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Towards an enhancement of the climate change mitigation capacity of inland saline shallow lakes through hydrological regime and vegetation management: a modelling approach

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ABSTRACT
Inland saline shallow lakes play a role in the carbon and greenhouse gases exchange with the atmosphere and their climate regulation capacity is highly influenced by their ecological status and management. Our aim was to evaluate, through numerical modelling, the behaviour of representative saline shallow lakes, the influence of the lake management on the metabolic rates and the carbon balance under different management scenarios. The possible effects of management actions were modelled in relation to water regime and vegetation cover, showing the importance of the temporary flooding pattern and the key role of marginal vegetation for the carbon and greenhouse gas balances. Management recommendations mostly rely on recovering natural hydrological conditions.

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Introduction

Mediterranean wetlands and ecosystem services

The Iberian Mediterranean region displays semi-arid climate conditions where rainfall is relatively scarce and seasonally distributed, with the warmest periods also being the driest. Despite (natural) water availability being a limiting factor, especially in summer, the Mediterranean biogeographic region hosts a wide variety of wetlands constrained by the particular environmental conditions. Lentic ecosystems are characterized by extreme water level fluctuations leading, in many cases, to summer drying, thus showing a natural temporary flooding pattern (Doña et al., 2016). The abundance and diversity of lentic ecosystems (standing water, that is, water bodies where the water remains stagnant) in the Mediterranean entail high levels of biodiversity and invaluable ecological features.

The importance of these aquatic ecosystems can also be assessed from the ecosystem services approach, considering the benefits they provide to humans. Ecosystem services can be grouped according to their provisioning, cultural and recreational and regulatory

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benefits (MEA, 2005). Even sometimes with a lower direct perception by the society, regulatory services help to ensure human well-being due to, for instance, the control of floods, droughts and even the regulation of regional and global climate (Mitsch et al., 2015). The climate regulation capacity of wetlands has a huge relevance in a framework of climate change (Moomaw et al., 2018), whose consequences are expected to be especially severe in the Mediterranean, with longer periods of drought and higher increases of temperatures on average than in other parts of the world, as well as increasingly uneven distribution of rainfall (IPCC, 2014). The consequences of these changes in climate may lead to the loss of many Mediterranean wetlands, which are already highly threatened and altered (Perennou et al., 2012). Therefore, an adequate management of these ecosystems is necessary to protect their natural features under a climate change context, as well as to try to strengthen their climate mitigation capacity.

Climate regulation capacity of wetlands

In addition to the thermic water inertia, and its water retaining capacity, the climate regulatory ability of wetlands comes from their high biogeochemical transformation capacity, favouring active rates of carbon (C) greenhouse gases (GHG) exchange with the atmosphere (DeLaune & Reddy, 2008; Mitsch et al., 2013; Morant et al., 2020a, 2020b; Morris et al., 2013). One of the most widely used approaches to study the carbon balance in wetlands utilizes a metabolic approach, by determining the rates of the C-GHG exchange processes (Cole et al., 2007). In lentic ecosystems, the main biological processes involved in carbon-fixation are the photosynthesis by planktonic and benthic primary producers, as well as the marginal vegetation primary production (both by helophytes, and, in saline lakes, also halophytes), whose net production, overall, accounts for the biological capture of atmospheric carbon. On the other hand, processes emitting carbon greenhouse gases are both aerobic and anaerobic respiration processes releasing CO_2, whereas the anaerobic methanogenic respiration mostly occurs in the sediment that releases methane (CH_4). Though the exchange of methane with the atmosphere results from the balance between methanogenesis and methane oxidation, the latter mostly occurring within the water column (Camacho et al., 2017). Methane is also a greenhouse gas, but with a much higher warming potential in a 100-year time horizon than CO_2 (Whiting & Chanton, 2001). The balance between these metabolic processes determines the capacity of the lentic ecosystem to retain or release C from/to the atmosphere, as well as the mitigating or warming capacity, led by the relative exchanges through CO_2/CH_4 emissions.

Under proper conditions, wetlands can act to sequester carbon and store it, thus decreasing its concentration in the atmosphere (Mitsch et al., 2013; Morris et al., 2013). However, wetlands conditions (e.g., flooding) determine the C balance, and the final capture or release capacity, since an alteration in wetland structure and/or function due to climate change or other anthropogenic changes could shift the C balance (Morant et al., 2020a; Thorslund et al., 2017). The maintenance of natural characteristics, such as the seasonal flooding pattern, vegetation cover and wetland functional biodiversity and integrity, are necessary to guarantee ecosystem services (Erwin, 2009). Wetland management actions can significantly influence the C-balance as well, in such a way that they can strengthen the carbon retention capacity, but also reverse this function and increase carbon-greenhouse gas emissions to the atmosphere (Morant et al., 2020a). Therefore, these actions can be considered in the strategies to mitigate climate change and, consequently, ecosystems recovery to strengthen the carbon uptake would be plausible (Burkett & Kusler, 2000; Morant et al., 2020a).

Inland saline shallow lakes as a valuable wetland type

Among the ecological diversity of lentic ecosystems in the Mediterranean, inland saline shallow lakes are one of the most remarkable wetland types, for their abundance, uniqueness, and their ecological features determined by the Mediterranean climate. These endorheic ecosystems, when not altered, have a temporary hydrological pattern and high water mineralization from the accumulation of salts within the lake beds, both subject to high seasonal fluctuation (Camacho et al., 2003). However, in the Iberian Peninsula, where most inland saline lakes in Western Europe are located, distributed along several lake districts, many of these lakes have suffered important alterations during recent decades (Corrales-González et al., 2019). When not dried out and their land reclaimed for other purposes, they have been used to exploit salts, or as a final point for sewage disposal from towns nearby, without treatment until a few decades ago (García-Ferrer et al., 2003), but even now some of them receive treated wastewater from wastewater treatment plants. Furthermore, those partially fed by groundwater currently suffer from reduced water supply due to aquifer overexploitation, which affects not only the hydroperiod length, but also the development of halophytic vegetation on the lake shores (Camuñas et al., 2018). In terms of their carbon balance, the Mediterranean saline shallow lakes are mostly climatically neutral under well-preserved conditions, but they are highly vulnerable to pressures and threats, especially hydrological changes, driving to increases of GHG emissions and warming potential when degraded (Morant, 2022). When the hydroperiod extends in the time towards the warmest months, their methane emissions increase since higher temperatures activate the metabolism of methanogens (Camacho et al., 2017).

Many of the Spanish saline lakes are protected at several administrative levels (e.g., regional, national, international). The highest abundance of these ecosystems is found in the centre of the Iberian Peninsula, within 'La Mancha Húmeda' UNESCO Biosphere Reserve (Camuñas et al., 2018). These lakes, culturally linked to local populations, hold region's cultural and environmental heritage, being a source of income and a subject of tourist attraction (Camuñas et al., 2018). However, the management carried out for some of these lakes and their catchments has deeply altered their natural characteristics, in favour of certain economic and social demands (Camuñas et al., 2018), though damaging some of their ecosystem services such as climate mitigation.

Management and restoration of inland saline shallow lakes

The management and restoration of Iberian saline lakes is a priority given their ecological importance and the services they provide, following their Natural Resources Management Plans. Restoration does not only concern the lakes themselves, but also their catchments and the underlying aquifers. Knowing their potential climate regulatory capacity (Morant, 2022), among other ecosystem services, new strategies for management and restoration should consider the climatic perspective, aiming to enhance the carbon capture capacity while maintaining their ecological values, to strengthen their climate change mitigation services. Accordingly, it seems necessary to know what could be the influence of the different management modes and actions on the ecosystem services provided by these wetland types and, more specifically, on the climate change mitigation capacity of these inland, saline, shallow, temporary lakes.

Aim of the study

The aim of this study was to assess different management scenarios for inland saline shallow lakes, in order to determine their influence in the carbon capture capacity and climate change mitigating effect (through greenhouse gases exchanges), thus establishing a scientific basis and new guidelines to restore and manage these important ecosystems. The study focused on three representative (pilot) saline shallow lakes located in 'La Mancha Húmeda' Biosphere Reserve (central Spain), selected as representative because they are managed in different ways, display a different conservation status, and show several types of alterations. The modelled management actions were those related to the main hydrological management actions and alterations that are set for most saline lakes within the region. The management actions simulated encompassed the aquifer flow inputs for both Laguna de Alcahozo and Laguna de Manjavacas. Furthermore, the flow contributions from the wastewater treatment plant (WWTP) were taken into account specifically for Laguna de Manjavacas, and these contributions were also simulated by the model. The management of the Cigüela river flow contributions was modelled for Laguna Grande de Villafranca. Additionally, the management of the vegetation was modelled for the three selected lakes.

A methodology based on the numerical modelling of the carbon metabolic balance, calibrated and validated with observational and experimental data from the own and nearby lakes, was used as an assessment tool (Morant, 2022), then applied to particular management scenarios, addressing the main alterations experienced by these lakes. Simulation modelling results have been used to assess and propose the most appropriate management measures favouring carbon sequestration and the climate change mitigation service, while maintaining the ecological integrity of these lakes.

Methodology

Study site

Three inland saline shallow lakes located in 'La Mancha Húmeda' Biosphere Reserve, in the centre of the Iberian Peninsula (Figure 1), that are representative of the different alterations and possible management scenarios commonly experienced by these types of lake, were selected for this study. Like most of the saline lakes in the region, these lakes are endorheic (without surface outputs) and were naturally temporary. However, artificial water inflows may expand their hydroperiod to semi-permanent or permanent flooding. The area displays a continental Mediterranean climate, which largely determines the hydrological (flooding-drying) patterns of the lakes. Precipitation is seasonally distributed throughout the year, with average annual values of around 410 mm. Summer

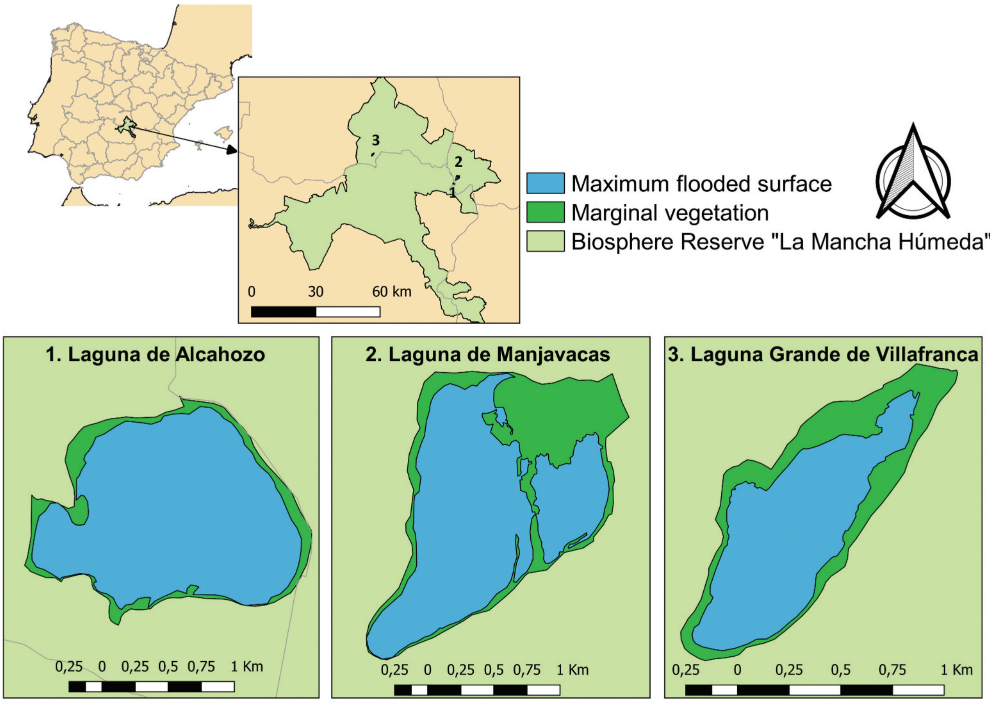

Figure 1. Location of the 'La Mancha Húmeda Biosphere Reserve' and maps of the three studied lakes. The maximum flooded area (blue) and current coverage of marginal vegetation (green), halophytes and/or helophytes are shown.

periods reach daily average temperatures of 25 °C, peaking in July, with monthly precipitation then usually being below 7 mm. The highest precipitation records are concentrated in autumn and spring, with averages of around 50 mm in the wettest months. This shapes the natural flooding pattern, with natural flooding ranging from autumn to middle spring, though currently modified by aquifer exploitation, or external water inputs from diverse sources, according to the alterations and management modes in each of the lakes.

The three selected lakes display different ways of management, conservation status and types of alterations, being representative of the main situations found in the saline shallow lakes within the Mediterranean basin (Table 1). Laguna de Alcahozo represents the situation of a relatively well-preserved site, with a temporary hydroperiod and high water mineralization, though water stress has led to a more ephemeral hydrological pattern due to aquifer overexploitation, with subsequent reduction of the groundwater feeding. In this lake, marginal vegetation lacks helophytes and is mainly composed of halophyte communities dominated by species of the genera *Salicornia* and *Suaeda*, characteristic and original to these lakes. Contrarily, Laguna de Manjavacas suffers both hydrological and trophic alteration due to the discharge of the wastewater treatment plant (WWTP) of the nearby Mota del Cuervo town, which increases the trophic level, reduces the salt concentration and extends the flooding period. As a consequence of the reduced water salinity, marginal vegetation has shifted to the dominance of helophytic

Table 1. Location and main ecological characteristics and conservation/alteration status of the studied lakes.

	Laguna de Alcahozo	Laguna de Manjavacas	Laguna Grande de Villafranca
Latitude	39°23′29.51″ N	39°24′58.94″ N	39°27′10.26″ N
Longitude	2°52′38.02″ W	2°51′50.20″ W	3°2″6.69″ W
Current hydroperiod (average flooded months)	October to March- May	September to July	Artificially permanent
Maximum flooded area (Ha)	66.6	179.4	54.3
Marginal vegetation cover (Ha) and dominant taxon	10.5 (*Salicornia europaea*)	45.0 (*P. australis*) 34.3 (*S. europea*)	20.7 (*Phragmites australis*)
Maximum depth (cm)	30	25	106
Conductivity, mean ±std. dev. (mS cm^{-1})	53.0 ± 53.3	35.3 ± 32,3	9.9 ± 2,.5
Chl-*a* concentration, mean ± std. dev. (mg m^{-3})	10.9 ± 12.2	24.1 ± 23.8	2.5 ± 2.8
Conservation status/ alterations	Well preserved. Overexploited aquifer	Hydrologically and trophic altered (WWTP input). Overexploited aquifer.	Hydrologically altered (Cigüela River input)

species (mostly *Phragmites australis*) in the northern area affected by the wastewater inflows, whereas halophytes still remain in the rest of the lake shore areas. This vegetation shift is also frequent in many other lakes nearby that receive similar freshwater inflows. Finally, Laguna Grande de Villafranca was originally a saline lake that some centuries ago, together with Laguna Chica de Villafranca, was connected through a channel to the Cigüela river. This connection allows continuous freshwater inflows that have transformed Laguna Grande de Villafranca into a strongly hydrologically altered regulated lake, shifting to permanent flooding controlled for recreational purposes. Freshwater inlets come from a river (Cigüela river), and water mineralization is significantly lower than it was originally, whereas marginal vegetation is solely composed of helophytic species dominated by *P. australis* and *Typha* and *Scirpus* species (Cirujano & Medina, 2002).

Measurement of the rates of carbon-processes (carbon fluxes) and experimentation for model calibration

In order to estimate the climate regulation capacity of the studied lakes through the estimation of their greenhouse gases exchanges, a metabolic approach was used. This approach entails an in-situ quantification of the rates of the biological processes (primary production and respiration of the biota integrated in the wetland compartments) linked to the carbon exchange between the lake and the atmosphere along the hydrological cycles, following gas exchange (plankton and benthos) or harvesting (marginal vegetation) procedures as described in Morant et al. (2020b).

The main metabolic processes studied, related to the metabolic carbon balance, were:

- Gross primary production integrated for the water column and the benthic communities (plankton-benthos).
- Helophytes and/or halophytes marginal vegetation biomass production.

- Aerobic respiration integrated for the water column and the benthic communities (plankton-benthos).
- CH_4 emissions resulting from the methanogenesis (anaerobic respiration) – methanotrophy balance.

Furthermore, experiments were carried out to quantify the response of the metabolic rates linked to the carbon balance to the most relevant environmental factors capable of modifying metabolism in these lakes; water level, temperature and salinity, as described in Camacho et al. (2017) and Morant (2022). These consisted of incubating several replicates of sediment-water-air cores under different environmental conditions. For temperature, the incubations were made at 4 °C, 14 °C, 20 °C, 25 °C and 30 °C (six replicates of each temperature) and they were incubated for 2–5 days depending on the incubation temperature. To determine the effect of salinity (measured as conductivity), we ran six replicates of five different salinity levels which, dependent on the original conductivity of each lake's waters, incubated at a temperature of 20 °C for 2–3 days.

Model

Model building

The results obtained from both the in situ measurements and the experiments were integrated into a mathematical numerical model to obtain estimations of the global carbon-greenhouse gases balance and radiative potential (global warming potential) per lake, integrating the metabolic rates with the meteorological, hydrological and ecological variables, thus enabling modelling changes expected from the defined management proposals (Table 2). The carbon balance was defined from the carbon inputs and carbon outputs in the system, all of them linked to the environmental factors studied in the experimental part. The model was developed using Stella software (Shiflet & Shiflet, 2006), which serves to graphically model the dynamics of systems using symbols, incorporating mathematical quantitative 2-D models of the system's response to driving variables. This software allows for simulating the response of dynamic systems under various conditions, which is useful for better understanding the system's behaviour and

Table 2. Summary of the management actions that were run in the carbon–greenhouse gases (C-GHG) model for each study site. Increases or decreases of 25/50/75/100% regarding the current conditions are referred to the water inputs or outputs, or to the surface of vegetation coverage.

Laguna de Alcahozo	Laguna de Manjavacas		Laguna Grande de Villafranca	All
Management of aquifer contributions	Management of aquifer contributions	Management of WWTP contributions	Management of the Cigüela river contributions	Management of vegetation coverage
Current conditions (CC)	CC	CC	+50% CC	+50% CC
+25% CC	+25% CC	−25% CC	CC	CC
+50% CC	+50% CC	−50% CC	−25% CC	−50% CC
+100% CC	+100% CC	−75% CC	−50% CC	Without vegetation
		Without WWTP inputs	Without river inputs	

predicting how it will respond under simulated conditions (Cervantes-Sandoval et al., 2009).

Model calibration and validation

The model was previously calibrated with a data set from 2016 to 2018, then validated with additional data from 2001 to 2016, and assessed through a sensitivity analysis (Villaescusa et al., 2016). We used all hydrological data reported by Camuñas et al. (2018). The 2016–2018 water regimes and carbon balance data were used for the model calibration, and the experiments to determinate the response of carbon fluxes to management actions (flooding, etc.) were performed on samples from these years. Then, model validation for the water regime, that needs to be done with data from a different dataset to that used for validation (Jørgensen & Fath, 2011), was performed using, for the three sites, a series of data from 2001 to 2016, being the results shown in the outputs from the model for a typical average year. The model was run with an average of the meteorological conditions (temperature plus precipitation, used for the hydrological model) obtained from the data series from 2001–2016. The outputs of the modelling are valid for an average year for the whole period of data retrieving, but these average data can also be changed in the model by the hydrological data of a specific year to obtain the response of carbon fluxes to the hydrological conditions of a particular year.

Hydrological part of the model

The hydrological characteristics of Laguna de Alcahozo were determined by water exchanges. Inflows resulted from the direct rainfall within the very small catchment and the lake basin, and from the aquifer, whereas both evapotranspiration and infiltration to the aquifer accounted for the outputs. For Laguna de Manjavacas, similar water inputs and outputs as in Laguna de Alcahozo were considered, but the inputs from the wastewater treatment plant were additionally included for the former, which on average accounts for 35% of the total. Finally, the hydrology of Laguna Grande de Villafranca, which has no interaction with the groundwater table, display similar processes for the inputs plus the monthly regulated contributions from the Cigüela River, which accounts for 55% of the total inflows on average (Camuñas et al., 2018), whereas evapotranspiration was the only output.

From the hydrological model, not only the hydrological pattern, but also the flooded area (in m^2) was determined during the whole hydrological cycle. The flooded area was used to make estimations of the projected annual metabolic rates modelled over the hydrological cycle (mg C m^{-2} d^{-1}) along with the rest of environmental variables. Then, this area was used to obtain the absolute data of the carbon and global warming potential balances (g C m^{-2} yr^{-1}) integrated annually for each lake and their respective management scenarios. The areas covered by marginal vegetation, either helophytes or halophytes, were also integrated in the model to estimate the relative and absolute contribution of helophytes/halophytes to the carbon balances.

Carbon balances modelling

In order to determine their carbon budgets and GHG emissions through their metabolic activity, three balances were estimated for each of the lakes as described by Morant et al. (2020a, 2020b). These three balances reflect an approach of the carbon exchange with the atmosphere, considering different compartments and in different units (carbon or carbon dioxide equivalents) as explained below.

The first balance was a (open) water carbon balance, considering only metabolic rates of the flooded areas non-covered by helophytes (i.e., plankton and benthos compartment, as well as methane emissions from the flooded sediments), informing on their autotrophic or heterotrophic behaviour. The second balance was an estimation of the total carbon balance, including both the open water metabolic rates and the marginal vegetation helophytes/halophytes net production, giving an approach of the carbon retention/release capacity. And finally, the third balance, was a global warming potential balance, in order to determine the warming/mitigating potential capacity from the carbon-greenhouse gases globally exchanged by all lake components in terms of CO_2-equivalents under the different management scenarios. When considering the carbon inputs and outputs to quantify the open waters and the total carbon balance (net ecosystem metabolism, in carbon units), carbon inputs (by primary production) were designed as negative values, as carbon-greenhouse gases are removed from the atmosphere, whereas outputs by respiration are marked as positive values, as carbon-greenhouse gas are then released to the atmosphere. A positive value would indicate that the outputs are higher than the inputs, therefore, more carbon-greenhouse gases would be emitted than would be assimilated, with the system functioning as a carbon source. On the contrary, a negative balance would indicate that the carbon inputs are bigger than the outputs, therefore, the system works as a carbon sink. To estimate the global warming potential balance, carbon units were converted to CO_2-eq units, considering the relationship 1:28 for the CO_2:CH_4 warming capacity of the two main carbon-greenhouse gases included in the balance.

Application to management scenarios

To assess the potential impact of changes in each lake on the carbon balance, induced by management measures in one direction or another, a series of scenarios were defined projecting different conditions in the studied lakes (Table 2). Two types of scenarios were conducted, one related to hydrology and another related to the marginal vegetation.

In Laguna de Alcahozo, the main water sources, in addition to precipitation, are contributions from the aquifer. This aquifer is overexploited, resulting in a reduced water supply to the lake compared to the past. Therefore, scenarios were studied involving recoveries in aquifer contributions of 25%, 50%, and 100% more annual volume than the current levels. This would potentially extend the hydroperiod and decrease salinity (conductivity) due to dilution effects.

For Laguna de Manjavacas, two types of hydrological scenarios were conducted. The first one focused on the inputs from the Mota del Cuervo wastewater treatment plant and the second one on the aquifer inputs. Regarding the wastewater treatment plant management scenarios, as they are artificial inputs, scenarios proposing reductions in inputs and even complete elimination of this input were suggested, namely a reduction of 25%, 50%, 75% and 100% of treated wastewater inflows. This would potentially alter the hydroperiod, transforming the lake into a seasonal one, as it would naturally occur. Additionally, salinity would increase, and eutrophication caused by nutrient inputs would be reduced. Regarding the aquifer management scenarios, as it feeds on the same groundwater as

Laguna de Alcahozo and faces the same problem, the same actions were projected, namely increases of 25%, 50%, and 100% in water inputs compared to current levels, while keeping the inputs from the wastewater treatment plant unaltered in that simulation.

The main contributions to Laguna Grande de Villafranca come from the Cigüela river, accounting for an average of 55% of total inputs. Some centuries ago, there was no inflow from the river into the lake, and this was the natural situation prior to that alteration. Therefore, scenarios were proposed to reduce river inputs by 25%, 50%, 75% and even 100%. Another proposed scenario was to increase the input by 50% due to the demand for a greater amount of water from the nearby population (Villafranca de los Caballeros) to enhance some of the ecosystem services provided by the lake, such as recreation. A lower water input would result in the lagoon becoming temporary, as it would dry up during a certain period of the year. Additionally, salinity would increase as the reduced water would lead to salt concentration through evaporation.

Finally, the proposed scenarios regarding marginal vegetation involved a 50% increase in the occupied area, a 50% reduction in favour of other uses such as agriculture surrounding and bordering the lake, and complete disappearance of marginal vegetation, leaving only the flooding basin.

Different management scenarios were defined to explore their potential effect on the carbon balance and greenhouse gases exchange capacity of the pilot studied lakes. Different conditions were projected by modelling and modifying the values of the new environmental conditions induced by each of the management scenarios in the model. Two types of scenarios were modelled, one related to hydrological management actions and the other related to the management of marginal vegetation (Table 2).

Results

Results are summarized by management actions, the vegetation management for the three studied lakes (Figure 2), the aquifer recovery for Laguna de Alcahozo (Figure 3) and Laguna de Manjavacas (Figure 4); the wastewater treatment plant contributions for Laguna de Manjavacas (Figure 5) and finally the shifts in water inputs from a river for Laguna Grande de Villafranca (Figure 6).

Metabolic rates responses

The response of the metabolic rates to the main environmental drivers (temperature and salinity) followed significant mathematical functions. Positive trends (enhancement) were found for temperature, and negative trends (drop) for salinity. GPP and respiration rates followed a linear response increasing with temperature, meanwhile methane emissions exponentially increased with temperature, whereas they show a power negative correlation with salinity (measured as electrical conductivity).

The helophytes and halophytes growth curves followed their vegetative cycle, with a production peak in late spring and early summer, whilst there was no net production during the coldest months. In Laguna de Alcahozo, the maximum halophytes production (mainly *Salicornia* sp.) occurred between April and May, with a maximum of about 1400 mg C m^{-2} d^{-1} (Figure 2a). Laguna de Manjavacas holds both helophytes and

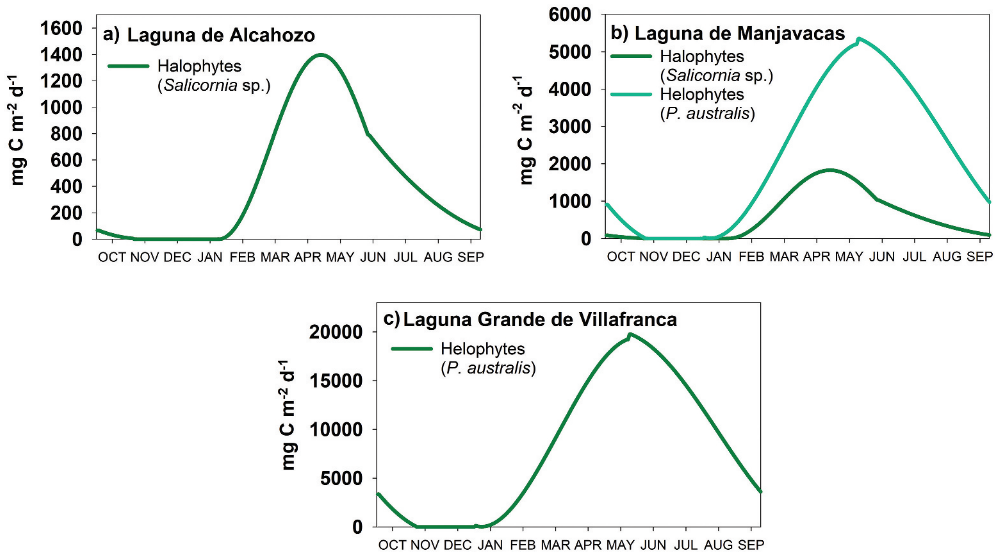

Figure 2. Modelled annual pattern of the areal marginal vegetation net primary production in: a) Laguna de Alcahozo; b) Laguna de Manjavacas and c) Laguna Grande de Villafranca (g C m^{-2} d^{-1}).

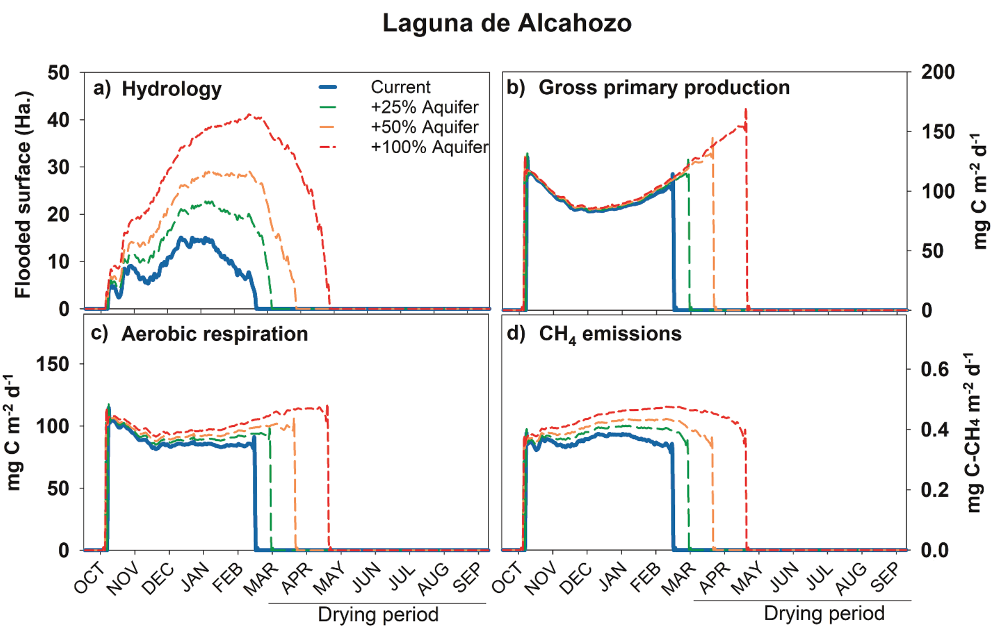

Figure 3. Modelled annual pattern of the: a) water regime, in ha of lake surface flooded; b) gross primary production (GPP); c) aerobic respiration and d) CH_4 emissions (g C m^{-2} d^{-1}) in Laguna de Alcahozo under the scenarios modelled for the management of aquifer contributions.

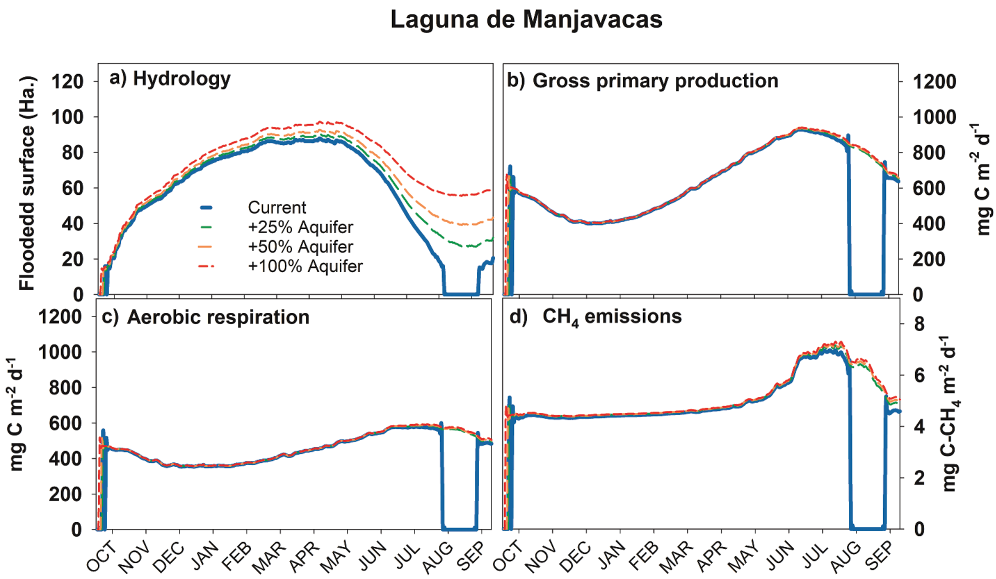

Figure 4. Modelled annual pattern of the: a) water regime, in ha of lake surface flooded; b) gross primary production (GPP); c) aerobic respiration and d) CH_4 emissions (g C m^{-2} d^{-1}) in Laguna de Manjavacas under the scenarios modelled for the management of aquifer contributions.

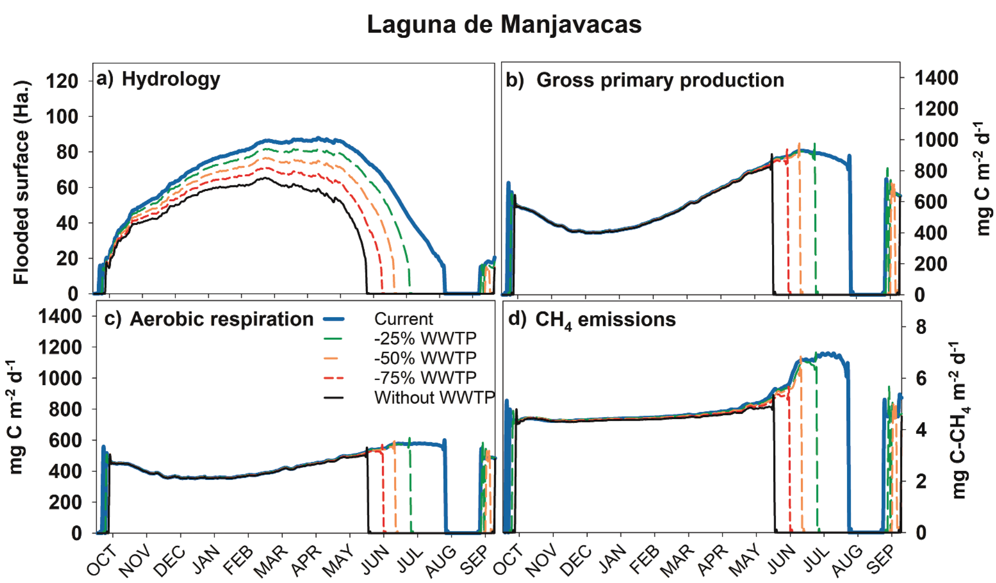

Figure 5. Modelled annual pattern of the: a) water regime in ha of lake surface flooded; b) gross primary production (GPP); c) aerobic respiration and d) CH_4 emissions (g C m^{-2} d^{-1}) in Laguna de Manjavacas under the scenarios modelled for the management of wastewater management plant (WWTP) flow contributions.

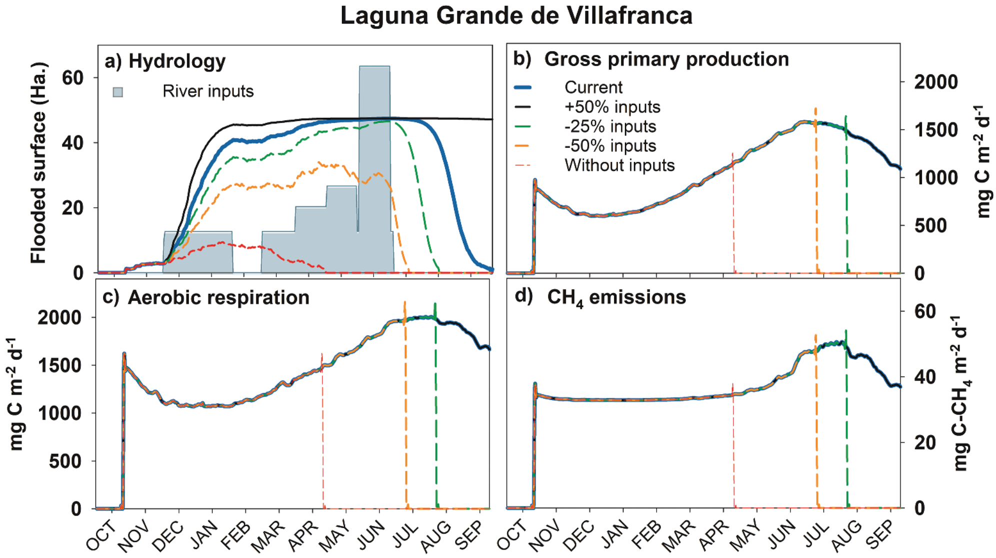

Figure 6. Modelled annual pattern of the: a) water regime, in ha of surface flooded; b) gross primary production (GPP); c) Respiration and d) CH_4 emissions (g C m^{-2} d^{-1}) in Laguna Grande de Villafranca under the management scenarios modelled for the of Cigüela river flow contributions.

halophytes, nevertheless, the helophytes community is dominated by *Phragmites australis* and presented a higher productivity compared with halophytes, with a maximum in May of 5500 mg C m^{-2} d^{-1} (Figure 2b) for the former. Finally, the helophytes of Laguna Grande de Villafranca showed a maximum production rate between May and June of around 20,000 mg C m^{-2} d^{-1} (Figure 2c).

The mathematical functions of these curves were included in the model to feed-up the response of the total carbon balance to changes induced by the modelled management scenarios. Once integrated with the hydrological and meteorological model, the behaviour of the above defined management scenarios was studied from each of the lake's models.

Hydrological management scenarios

Aquifer recovery scenarios (Laguna de Alcahozo and Manjavacas)

Groundwater contributions to both Laguna de Alcahozo and Laguna de Manjavacas have diminished for years due to the overexploitation of the aquifers. Simulations were addressed to test the possible effects of the recovery of these aquifers and, consequently, the recovering of the groundwater supply to theses lakes.

The hydrological model of Laguna de Alcahozo, considering its current average water inputs and outputs, showed a flooding period usually lasting from October to March (Figure 3a). Both the flooding period and the maximum flooding area would be increased in the aquifer recovery scenario (Figure 3a). A 100% increase, this is, doubling groundwater feeding, would result in a longer hydroperiod, being flooded from October to May on average, and reaching up to 40 ha of maximum flooding area, compared to the 15 ha under the current groundwater exhaustion scenario.

The response of the metabolic rates to these hydrological changes would result in a more extended activity associated to the expanded flooding period. Under current conditions, gross primary production would reach a maximum value of 130 mg C m^{-2} d^{-1} while the maximum for aerobic respiration would be around 110 mg C m^{-2} d^{-1}, both in late summer or early autumn (Figure 3b and 3c). Maximum values of carbon emitted from methane emissions would not exceed 0.4 mg C m^{-2} d^{-1} (Figure 3d).

The spatial and temporal extension of the flooding area in the simulated scenarios would result in an increase of annual maximum values (by plankton and benthos) for net primary production and for aerobic respiration under the aquifer full recovery scenario, up to 170 mg C m^{-2} d^{-1} and 120 mg C m^{-2} d^{-1}, respectively, all in spring, while the maximum methane emission rate would reach 0.5 mg C m^{-2} d^{-1} (Figures 3b–d).

The carbon balance estimated from the integrated metabolism of plankton and benthos, without considering the halophytes production, would show a slight autotrophic but nearly neutral balance reaching −0.7 g C m^{-2} $year^{-1}$ (negative values mean carbon sequestration) under current conditions, and −1.2 g C m-^{2} $year^{-1}$ in the full groundwater recovery (Table 3). However, the global warming potential balance would slightly promote warming, though with almost neutral effect of around 0.6 g CO_2-eq m^{-2} $year^{-1}$ under current conditions and 1.1 g CO_2-eq m^{-2} $year^{-1}$ with the maximum aquifer inputs increases.

The total carbon balance of lake Alcahozo, including the halophytes production, would be approximately −17 tonnes C $year^{-1}$, indicating a certain, though modest, carbon sink capacity. When increasing the water contributions from the aquifer, no significant variations appear (Table 3) since the weighting of the halophytes is greater, accounting for about 96% of the total C balance with a minor contribution of plankton and benthos. Regarding the global warming potential, the balance value would also be around −17 tonnes CO_2-eq. $year^{-1}$, given the small relevance of the very low methane emissions in global terms.

A similar aquifer recovery simulation by running the model for a semi-permanent lake showed different results, both in the hydrology and in the carbon-related metabolic rates. In Laguna de Manjavacas, by increasing the inflows of the aquifer and keeping the external inputs from the WWTP constant, the lake would have a continuous water supply, making it permanent (Figure 4a)

Regarding the metabolic rates, in Laguna de Manjavacas, the changes between the simulated aquifer recovery scenarios would not show marked differences during the usual flooding period for plankton and benthos, (Figure 4b–d), as WWTP water inlets already overcompensate the decreases of aquifer recharges. Looking at the modelled metabolic rates, the maximum rates of primary production under current conditions would be around 900 mg C m^{-2} d^{-1} reached in summer (Figure 4b). Aerobic respiration would reach a maximum of about 600 mg C m^{-2} d^{-1} also in summer (Figure 4c), while maximum methane emissions would reach up to 7 mg C m^{-2} d^{-1} (Figure 4d).

By integrating the metabolisms, a slight increase in the autotrophic capacity would be appreciated in the carbon balance for plankton and benthos by increasing the contributions of groundwater to Laguna de Manjavacas. Moreover, a slight decrease in its global warming mitigation capacity was predicted. These values oscillating around −57 to −66 g C m^{-2} $year^{-1}$ in the C balance for plankton and benthos and −14 to −16 g CO_2eq. m^{-2} $year^{-1}$ for the warming mitigation capacity (Table 3). On the other hand, in the total C

Table 3. Modelled annual changes in the carbon (C) and global warming potential (GWP) balances forecasted by modelling the different management scenarios for the three studied lakes.

Lake	Management scenario		C balance in open waters (g C m^{-2} y^{-1})	% Change	GWP in open waters (CO_2-eq m^{-2} y^{-1})	% Change	Total C balance (Tons C y^{-1})	% Change	Total GWP (Tons CO_2-eq y^{-1})	% Change
Laguna de Alcahozo	Aquifer recovery	CC	−0.7		0.6	0.0	−16.9	0.0	−16.8	0.0
		25%	−0.6	13.6	1.0	−54.7	−17.0	−0.1	−16.7	0.6
		50%	−0.8	−27.3	1.0	−62.5	−17.0	−0.4	−16.6	1.2
		100%	−1.3	−89.4	1.1	−78.1	−17.2	−1.3	−16.4	2.3
	Variations in vegetation cover	CC					−16.9	0.0	−16.8	0.0
		50%					−25.4	−49.9	−25.3	−50.2
		−50%					−8.5	49.8	−8.4	50.2
		−100%					−0.1	99.7	0.1	100.5
Laguna de Manjavacas	Variations in WWTP contribution	CC	−57.8		−14.1	0.0	−467.8	0.0	−440.9	0.0
		−25%	−47.5	17.9	−10.1	28.7	−461.1	1.4	−438.2	0.6
		−50%	−41.1	28.9	−7.7	45.7	−456.1	2.5	−436.3	1.0
		−75%	−36.6	36.7	−5.7	59.9	−451.8	3.4	−434.7	1.4
		−100%	−31.9	44.8	−3.2	77.5	−447.8	4.3	−433.1	1.8
	Aquifer recovery	CC	−57.8	0.0	−14.1	0.0	−467.8	0.0	−440.9	0.0
		25%	−65.5	−13.3	−15.8	−12.1	−472.8	−1.1	−442.3	−0.3
		50%	−65.8	−13.7	−15.7	−11.2	−476.1	−1.8	−443.3	−0.5
		100%	−66.2	−14.5	−15.5	−10.2	−481.4	−2.9	−444.9	−0.9
	Variations in vegetation cover	CC					−467.8	0.0	−440.9	0.0
		50%					−683.8	−46.2	−656.6	−48.9
		−50%					−252.1	46.1	−224.9	49.0
		−100%					−36.3	92.2	−9.1	97.9
Laguna Grande de Villafranca	Reduction of river inflows	CC	160.4	0.0	504.1	0.0	−561.9	0.0	−444.9	0.0
		50%	161.0	−0.4	505.7	−0.3	−550.8	2.0	−413.1	7.2
		−25%	131.4	18.0	418.5	17.0	−575.8	−2.5	−490.3	−10.2
		−50%	117.5	26.8	366.9	27.2	−588.7	−4.8	−536.5	−20.6
		−100%	88.4	44.9	254.7	49.5	−606.9	−8.0	−598.4	−34.5
	Variations in vegetation cover	CC					−561.9	0.0	−444.9	0.0
		50%					−870.1	−54.9	−758.2	−70.4
		−50%					−258.7	54.0	−146.8	67.0
		−100%					47.1	108.4	158.9	135.7

balance of Laguna de Manjavacas, there are almost no variations between the aquifer management scenarios, due to the huge relative relevance of the marginal vegetation in the global balance, with vegetation contributing 88% of the total carbon balance, and minor contributions of the plankton and benthos compartments.

Wastewater treatment plant contributions scenarios (Laguna de Manjavacas)

Under the current conditions, Laguna de Manjavacas only dries up for a few weeks during late summer, although in the WWTP discharge input area, occupied by helophytes, there is a very shallow permanent water sheet or at least a permanently wet sediment. The hydrological model showed a flooding area about 90 ha under current conditions (Figure 5a). Application of management scenarios with a reduction in the contributions of the WWTP showed decreases in both the length of the hydroperiod and the flooding surface, simulated by keeping the current condition of overexploitation of the aquifer. Current metabolic rates for plankton and benthos (as already indicated in the previous section) would not significantly differ under the WWTP contribution management scenarios (Figure 5b–d), as just the reduction of the flooding period would reduce these rates when the lake dries up.

The integration of all metabolisms in the carbon balance suggests an autotrophic behaviour in the plankton-benthos compartment, capturing almost 60 g C m^{-2} $year^{-1}$ under current conditions (Table 3). With reductions of the water contributions of the wastewater treatment plant, the autotrophy and the warming mitigation capacity (global warming potential) would also be reduced (Table 3). When accounting for the total C balance of the lake, where the marginal vegetation is considered, higher C assimilation was forecasted, reaching around 450 g C m^{-2} $year^{-1}$ captured in every scenario, showing again the importance of marginal vegetation in the total carbon balance.

Scenarios of shifts in water inputs from a river (Laguna Grande de Villafranca)

In Laguna Grande de Villafranca, management scenarios including progressive reductions of the water flow from the Cigüela river (to regulate and maintain the permanent flooding) would result in a reduction of the length of the flooded period. Currently, 9072 m^3 d^{-1} were modelled to be the inflows peaking in June, around 3800 m^3 d^{-1} in May and 1800 m^3 d^{-1} during winter. Maximum flooded surface area, under current conditions, reaching up to 50 ha, would also be slightly reduced with reductions of the water inflows (Figure 6a).

Gross primary production by plankton and benthos in Laguna Grande de Villafranca, under current conditions, reach the maximum carbon uptake during the warmest months, with more than 1500 mg C m^{-2} d^{-1} (Figure 6b). Maximum values of C release by aerobic respiration around 2000 mg C m^{-2} d^{-1}, also reached in summer, would exceed photosynthetic uptake, (Figure 6c). Minimum values of respiration would be above 1000 mg C m^{-2} d^{-1}, and around 750 mg C m^{-2} d^{-1} for primary production. For methane emissions, maximum values would not exceed 50 mg C m^{-2} d^{-1} (Figure 6d). Similar values would be maintained in the different scenarios projected for all these activities

The carbon balance for plankton and benthos in Laguna Grande de Villafranca, from the integrated metabolisms, would show a global heterotrophic behaviour, since respiration would greatly exceed primary production (Table 3). Under current conditions, around 160 g C m^{-2} $year^{-1}$ would be released by plankton and benthos. Reductions in water inflows, and, therefore, in the extent of the flooding period, would lead to a smoother heterotrophic behaviour, with values slightly lower than 90 g C m^{-2} $year^{-1}$ when the river contributions are totally removed. Regarding the estimated global warming potential, decreases would also be predicted.

The total carbon balance in Laguna Grande de Villafranca considering both the helophytes and the plankton and benthos contributions, would show a marked capture capacity. Under current conditions, values of around −560 tonnes C $year^{-1}$ of capture capacity, and −440 tonnes CO_2-eq. $year^{-1}$ of mitigating capacity were estimated. As in the plankton and benthos balance, when reducing the river contributions, the lake would increase the capture and mitigating capacity. In a situation where river contributions were completely removed, the C balance would reach −600 tonnes C $year^{-1}$ with the helophyte coverage maintained, while the removal of the global warming potential would also be close to −600 tonnes CO_2-eq. $year^{-1}$, which means that the mitigation capacity would be increased.

Vegetation management scenarios

As shown above for the total carbon balances, marginal vegetation production played a key role, accounting for 77% to 96% of the carbon captured in the three lakes studied. Considering possible increases in the marginal vegetation coverage, given the higher strong weight in the total carbon balance, the carbon retention capacity would markedly increase in all sites, independently of the water management scenarios (Table 3). In Laguna de Alcahozo, by increasing 50% the halophytic coverage, the carbon sequestration would increase to 25 tonnes C $year^{-1}$, 30% more than under current conditions. The warming mitigating capacity would also be markedly enhanced with increases in the vegetation coverage, though possible increases in methane emissions in the vegetation covered areas have not been considered here for any of the lakes, and this could slightly change the global warming potential balance.

In Laguna de Manjavacas, the scenario simulating variations in the marginal vegetation coverage showed how an increase of 50% of this coverage would increase the carbon capture capacity to more than 680 tonnes C $year^{-1}$, and also the mitigating capacity would increase to 650 tonnes CO_2-eq $year^{-1}$. In contrast, with a removal of the helophytes plus halophytes coverage, the C-sink and climate warning mitigation capacity would be reduced to an almost neutral carbon-balance of −36 tonnes C year $^{-1}$ and a warming mitigating capacity of just −9 tonnes CO_2-eq. $year^{-1}$, respectively (Table 3).

Finally, in Laguna Grande de Villafranca, the management scenario exploration when helophyte cover surfaces are modified showed important different balances. The carbon capture capacity with 50% more coverage would be increased from around 560 to 870 tonnes C $year^{-1}$, which means, 35% more carbon capture than under the current conditions. In the scenarios where the helophytes surface is reduced, a decrease in the capture and mitigating effect would be observed, up to the scenario when all marginal vegetation has disappeared, where the carbon balance would be heterotrophic, releasing C at around 47 tonnes C $year^{-1}$ and turning to a positive warming potential of 159 tonnes CO_2-eq. $year^{-1}$ (Table 3).

Discussion

Anthropogenic changes in Mediterranean inland saline shallow lakes

Aquatic ecosystems are among the most vulnerable to the threats of climate change (Erwin, 2009; Johnson et al., 2005; Mitsch et al., 2013), especially in the Mediterranean, where climatic conditions, which largely determine the hydrology and ecological features of shallow lakes and wetlands, are undergoing significant changes. For this semi-arid region, changes in precipitation patterns are expected, enlarging the drought periods, as well as a general increase in temperatures, which would cause both a direct reduction of water feeding to wetlands and increases in evapotranspiration (Lefebvre et al., 2019). This would increase the otherwise typical water stress of these ecosystems. Climate-induced changes are projected to drive reductions in water levels and shorten wetland hydroperiods (Lee et al., 2015), as well as to change water physical-chemical characteristics and other ecological features. Management becomes essential to reduce the impacts associated to climate change by favouring the resilience of the aquatic ecosystems.

Changes in environmental conditions can also lead to changes in carbon metabolic rates and carbon balances, interfering with the ultimate ability of wetlands to retain carbon and regulate the climate (Morant et al., 2020a, 2020b; Thorslund et al., 2017). However, as we demonstrated in this study, some management actions can strengthen carbon retention and reduce greenhouse gas (GHG) emissions, thus improving not only the climate adaptation, but also the wetlands mitigating service and climatic regulation.

Aligned to other studies (Burkett & Kusler, 2000; Morant, 2022), the Mediterranean shallow lakes here studied showed some carbon sequestration capacity, but also greenhouse gases emissions, being the rates of the related processes likely to be affected by management measures (Adhikari et al., 2009; Erwin, 2009; Morant, 2022). Our study forecasts the effect of management actions on the carbon metabolic balance of inland saline shallow lakes, from which the importance of water regime and water quality, as well as of marginal vegetation, both helophytes and halophytes, were demonstrated to play a major role in their climate regulatory service. Our results pointed out the relevance of the relationship between carbon capture and greenhouse gases emissions with conservation status and management. These are key to unveiling the mechanisms and response of these particular ecosystems to management under a climate change situation, fostering their climate change mitigating capacity.

Modelling carbon balances under different management scenarios

We used models to estimate the possible effects of management on the carbon balance. The ecological modelling has been applied in many other studies, due to its suitability to predict scenarios using mathematical projections (Camacho et al., 2014; Jørgensen & Fath, 2011; Villaescusa et al., 2016; Zhang et al., 2002). Modelling results showed that the flooding pattern, and especially the marginal vegetation, were determinants for carbon balance regulation. Management, as seen, is becoming crucial for the wetlands' climate change mitigation capacity. The knowledge of the projections and estimated trends in carbon balance and greenhouse gases emissions in both well-preserved and altered saline shallow lakes under future climate scenarios could help in the selection of appropriate actions under a climate change mitigation perspective (Morant, 2022). Therefore, water regulation and marginal vegetation management are two key components of wetlands climate change mitigation capacity. An adequate knowledge of their influence on the carbon and greenhouse gases exchanges with the atmosphere, together with a proper predictive capacity, are essential to strengthen their carbon retention and mitigating capacity. Management actions directly affecting the water regime are usually focused on regulating and monitoring water inputs and outputs. From an ecological point of view, the water regime alterations cause a change in the ecosystem structure and functioning, not only due to shifts in the hydroperiod, but also in the chemical composition of the water when water flows come from sources that chemically differ from the natural features of the lake water. These structural and functional changes can modify the mechanisms that regulate the metabolic exchange of carbon in lakes (DeLaune & Reddy, 2008), Thus, changes in hydrological patterns can lead to changes of different magnitude in metabolic rates such as those of primary production and respiration in lake components like plankton and benthos, driving modest to moderate changes in the carbon and global warming potential balances, as described elsewhere (Dietrich et al., 2007; Maher & Eyre, 2012). Our results showed the interference of the hydroperiod extents on the activation of metabolic rates, both carbon-retention and carbon-release rates, mainly when the higher temperatures during warmer months, as experimentally demonstrated (Camacho et al., 2017), are overlapped by extended hydroperiods.

Water management

The results of this study showed just slight variations in the total amount of carbon with changes in the hydrological patterns induced by water management. These changes, however, were not predicted as being so crucial in defining the behaviour of the lakes with respect to the carbon balance, as marginal vegetation, which is less affected by these hydrological changes than plankton and benthos, accounted for 77 to 96% of the total integrated carbon-balance, confirming the pattern described in other study sites (Brix et al., 2001; Morant et al., 2020a). However, despite sharing the dominant role of marginal vegetation in the carbon transfer, each of the studied lakes differed in the effects of hydrological management modes on the carbon balances.

For example, the aquifer overexploitation, due to excessive water demand, reduced the natural water contributions in lakes like Laguna de Alcahozo. This situation is expected to be more pronounced and widespread due to climate change (Dwire et al., 2018). The hydraulic connectivity between wetlands and groundwater allows the aquifer water flow in both directions. When modelling the recovery from aquifer overexploitation to extend the groundwater supply to natural levels, thus recovering the extent of the lake hydroperiod of this temporary lake, just slight increases in the total annual amount of carbon retained are forecasted, since most of the carbon sequestered in that lake is accounted for by marginal halophytes and not by plankton and benthos. It should be noted that very high salinity, as displayed by Lake Alcahozo, restricts metabolism (Herbert et al., 2015), which results in very low metabolic rates in the flooded area that contribute much less than marginal halophytes to carbon storage, resulting in near-equilibrium carbon-balances in the flooded area, but overall keeping a certain sequestering capacity because of the carbon capture by halophytes (Morant, 2022). Aquifer recovery would also promote the resilience and adaptation of groundwater fed lakes to climate change, due to the higher groundwater inertia against the estimated droughts expected for the Mediterranean environment (IPCC, 2014), though with relatively little impact on carbon-sequestration. On the other hand, a larger hydroperiod would also be beneficial in maintaining marginal or even increasing halophytic vegetation, and the amount of carbon it assimilates, which would show significant increases relative to the rise of vegetation covering. All of this is of paramount importance for maintaining the carbon storage capacity as shown by our results. On the contrary, temporary shallow lakes tending to have a more ephemeral hydroperiod than natural could lose some of the marginal vegetation coverage, thus lowering its carbon sequestration and climate change mitigation capacity.

When flooding extends to the summer months in naturally temporary lakes driving to (semi)-permanent conditions, the predicted changes in carbon balances become more significant. Carbon emissions to the atmosphere are usually much lower during the dry season (Ju et al., 2006). However, as shown in Laguna Grande de Villafranca, which has been managed for centuries to be permanently flooded for recreational purposes, when the hydroperiod remains enlarged and flooding remains in summer, metabolic rates accelerate due to the higher temperatures of these warmer months. As most water comes from a river, which is a source of external organic matter susceptible to being consumed by heterotrophs, respiration in water is higher than primary production and the flooded area acts as a heterotrophic system. Not only aerobic respiration, but especially anaerobic pathways, such as methanogenesis, are enhanced more than photosynthesis by the higher summer temperatures, promoting the activation of CH_4 emissions (Camacho et al., 2017) and strengthening the greenhouse effect and global warming potential (radiative forcing) generation (Whiting & Chanton, 2001). These changes, although more relevant in Laguna Grande de Villafranca than in Lake Alcahozo, are yet of relatively low relevance with respect to the total carbon balance, as most net carbon capture is still performed by helophytes (16.2 tonnes C yr^{-1}). All this results in a small reduction of the carbon storage capacity when the river inflows are modelled to be reduced in order to recover the temporary hydroperiod, but an improvement of the global capacity for climate change mitigation is achieved as greenhouse gas emissions are reduced further than carbon capture when enlarging the dry period.

Besides changes in the hydroperiod, the different mineralogical composition of the water inlets in originally endorheic saline lakes (Corrales-González et al., 2019) can also cause changes in the metabolic rates associated with the carbon exchange (Herbert et al., 2015; Morant et al., 2020b). Methanogenesis, which occurs in the lake sediments under anaerobic conditions, increases exponentially with increases of temperature, whereas it is reduced following a power function with reduced salinity (Camacho et al., 2017). That means that extending the hydroperiod to summer, to a time where the lakes should naturally be dry, increases more rapidly the production of methane than the capture or release of CO_2, thus enhancing the warming effect as methane has a much higher warming potential at short-medium term (Myhre et al., 2013; Olsson et al., 2015). These effects may be amplified under future climate change scenarios when temperatures would be even higher, when expanding the hydroperiod towards warmer periods with no natural inflows could shift the climate change mitigation capacity of these lakes, making them net contributors to warming due to the increase of methane emissions, this gas generating a much higher radiative effect than CO_2 (Camacho et al., 2017). On the other hand, both plankton and benthos primary production and respiration (aerobic and anaerobic) are negatively correlated with salinity (Morant, 2022), in such a way that the decrease in salinity caused by freshwater inputs would increase the metabolic rates, but especially aerobic respiration and methane production, thus promoting warming. Concerning vegetation, both helophytes and halophytes, the drops in water mineralization favour the helophyte growth over halophytic plant communities. The common reed (*Phragmites australis*), which is among the most productive marginal plants in aquatic ecosystems (Brix et al., 2001; Mitsch et al., 2013), is the dominant plant species when water salinity drops over the normal levels in these saline systems. Thus, helophytes are favoured by longer hydroperiods and lower salinities compared to the natural conditions of these lakes. Therefore, for carbon sequestration purposes, maintaining or increasing marginal vegetation, and more specifically reed-dominated communities, would be positive for increasing carbon sequestration, though this desalination could promote inadmissible losses of biodiversity as the biota of these lakes is strongly linked to its saline and temporary character. On the other hand, the maintenance of the naturally restricted temporary flooding pattern of this type of saline lakes would prevent the release of significant amounts of CH_4 and CO_2 emissions, as greenhouse gases releasing processes are more favoured than primary production by the higher temperatures when the hydroperiod expands to the warmer season (Sha et al., 2011).

Wastewater treatment plant influence

Another common alteration in the saline shallow lakes of 'La Mancha Húmeda' Biosphere Reserve is their use as an end point for wastewater treatment plant discharges (Camuñas et al., 2018). These discharges, which are currently regulated and are limited to waters having been treated at least with secondary treatment, were spilled untreated until a few decades ago. In lakes like Laguna de Manjavacas, this resulted not only in the extension of the hydroperiod and the reduction of salinity, becoming a semi-permanent lake with less saline waters, but also, due to the eutrophication process, in very high organic loads accumulated both in the water column and, especially, in the sediments. The example of Laguna de Manjavacas showed stronger alteration of metabolic rates and carbon balances from plankton and benthos, compared to Laguna de Alcahozo, originally similar, which has maintained its natural ecological features. In the short term, a reduction in the nutrient-rich water supply to Laguna de Manjavacas would cause a reduction in its climate change mitigating effect, since a higher trophic level initially favours gross primary production (Pacheco et al., 2014). This situation, however, would reverse at the medium-long term, as all the increased organic matter amounts accumulated in the sediments under low redox anaerobic conditions would enhance methanogenesis (Camacho et al., 2017; Maynard et al., 2014; Yarwood, 2018), additionally to increase aerobic respiration rates both in the water column and surface sediments. For this reason, eutrophication should not be considered a favourable condition to promote carbon sequestration and mitigation capacity, but instead enhancing the warming potential created by wetland's greenhouse gases emissions. Even more important is, in these cases, that the excess water coming from the wastewater treatment plant enlarges the hydroperiod and, as already discussed, this favours an increase in greenhouse gases emissions as the greenhouse gas releasing processes are usually more activated by increased temperatures than carbon sequestering processes. On the other hand, and because most of the carbon captured in Laguna de Manjavacas is accounted for by the marginal vegetation (here both helophytes and helophytes), the recovery of the aquifer, which contrary to the reduction of the inflows of the wastewater treatment plant would extend the flooding period, is not so crucial, neither for the carbon-balance nor for climate change regulation services of the lake.

Not only for water-related management measures, but also marginal vegetation management in lakes functioning as end points of water treated in wastewater treatment plant is of major relevance in the carbon balance account. The fact that lower water salinity favours helophytic vegetation, as it occurs in the surroundings of the water inlet of Laguna de Manjavacas, with helophytic vegetation capable of capturing large amounts of carbon, overpasses the increases of CH_4 and CO_2 linked to the prolonged flooding. However, these high-nutrient freshwater inflows alter the essential ecological features of saline lakes, and consequently its use as a possible management approach to increase the climate change mitigation capacity of saline shallow lakes should be approached with caution.

Relevance of vegetation management

Our modelling approach, based on field and experimental calibrations and process weighting, shows that marginal vegetation is essential in determining the role of lakes as a carbon source or sink, as observed in the hydrological and vegetation management scenarios projected in this study. When vegetation coverage is reduced, the carbon balance is also reduced up to neutral, or even heterotrophic (carbon and greenhouse gases net release) in the three studied lakes if vegetation totally disappeared, thus contributing to increased warming in the extreme cases. When maintaining or even increasing vegetation coverage, our model predicted an increase in the carbon retention capacity and a higher contribution to the warming reduction, as suggested for other study sites (Brix et al., 2001). The differences in the total amount of carbon captured for each site studied are based on the predominant plant communities, being more productive with helophytes (*P. australis* as dominant) than halophytes (*Salicornia* sp. dominant). Even with the higher carbon capture capacity of helophytes communities, which are favoured over halophytes in less saline ecosystems, the latter are of high importance, not only from the climatic change mitigation perspective (Morant, 2022), but also for their ecological relevance, adaptability to such extreme environments, resilience to climate change and sustenance of biodiversity.

Management recommendations

After modelling the relationships between the different management procedures and the response of the carbon sequestration and climate mitigation capacity in saline lakes, management actions and guidelines can be analysed to include a climatic perspective where the role of these ecosystems on climate change mitigation or enhancement is considered. This can be further extrapolated, for the hydrological and vegetation management scenarios, to deal with the main alterations of the natural features of shallow saline temporary lakes here modelled, mimic those found in most lakes of this type in the Iberian Mediterranean.

In relatively well-preserved shallow saline lakes, which maintain their temporary hydroperiod and high levels of water mineralization, such as Laguna de Alcahozo, groundwater contributions are necessary to maintain and/or recover the flooding pattern, even more under future climatic scenarios when the water stress typical of the Mediterranean climate can be exacerbated. No significant changes in carbon balances would occur in these scenarios, but they would help to keep the lakes in good ecological condition, which is associated to slight amounts of carbon sequestration and the maintenance of a certain capacity for climate change mitigation. Further, the recovery of the flooding period would contribute to the renaturalization of degraded shoreline areas that could be recolonized by halophytes, with an increase of the marginal vegetation coverage, including some helophyte species, such as *Cladium mariscus*, that once inhabited the area (Cirujano & Medina, 2002), and would therefore increase the carbon capture and climate change mitigation capacity of these lakes.

Lakes functioning as the end point of water from WWTP are more complex to manage, especially when the alteration of the ecological characteristics lasted for decades with a marked footprint in the lake's ecological characteristics. Considering Laguna de Manjavacas as an example for this situation, if external water contributions would not increase the trophic status of the lake nor significantly decreased salinity, they could compensate for the decreased aquifer inflows due to overexploitation. With these compensations, an important helophytic coverage could still be settled, which would maintain at the least the carbon retention capacity. However, the use of treated waters coming from WWTP could only be considered with strict tertiary treatments to minimize eutrophication effects. Inflows should also be well regulated to achieve a temporary hydroperiod mimicking the non-impacted conditions, also maintaining the natural salinity levels. This management approach would help to maintain high carbon retention rates and reduce methane emissions that cause losses in the mitigation capacity when the hydroperiod is abnormally enlarged.

Finally, in the specific case of the Laguna Grande de Villafranca, its Natural Resources Management Plan proposes management measures to promote recreational, tourist, cultural and educational activities, some of which require the maintenance of permanent flooding. These measures are not currently fully compatible with the original natural values of this protected natural area, considering that some of the natural ecological features of inland saline shallow lakes, and especially the high salt concentrations in water, are altered with such a hydrological regime including extensive freshwater inflows. For this reason, and as shown by our modelling results, when maintaining the external river water contributions to ensure recreational activities with flooding during summer, the lake loses part of the climate change mitigation potential characterized by other well-preserved saline shallow lakes. This is because summer months flooding increases the relevance of the radiative forcing of greenhouse gases emitted in summer within the annual balance, although the well-established helophyte coverage keeps safe most of the lake's carbon retention and climate change mitigation capacity. Anyhow, moderate reductions of the river water inflows would benefit in terms of carbon capturing and climate mitigation, especially in reducing CH_4 emissions, getting closer to its natural ecological structure and functioning, though recreational services would be reduced if flooding is not kept during summer, when the lake is used for bathing.

It would be interesting and relevant to explore the management of these ecosystems from a more comprehensive geographical perspective, as just three of the several dozens of lakes and wetlands included in ‘La Mancha Húmeda’ Biosphere Reserve, harboured in a large area with great diversity and abundance in inland saline shallow lakes. The Biosphere Reserve, as a whole, could help contribute to climate change mitigation through the proper management of the hydrological regimes of the lakes to mimic natural patterns, and especially with the maintenance and expansion of the lake marginal vegetation. The recovery and protection of their natural ecological features, both in water and vegetation, will also improve their ability to adapt and its resilience to climate change. A strategic management plan of the Biosphere Reserve may, however, allow for specific management measures in specific lakes that favour other ecosystem services such as cultural, recreational and tourist services, even artificially increasing the water supply to some temporary lakes, if this ensures the maintenance or even the increase of the global climate change mitigating capacity of the entire Biosphere Reserve.

Conclusions

The estimation of metabolic rates and their integration in a carbon balance modelling is an effective approach to evaluate the carbon capture and mitigating role of lentic ecosystems, where management scenarios can be projected to determine their effectiveness in the climate regulatory service. Given the role played by Mediterranean inland saline shallow lakes on climate regulation, effective management is essential to promote carbon capture and prevent greenhouse gases emission while maintaining their natural ecological values, which can otherwise be altered by inadequate management actions and by climate change effects. Measures focused on the hydrological regime were demonstrated to be relevant in regulating carbon and greenhouse gases exchange mechanisms. An effective measure to increase carbon sequestration and, especially, reduce the worse greenhouse gases emissions of saline shallow lakes, would be favouring their natural temporary regime preventing its flooding during summer, as this would reduce the emissions of greenhouse gases with higher radiative forcing capacity, such as methane. In addition, the quality and nature of water inflows also becomes crucial in regulating the carbon balance. Measures aimed at maintaining high levels of mineralization, and reducing organic and nutrient loads, can be effective in reducing CH_4 emissions in saline shallow lakes. Marginal vegetation plays an important role in the total carbon balance, and greatly determines the lake’s carbon capture and climate change mitigation capacity. The protection or increase of the helophytic cover, and specifically the growth of reeds associated with a longer hydroperiod and lower water mineralization, might be a key to significantly increase carbon sequestration. Therefore, marginal vegetation management and protection were shown to be highly important for the global warming mitigation.

In shallow saline lakes, a very valuable type of ecosystem from the conservation point of view, both hydrological and trophic alterations can cause contrasting effects on the capacity of these ecosystems to manage carbon and greenhouse gases (GHG) exchanges with the atmosphere, thus interplaying with climate change. For instance, for hydrological alterations, extra freshwater inputs would reduce water salinity and extend of the hydroperiod, thus causing an increase of methane emissions both by decreasing the competence of methanogens with sulphate-reducers and by extending the flooding period towards warmer period that favours exponential growth in methane production. But, on the other hand, the reduction in salinity would also favour helophytes growth, thus increasing carbon sequestration by these emerged plants. Both effects, increase of methane and of carbon sequestration by helophytes that are a consequence of the drop of salinity caused by increased artificial freshwater inputs, have counteracting effects with respect to the capacity of these saline shallow lakes to mitigate or enhance climate change.

This is an example, together with the additional modelled management scenarios, of the complexity of the interplay of the effects of each type of management action on these types of ecosystems. It also demonstrates that modelling can help to understand these interactions and, consequently, to select the most appropriate management actions to increase the climate change mitigation capacity of these valuable ecosystems. These management approaches, apart from enhancing the climate regulatory capacity, may protect the natural ecological features, and improve the resilience and adaptation to climate change of inland saline shallow temporary lakes.

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