.38 g m^{-2} h^{-1}, a very similar value to the global CO_2 emission suggested by Keller et al. (2020) from reservoir dry sediments (0.35 ± 0.87 g m^{-2} h^{-1}), as well as to the mean

CO_2 evasion from Mediterranean fluvial networks collected by Gómez-Gener et al. (2015). They are slightly higher than the mean value from exposed sediments of different types of inland waters (0.2 g m^{-2} h^{-1}) provided by Marcé et al. (2019). Interestingly, it also resembles the range of CO_2 efflux from Mediterranean soils (Bond-Lamberty & Thomson, 2010; Von Schiller et al., 2014; Gómez-Gener et al., 2015). However, despite high respiration rates, terrestrial soils use to be carbon sinks due to elevated primary production of overlying vegetation, while dry exposed sediments of reservoir ecosystems frequently lack primary producers to compensate for CO_2 production, and constitute CO_2 sources (Almeida et al., 2019).

Mean CO_2 efflux from El Gergal reservoir drawdown area exposed sediments was on average ~ 70 times higher than the mean annual CO_2 emissions from the reservoir surface at lacustrine zone (~ 5.4 mg m^{-2} h^{-1}, Montes-Pérez et al., 2022), revealing that El Gergal drawdown area constitutes a relevant CO_2 emission hotspot. In agreement, a review by Almeida et al. (2019) suggested that the average CO_2 flux from global exposed sediments (considering very different aquatic ecosystems, such as reservoirs, temporary ponds, temporary streams and rivers) is roughly one order of magnitude higher than the average of CO_2 flux from global reservoir surfaces.

The highest mean CO_2 emissions from drawdown areas were measured at site 1 (mean 0.51 ± 0.5 g m^{-2} h^{-1}, minimum 0.01 g m^{-2} h^{-1}, maximum 3.08 g m^{-2} h^{-1}), and site 3 (mean 0.42 ± 0.32 g m^{-2} h^{-1}, minimum 0.05 g m^{-2} h^{-1}, maximum 1.50 g m^{-2} h^{-1}), with dry-bed efflux similar to those measured by Gómez-Gener et al. (2015) in a Mediterranean reservoir (0.4 ± 0.3 g m^{-2} h^{-1}) and by Deshmukh et al. (2018) (0.5 ± 0.05 g m^{-2} h^{-1}) in the drawdown areas of Nam Theun reservoir (Laos). Mean CO_2 emission were lower at El Gergal site 2 (mean 0.22 ± 0.19 g m^{-2} h^{-1}, minimum 0.03 g m^{-2} h^{-1}, maximum 1.41 g m^{-2} h^{-1}), and site 4 (0.27 ± 0.14 g m^{-2} h^{-1}, minimum 0.05 g m^{-2} h^{-1}, maximum 0.58 g m^{-2} h^{-1}). In this context, Jin et al. (2016) measured similar mean daily CO_2 efflux (0.26 g m^{-2} h^{-1}) from the exposed sediments of the deepest and largest reservoir in South Korea.

Although all sampled sites were CO_2 emitters to the atmosphere, the spatial distribution of CO_2 emissions from El Gergal exposed sediments varied substantially in space. In agreement with Catalán et al. (2014) and Von Schiller et al. (2014), emissions were generally low at every sampling station, with strong emission patches frequently associated to permanent rivers and intermittent streams channels (Rivera de Huelva River at site 1, and Cantalobos intermittent stream at sites 2 and 3, see Fig. 2), which receive high allochthonous organic matter loads during flooding periods.

Taking into account all sampling points, CO_2 emissions from El Gergal drawdown areas were negatively related to the distance to the shore ($r = -0.18$; $p < 0.05$, Fig. 3a), revealing that recently exposed sediments sustain higher CO_2 emission (Jin et al., 2016; Paranaíba et al., 2020), and pointing out the role of rapid hydrological changes on CO_2 evasion from drawdown. Exposed sediments particle size also depicted a negative relation with CO_2 emission, with significant higher CO_2 efflux in fine sand areas than in coarse sand zones, while there were no CO_2 emissions from the larger particle's patches (see Fig. 2 and Fig. 3b). Previous studies have demonstrated that higher proportion of small-size particles is usually associated to higher organic matter and moisture (Burke et al., 1984; Buschiazzo et al., 2004), and Austin et al. (2004) suggested that this may promote microbial respiration in soils of arid and semiarid ecosystems. No significant relationship between CO_2 emissions and the drawdown slope was found in El Gergal reservoir ($r = -0.15$; $p = 0.07$).

El Gergal drawdown exposed sediments were slightly acidic, with mean pH of 6.2 ± 0.7 (minimum 4.34; maximum 7.1). CO_2 emissions were positively related to the pH of exposed sediments ($r = 0.39$; $p < 0.001$, Fig. 3c). Previous studies have described similar correlations between pH and CO_2 efflux from soils (Gómez-Gener et al., 2016; Oertel et al., 2016), suggesting that acidic soil and sediment conditions lead to lower CO_2 emissions (Oertel et al., 2016) and that increased pH enhances bacterial respiration and CO_2 emission.

Dry sediment temperatures were high throughout the survey, depicting a mean value of 29.1 ± 3.5 ºC, with a range of 20.8 - 37.7 ºC.

We found a non-linear unimodal relationship between exposed sediment temperature and CO_2 efflux, with a temperature threshold value around 25.5 ºC (Fig. 3d). CO_2 emissions increased with increasing dry sediments temperatures from ~ 21 ºC to ~25.5 ºC. By contrast, at higher temperatures CO_2 efflux and sediment temperature showed a negative relationship. It is well known that an increase of soil temperature leads to higher microbial respiration rates and higher CO_2 emission (Oertel et al., 2016). In this context, Gómez-Gener et al. (2016) found a positive relationship between dry streambeds with temperature ranging between 18 - 25 ºC and CO_2 efflux. Under field conditions, moisture and temperature effects on CO_2 emissions frequently overlap (Oertel et al., 2016), and the CO_2 emission decreasing trend found in El Gergal drawdown warmer than 25.5 ºC could be related to water stress. In agreement, we found a positive and significant relationship between exposed sediment temperature and distance to the shoreline ($r = 0.24$; $p < 0.001$), so warmer exposed sediments were also probably the drier, and some water content is essential as a transport medium for nutrients required by microbial communities. Accordingly, Paranaíba et al. (2020) found peaks in CO_2 emissions when exposed reservoir sediments transitioned from wet to dry, with fluxes declining as sediments dry out.

Our results support that exposed sediments of reservoirs are active sites for organic carbon remobilization to the atmosphere. Projected changes in hydrological trends will enhance this carbon source. In the Mediterranean region up to 50 % decreases in river discharge is expected (Schewe et al., 2014). These changes will impact hydrology in the whole river network including reservoirs (Catalán et al., 2016), which will significantly modify the exposure of sediments to air, favoring the remobilization of organic carbon stored in reservoir sediments and increasing CO_2 emissions to the atmosphere, perhaps until a further increase of soil temperature will decrease carbon emissions due to water limitation of microbial activity. In this context, Gómez-Gener et al. (2015) recently pointed out that extreme droughts associated to global change in the Mediterranean region would double CO_2 efflux from fluvial networks. This anthropically-enhanced carbon source to the atmosphere should be considered in global carbon budgets and in design of climate change adaptation and mitigation policies.

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