Biodiversity impacts from salinity increase in a coastal wetland

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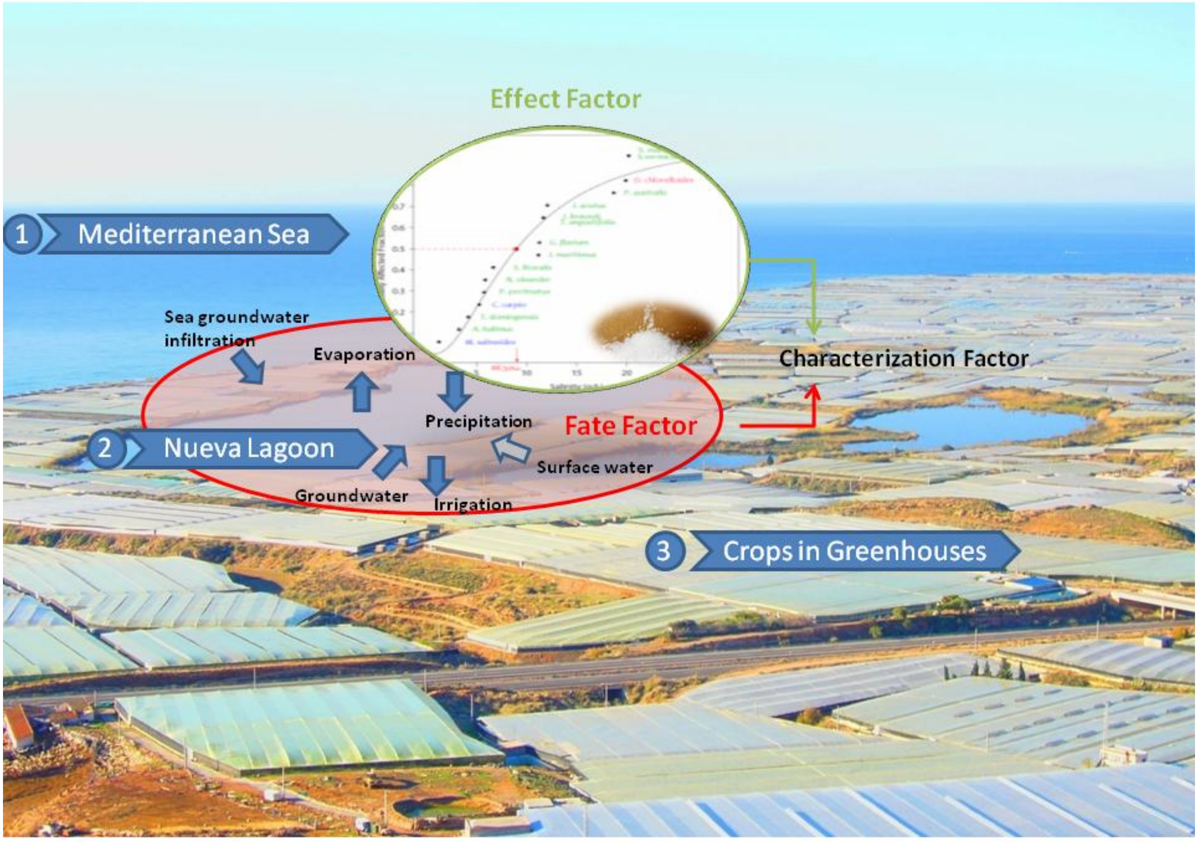
Abstract

A Life Cycle Impact Assessment (LCIA) method was developed to evaluate the environmental impacts associated with salinity on biodiversity in a Spanish coastal wetland. The developed characterization factor consists of a fate and an effect factor and equals $3.16 \times 10^{-1} \pm 1.84 \times 10^{-1}$ $PAF \cdot m^3 \cdot yr \cdot m^{-3}$(PAF: Potentially Affected Fraction of species) indicating a "potential loss of 0.32 m^3 ecosystem" for a water consumption rate of $1 m^3 yr^{-1}$. As a result of groundwater consumption with a rate of 1 m^3 per year means that the PAF in the lost cube meter ecosystem is equal to 0.05 which has been proposed as the maximum tolerable effect to keep the ecosystem intact. The fate factor was calculated from seasonal water balances of the wetland Albufera de Adra. The effect factor was obtained from the fitted curve of the potentially affected fraction of native wetland species due to salinity and can be applied to other wetlands with similar species composition. In order to test the applicability of the characterization factor, an assessment of water consumption of greenhouse crops in the area was conducted as a case study. Results converted into ecosystem quality damage using the ReCiPe method were compared to other categories. While tomatoes are responsible for up to 30 % of

the impact of increased salinity due to water consumption on ecosystem quality in the studied area, melons have the largest impact per tonne produced.

TOC Art.



Introduction

In 2006 the Food and Agricultural Organization of the United Nations (FAO) estimated the global water withdrawals to be 3,830 $km^3 \cdot yr^{-1}$, of which 70% was used for agriculture.[1] Additionally, water availability and use related to agricultural production are faced with important challenges such as growing population, climate change and changing dietary patterns. It is thus fundamental to assess impacts and changes in agriculture, in order to respond to challenges in the near future.

Wetlands are important and vulnerable ecosystems. More than 50% of all wetlands worldwide were destroyed during the twentieth century, more than 60% in Spain and Greece, and more than 70% in Italy[2], mostly due to agricultural drainage.[3] During the last decades, the use of greenhouses instead of traditional farming systems has often been accompanied by additional groundwater withdrawal for irrigation.[4] In coastal areas, over-pumping of aquifers leads to sea water intrusions, thus increasing the salinity in aquifers. At the same time, coastal wetlands, where fresh water and salt water are often mixed, are among the most productive, valuable, and yet most threatened ecosystems in the world.[5] Coastal wetlands in arid and semi-arid zones experience periods of increasing salinity as a consequence of high evaporative conditions, variability of inflows, their proximity to the sea but also due to impacts of human pressures,[6] such as overpumping of aquifers. Due to the inflow of salty water, coastal wetlands might experience an increase in salinity, which could potentially be detrimental for the wetland's specific ecological system.

With an increasing awareness of the value and importance of wetlands, fostered by the Ramsar Convention,[7] numerous coastal wetlands have been designated as wetlands of international importance. Still, environmental impacts due to agricultural practices and dependencies upon wetlands are becoming increasingly significant.[8] Hence, balancing wetland conservation and wise water use, as well as assessing the prevalent impacts is important for the preservation of the remaining wetlands.

Life Cycle Assessment (LCA) is a method for evaluating the total environmental impact throughout the life cycle of a product or process.[9] The ISO 14044 standard defines Life Cycle Impact Assessment (LCIA) as the phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system with the purpose of interpreting the life cycle emissions and resource consumption inventory in terms of indicators for the three Areas of Protection (resources, human health, ecosystem quality).[10]Several methods have been developed for assessing damages from water use on ecosystems, such as the decrease of terrestrial biodiversity due to freshwater consumption,[11] the disappearance of terrestrial plant species due to a change in extraction of groundwater,[12] and the effects on freshwater fish species from water consumption in rivers.[13] We understand water consumption in this case study as general water consumption in the wetland (evapotranspiration, product integration, and discharge into the sea or into areas outside the wetland). Recently, a case study dealing with the effects of changes in water temperature and salinity on freshwater molluscs in the river Rhine has been published.[14] For wetlands in particular, a case study in the coastal arid area of Peru concerning the local plant biodiversity impacts of agricultural water use has been published.[15] However, so far no LCIA methodology has taken into account salinity impacts in coastal wetlands.

In order to develop a methodology for salinity impacts, we selected a coastal wetland in Spain called "Albufera de Adra" as an exploratory case study in order to learn (since water-related impacts are quite complex) how to include the impacts from salinity increases due to water consumption. It is located in a semi-arid region in Almería (South-East of Spain), where agricultural activities require substantial irrigation and areas with native vegetation and fauna are restricted to small patches and wetlands.[16] The aims of this study were (a) to develop a characterization factor (CF) in terms of potentially affected fraction of species (PAF)[17] for salinity impacts based on a new effect factor and a locally specific new fate factor, and (b) to apply it to a local case study and compare the impact of salinity with commonly used ecosystem quality impact categories.

Materials and Methods

Description of the wetland Albufera de Adra

The case study area is located in a semi-arid and mountainous area of South-Eastern Spain, in the province of Almería (N36º 45' 16'' / W 2º 57' 0''). Albufera de Adra contains two lagoons which together occupy 36.4 ha. Nueva lagoon is situated closer to the sea than Honda lagoon. The wetland is located at the south-eastern edge of the Adra River Delta [18] area close to the Mediterranean sea (Figure 1). Only Honda lagoon is recharged with surface water (ephemeral streams) while Nueva lagoon is predominantly fed by groundwater.[4] From 2003 to 2010, modifications in the surrounding agricultural practices led to differences in the hydrological dynamics in both lagoons.[4, 19] Specifically, an extension of irrigated areas and more efficient irrigation techniques have resulted in a reduced natural and irrigation return-flow to the aquifer. Consequently, the electrical conductivity (as proxy for salinity)[20] in Nueva lagoon has increased from 6 to 13 $mS \cdot cm^{-1}$ due to an increase in sea water intrusion[4], while in the Honda Lagoon the conductivity has decreased from 6 to 1$mS \cdot cm^{-1}$ due to an increase in surface water return flow.

Albufera de Adra is protected as a nature reserve by the Andalusian Autonomous Government and additionally classified as a wetland of international importance under the Ramsar convention. It harbors a large variety of fauna and flora like plants, fishes and algae and is especially important for waterfowl and autochthonous ichthyofauna.[4] In this study we focused on plants, fishes, algae and a crustacean.

Figure 1: Albufera de Adra (Spain) composed by the larger, coastal Nueva Lagoon and inland Honda Lagoon enclosed in the blue circle. The red line delimits the agricultural area of the study which consists of 899.2 ha[21] of greenhouses area (white areas). The main economic activity in that area is protected horticulture.[22-24](*Source Google Earth*[25]).

Developing the Characterization Factor

As commonly done in LCIA, Characterization Factors (CF, Equation 1) are calculated as the product of a Fate Factor (FF, Equation 2) and an Effect Factor (EF, Equation 9). The FF models the salinity increase in the wetland due to increased water consumption rate (in $g \cdot l^{-1} \cdot m^3 \cdot yr \cdot m^{-3}$) and the EF relates an ecological damage to the increased salinity measured as Potentially Affected Fraction (PAF) of species (in $PAF \cdot l \cdot g^{-1}$). The units from the characterization factor are based on g/l which comes from salinity, m^3 in numerator comes from the units of Nueva volume, the period time is for one year (9 wet months, 3 dry months) and the m^3 in denominator comes from ET_{crop}. The CF for the salinity impact in this coastal wetland is therefore defined as the change in PAF of species due to a change in groundwater consumption, which is affecting the salinity content via altered amounts of groundwater and seawater infiltration into the wetland. This can be translated into the effect per m^3 of water consumed.

$$CF = FF \cdot EF \; [\mathrm{m^3 \cdot PAF \cdot yr \cdot m^{-3}}]$$ **Equation 1**

The uncertainties from FF and EF were propagated with Monte Carlo simulation to quantify the 95% confidence interval of the characterization factor. The assessment was performed with the probabilistic risk assessment simulation software @risk, version 5.0.[26] Normal distributions were applied for the FF and EF. The sampling method applied was Latin Hypercube and the number of iterations was 10,000.

Fate Factor. The FF was developed for the Nueva Lagoon since it is closer to the sea and thus affected by sea water intrusions. Moreover, recharge to the wetland from the Adra River Delta aquifer is predominant in the Nueva lagoon, while Honda is mainly fed by surface water.[4] The FF was based on a salt and a water balance, and we split each up into wet (X) and dry (Y) months, since there is a natural seasonal cycle of salinity. According to Rodriguez et al.[4] there are 3 dry months (June, July, August) with almost no precipitation and 9 wet months. Due to the precipitation in the wet months, the salinity in the wetland decreases, since freshwater leads to a dilution and an exfiltration of saline water. Salinity increases during the dry period, when evaporation and saline water infiltration increase the salt concentration. Monthly water and salt balances were calculated for 1983, 2003 and 2008, respectively. For the FF calculation (Equation 2) the monthly results were aggregated to yearly values.

$$FF = \frac{\Delta FGW}{\Delta \mathrm{ETcrop}} \frac{\Delta C_N . V_N}{\Delta FGW} \; [\mathrm{g \cdot l^{-1} \cdot m^3 \cdot yr \cdot m^{-3}}]$$ **Equation 2**

The first ratio defines the net salinity change due to change in freshwater inflow ($\Delta C_N \cdot V_N/\Delta FGW$) while the second part is related to the change in fresh groundwater infiltration due to changes in crop water consumption ($\Delta FGW/\Delta ET_{crop}$). FGW ($m^3 \cdot yr^{-1}$) is the total fresh groundwater inflow to Nueva Lagoon in the dry and wet seasons (FGW_x+FGW_y). C symbolizes the salinity, V the volume of the Nueva lagoon and ET_{crop} is crop evapotranspiration. Δ symbolizes the change between years. We consider water consumption as crop evapotranspiration. There is not runoff because we are considering greenhouse crops and we estimated leaching fraction lost in sea water trough groundwater flows.

Irrigation on the fields of Almería province and close to Albufera de Adra uses 80% groundwater[27] and 20% surface water. For more details and explanations of the other constant parameters see Table 1.

Equation 2 is calculated for three time spans, 1983-2003, 2003-2008 and 1983-2008. We focused on these years because between 2003 and 2008 the salinity constantly increased from 4.5 to 7.5 g/l[4], and changes in irrigation techniques occurred, along with a trend of greenhouse extension out of the delta valley. We took 1983 as a year with a situation as natural as possible in order to compare to 2003 and 2008 since from 1975 until 1983 the salinity remained constant in Albufera de Adra.[28]

Table 1: Constant parameters in Nueva Lagoon for the years 1983, 2003 and 2008. Climatic parameters were provided by Adra weather station[29] and water bodies, salinities and morphometric characteristics by existing literature.[4]

Parameter	Definition	Unit	Value 1983	Value 2003	Value 2008	Comments
X	Wet months in a year[4]	month	9	9	9	Number of wet months: January, February, March, April, May, September, October, November and December
Y	Dry months in a year[4]	month	3	3	3	Number of dry months: June, July and August.
$\Delta C_{N,Y}$	Change in salinity from Nueva in dry months	g/l	0.6	0.6	0.6	Increase in salinity due to evapotranspiration and almost no precipitation assuming steady state in the individual years. This value was taken as assumption.
$\Delta C_{N,X}$	Change in salinity from Nueva in wet months	g/l	-0.6	-0.6	-0.6	Decrease in salinity due to higher precipitation levels and lower evapotranspiration during the wet months[4]. It is assumed that the salt balance must be zero in order to get the natural behavior of a stable situation over the year, so we assume that $\Delta C_{N2} = -\Delta C_{N1}$ as a simplifying assumption in steady state although is an evidence that salinity is increasing over the years.
V_N	Volume of Nueva taking area and depth from literature[4]	m^3	316,667	316,667	316,667	Assuming the volume as a cone with a maximum depth of 3.8 m and area of 25 ha took from literature. The water level did not change much between 2006 and 2008 according to the Rodriguez et al.[4]
C_{GW}	Salinity of the fresh groundwater[16]	g/l	1.6	1.6	1.6	Considering the salinity of the groundwater in the Adra River Delta Aquifer from the literature.
C_{Sea}	Salinity in the Mediterranean Sea	g/l	37.6	37.6	37.6	Assuming an average of the Mediterranean Sea from literature.
C_N	Salinity in Nuevalagoon	g/l	2.6	4.50	7.50	Salinity averages from 2003 and 2008 according to Rodriguez et al.[4] using as conversion 1mS=0.64 $g \cdot l^{-1}$
ET_Y	Nueva evapotranspiration in	m^3/month	59,325	39,432	41,098	Average evapotranspiration from dry months between 2003 to 2008. The values

	dry months from IFAPA weather station[29]					were taken from literature per area of 25 ha.
ET_X	Nueva evapotranspiration in wet months from IFAPA weather station[29]	m^3/month	24,331	21,337	23,737	Average evapotranspiration from wet months between 2003 to 2008. The values were taken from literature per area of 25 ha.
P_Y	Precipitation in 3 drymonths[29]	m^3/month	1,308	183.3	33.3	Average precipitation from dry months between 2003 to 2008 considering 25 ha of surface. The values were taken from literature.
P_X	Precipitation in 9wetmonths[29]	m^3/month	5,419	8,933	9,911	Average precipitation from wet months between 2003 to 2008 considering 25 ha of surface. The values were taken from literature.
ET_N	Evapotranspirationfrom Nueva[29]	m^3/month	33,079	25,860	28,076	Evapotranspiration's average from 2003 to 2008 taking into account the 25 ha surface of the lagoon.
P_N	Precipitation in Nueva[29]	m^3/month	4,392	6,745	7,442	Precipitation's average from 2003 to 2008 taking into account the 25 ha of surface of the lagoon.
ET_{crop}	Crop Evapotranspiration[30]	m^3/month	146,368	306,849	320,984	Taking into account the harvested areas for 2003 and 2008 from literature[23]
SW_Y	Surface water inflows in dry	m^3/month	0	0	0	In all equations SW_Y is the surface water inflows in dry months but we neglected it since it is irrelevant for the Nueva Lagoon
SW_X	Surface water inflows in wet	m^3/month	0	0	0	In all equations SW_X is the surface water inflows in wet months but we neglected it since it is irrelevant for the Nueva Lagoon

In order to obtain the unknown variables, FGW_Y, FGW_X, $SGW_Y$and SGW_X, we developed several equations for salt and water balances considering wet (X) and dry (Y) seasons. Equation 3 shows the salt balance for dry months, taking into account fresh groundwater inflows (FGW), subterranean sea water intrusions (SGW, henceforward called sea groundwater inflows) and groundwater outflow (GW_o) from Nueva Lagoon to the neighboring aquifer. Equation 4 shows the salt balance for wet months with inflows from fresh groundwater and sea groundwater, as well as groundwater outflow. Equation 5 is the yearly salt balance, incorporating both dry (Y) and wet (X) months and reflects the steady-state assumption, that the yearly balance is equal to zero. Equations 6, 7 and 8 are the water balances for dry (Y) and wet (X) months, respectively, as well as the yearly balance. The difference between evapotranspiration (ET) and precipitation (P) in dry months is greater than or equal to the sum of the respective inflows, which consists of fresh and sea groundwater inflows. Concerning the wet months, Equation 7 shows the difference between evapotranspiration and precipitation being lower than or equal to the sum of inflows and the groundwater outflow. To solve the system of equations we assume the algebraic sign in Equation 6 and Equation 7 to be equality instead of inequality. The yearly water balance (Equation 8) is zero due to the steady-state assumption.

Salt Balances

$$\frac{\Delta C_{N1} \cdot V_N}{Y} = SW_Y \cdot C_{SW} + FGW_Y \cdot C_{GW} + SGW_Y \cdot C_{Sea} - GW_{o,y} \cdot C_N \qquad \textbf{Equation 3}$$

$$\frac{\Delta C_{N2} \cdot V_N}{X} = SW_X \cdot C_{SW} + FGW_X \cdot C_{GW} + SGW_X \cdot C_{Sea} - GW_{o,x} \cdot C_N \qquad \textbf{Equation 4}$$

$$0 = Y \cdot SW_Y \cdot C_{SW} + X \cdot SW_X \cdot C_{SW} + Y \cdot FGW_Y \cdot C_{GW} + X \cdot FGW_X . C_{GW} + Y \cdot SGW_Y \cdot C_{Sea} + X \cdot SGW_X \cdot C_{Sea} - X \cdot GW_{o,x} \cdot C_N - Y \cdot GW_{o,y} \cdot C_N \qquad \textbf{Equation 5}$$

Water Balances

$$ET_Y - P_Y \geq SW_Y + FGW_Y + SGW_Y - GW_{o,y} \qquad \textbf{Equation 6}$$

$$ET_X - P_X \leq SW_X + FGW_X + SGW_X - GW_{o,x} \qquad \textbf{Equation 7}$$

$$0 = -ET_N \cdot 12 + P_N \cdot 12 + Y \cdot SW_Y + X \cdot SW_X + Y \cdot FGW_Y + X \cdot FGW_X + Y \cdot SGW_Y + X \cdot SGW_X - X \cdot GW_{o,x} - Y \cdot GW_{o,y} \qquad \textbf{Equation 8}$$

SGW_Y ($m^3 \cdot month^{-1}$) and SGW_X ($m^3 \cdot month^{-1}$) are the sea groundwater inflow into Nueva Lagoon in dry and wet months, respectively and $GW_{o,y}$ ($m^3 \cdot month^{-1}$) and $GW_{o,x}$ ($m^3 \cdot month^{-1}$) are the groundwater outflow from Nueva Lagoon in the dry and wet months, respectively. The values of the unknown variables of Equations 3 to 8 were obtained with the help of the solver GAMS©[31] using non-linear programming through the BARON [31] optimizer and the equation system was solved by minimizing the balance error. We established Equation 5 as the objective function which is to be minimized (to get close to zero) in that solver.

A sensitivity analysis was carried out by changing different constant parameters, such as salinities ($C_{N,1983}$, $C_{N,2003}$, $C_{N,2008}$,), the number of wet (X) and dry (Y) months and the amount of precipitation and evapotranspiration. Several assumptions were made in this section (see Supporting Information, sectionS2.1.).The confidence intervals for the FF were calculated by taking into account the maximum and minimum FF from the sensitivity analyses and assuming a normal distribution.

Effect Factor. Data describing the effect of salinity for various endpoints (e.g. survival, growth inhibition) on 18 species (plants, fish, algae and a crustacean) native to the "Albufera de Adra" wetland were collected from literature[32-48] and are shown in the Supporting Information (Table S1). This work focused on the indigenous species and the associated damages only. As is common in LCA, only negative impacts are considered and that potential benefits and changes in species composition are not included.

The use of EC50s from bioassays with different endpoints is the norm in the calculation of effect factors in LCA. A prime example for such practice can be found in USEtox, the LCIA toxicity model recommended by UNEP-SETAC: one of the two ecotoxicity effect factor databases used in this model[49], explicitly states that the EC50s, employed in the construction of SSDs and subsequently the derivation of EFs, can come from numerous different endpoints. Indeed it would be much more consistent to could construct SSDs based on EC50s describing the exact same effect (e.g. death or growth) of a stressor on an organism. However, in light of the absence of identical endpoints measured in bioassays, in LCIA the aggregation of many different endpoints is preferred over the use of much fewer data in the calculation of the EF.

The 50% effective concentration (EC50) due to salinity is the concentration where a 50% reduction in a given endpoint (e.g. growth) is observed compared to the control. EC50s were either calculated by fitting the log-logistic function to the salinity concentration-response plots (see figure S1), or were taken directly from literature.

Species Sensitivity Distribution (SSD) is an ecotoxicological tool that has been employed to calculate effect factors for different impacts (e.g. ecotoxicity, thermal pollution, eutrophication) in life cycle impact assessment. Several studies have been published in literature using SSD to obtain an EF, such as Meent et al.[50], who proposed a multisubstance potentially affected fraction (msPAF)-based method for calculating ecotoxicological effect factors for LCA,Verones et al.[51], who used SSD to calculate an EF for thermal pollution in freshwater aquatic environments and Struijs et al.[52], who constructed a field sensitivity distribution of macroinvertebrates in inland waters to derive an EF for eutrophication due to phosphorus.

The SSD for salinity was constructed by fitting the log-normal cumulative distribution function to the EC50s for native species (see Table S1). Equation 9 describes the effect factor (EF_{Sal}), which is the average change in the potentially affected fraction of freshwater aquatic species (ΔPAF_{Sal}) due to the change in salinity (ΔSal). The effect factor is calculated as the average gradient at the 50% hazardous concentration ($HC50_{Sal}$), defined as the concentration at which 50% or more of the species included in the SSD are exposed to concentrations above their EC50[53].

$$EF_{Sal} = \frac{\Delta PAF_{Sal}}{\Delta Sal} = \frac{0.5}{HC50_{Sal}} \ [\mathrm{PAF} \cdot \mathrm{l} \cdot \mathrm{g}^{-1}] \qquad \textbf{Equation 9}$$

A 95% confidence interval for the hazardous concentration was estimated by parametric bootstrapping and this uncertainty was propagated to the Effect Factor by taking Equation 9 into account.

Calculation of impact scores. The required amount of consumptive irrigation water (CW, m^3),resulting from the inventory of input/output data, is expressed by a functional unit (quantified performance of a product system for use as a reference unit).[10]In our case, the functional unit is a tonne of tomato, pepper, cucumber, zucchini, watermelon, melon, aubergine or green bean harvested in greenhouses close to Albufera de Adra.[24] The impact score (IS, $m^3 \cdot PAF \cdot yr$) is the product of the CF (Equation 1) and the CW. IS shows the impact of increasing salinity on aquatic species in the Nueva lagoon caused by the use of groundwater for agriculture.

Water consumption was calculated as the average evapotranspiration for the different cultivation periods for each crop following the irrigation crop management practices recommended by the experimental station of Cajamar research institute[30] to improve the efficiency of agriculture production close to the wetland.

We considered the area of greenhouses from the municipality of Adra[21] for the 8 main crops from 26 different vegetables that are produced in Almería. Amounts of production from the province of Almería[23] in 2008 were downscaled to the area around Albufera de Adra.

In order to compare the impact due to water consumption to that of other categories, results were converted to species per year following the recommendations of the ReCiPe method (species density for freshwater, 7.89×10^{-10} species·m^{-3}).[54]

Results and discussion

Fate Factor. There was fresh groundwater inflow (FGW_Y and FGW_X) from the Adra River Delta (ARD) aquifer in wet and dry seasons in all three years. Sea groundwater inflow occurs in dry months only, while groundwater outflow occurs in wet seasons only. This shows that there is less recharge to the wetland from the aquifer in wet months. We further simplified the groundwater system presented by Rodriguez et al.[4] by neglecting the blurred transition zone between low and high salinity parts of the aquifer, which is not a subsystem in our model. Since only salinities of the fresh groundwater and the sea water are known we assumed sharply separated sections of fresh and saline groundwater. Also, the location of the brackish-freshwater transition zone in the aquifer fluctuates during the seasons, which we did not take into account (Table 2).

Table 2: Unknown variables in Nueva Lagoon for the years 1983, 2003 and 2008. The values of the variables are obtained by solving the equation system of Equation 3 to Equation 8 with GAMS.[31]

Parameter	Definition	Unit	Value 1983	Value 2003	Value 2008	Comments
FGW_Y	Fresh groundwater inflow to Nueva Lagoon in dry months	m^3/month	$3.96x10^{+4}$	$3.92\ x10^{+4}$	$3.96\ x10^{+4}$	Calculated from Equation 3 to Equation 8
FGW_X	Fresh groundwater inflow to Nueva Lagoon in wet months	m^3/month	$8.63\ x10^{+4}$	$2.65\ x10^{+4}$	$2.18\ x10^{+4}$	Calculated from Equation 3 to Equation 8
SGW_Y	Sea groundwater infiltration into Nueva Lagoon in dry months	m^3/month	0	$1.49\ x10^{+1}$	0	Calculated from Equation 3 to Equation 8
SGW_X	Sea groundwater infiltration into Nueva Lagoon in wet months	m^3/month	0	0	0	Calculated from Equation 3 to Equation 8
$GW_{o,y}$	Groundwater outflow from Nueva Lagoon in the dry months	m^3/month	0	0	0	Calculated from Equation 3 to Equation 8

$GW_{o,x}$	Groundwater outflow from Nueva Lagoon in the wet months	m^3/month	6.12 x10^{+4}	1.41 x10^{+4}	7.46 x10^{+3}	Calculated from Equation 3 to Equation 8

In dry periods, groundwater from ARD aquifer enters the lagoon. For the years 2003 and 2008 the rate throughout the months of June to August was similar.[4] During wet periods the wetland and aquifer produce additionally a groundwater outflow to the sea, as has been found previously by Alcalá et al.[55] Still, the presence of the wetland at the south-eastern edge of the ARD aquifer reduced potential groundwater discharge to the sea because of the high evapotranspiration rates in the surface area of this wetland.[56]

Comparing the three years (1983, 2003, 2008), the ratio between outflow and inflow from and to the wetland is constantly reduced. In 1983, the outflow was 82% of the inflow, in 2003 it was 48% while in 2008 it was only 28%. We suggest as principal FF the one between 2003 and 2008 due to the best quality of the data and the stabilization of crop extension.

Results for the sensitivity analysis are shown in the SI Table S2. The maximum value of the FF occurs between 2008 and 2003 when the wetland salinity is increased by 20%and the other parameters are kept constant, which gives a $FF_{2008\text{-}2003}$ of 6.72 $g\cdot l^{-1}\cdot m^{3}\cdot yr\cdot m^{-3}$. On the other hand, the minimum value of the FF results by decreasing the salinity by 20% for the period between 2003-1983 with a FF of $2.50\times10^{-1} g\cdot l^{-1}\cdot m^{3}\cdot yr\cdot m^{-3}$. These two extreme scenarios were taken as minimum and maximum for the uncertainty assessment and for establishing the distribution function.

Effect Factor

Figure 2 shows the species sensitivity distribution (SSD) for salinity, for native species identified in the Nueva lagoon. The log-normal cumulative distribution function was fitted to ordered EC50 values, and the $HC50_{Sal}$ was found to be equal to 8.87 $g\cdot l^{-1}$ from the fitted curve. The 95% confidence interval for the $HC50_{Sal}$ was calculated as 6.29 – 12.5 $g\cdot l^{-1}$. The EF was then found to be 5.64×10^{-2} $PAF\cdot l\cdot g^{-1}$ with a standard error of $\pm0.76\times10^{-2}$ $PAF\cdot l\cdot g^{-1}$, calculated via propagating the error from the HC50 to the EF.

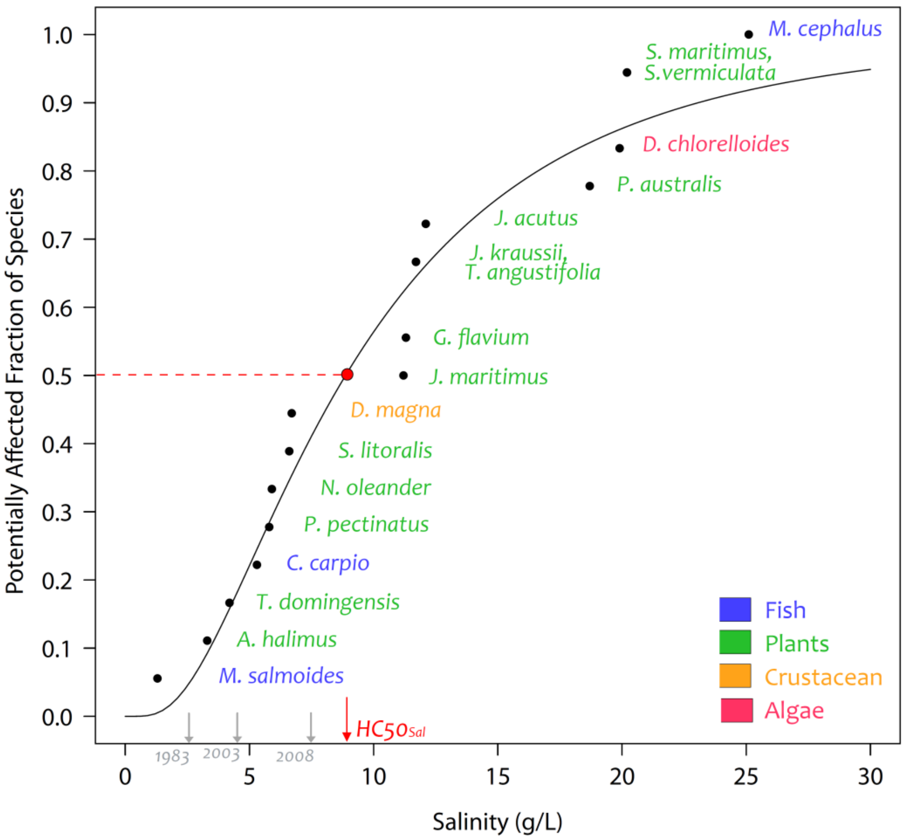


Figure 2:Species Sensitivity Distribution (SSD) for salinity for 18 species native to Nueva Lagoon. The grey arrows indicate the salinity in 1983 (2.6g·l^{-1}), 2003 (4.5 g·l^{-1}) and 2008 (6.5 g·l^{-1}).

Salinity in the Nueva Lagoon increased from 4.5 g·l^{-1} in 2003 to 7.5 g·l^{-1} in 2008 (Table 1), which, according to Figure 2, corresponds to an increase of approximately 20% of species potentially affected in this period. The absolute number of species estimated to be found in the wetland is 30[57],taking into account plants, fish, algae and crustaceans. The increase in salinity and eutrophication over the past years has already resulted in the disappearance of a specie in Albufera de Adra, namely *Scirpus lacustri*, which was cited by Losa and Rivas Godo in 1968[58] and Sagredo in 1987[59] but is no longer found in the lagoon today. From Figure 2 we observe that two fish species, *M. salmoides* (EC50 = 1.3 g·l^{-1}) and *C. carpio* (EC50 = 5.3 g·l^{-1}), are particularly sensitive to salt stress, and another fish species, *M. cephalus*(EC50 = 25.1 g·l^{-1}), is the least sensitive of all the native species included in this study. The EC50 of the algae included in the SSD, *D. chlorelloides* is 19.9 g·l^{-1} and is above $HC50_{sal}$ but the crustacean, *D.magna* is located below $HC50_{sal}$ with an EC50of 6.6 g·l^{-1}. Plants, the most abundant taxonomic group are distributed throughout the SSD, with 5 species lying below $HC50_{sal}$ and 8 species lying above it.

Data availability permitted the consideration of 18 species from Nueva Lagoon (13 plants, 3 fish, 1 algae and 1 crustacean) in this work. So, given a total of 30 species reported to be found in the wetland[57], with these 18 species we cover 60% of the species in the wetland. The calculated EF could, with some caution, be applied to other wetlands, assuming their native species composition is not entirely dissimilar to the one encountered in Nueva Lagoon.

For instance, Punta Entinas is an endorheic wetland, located in the arid southeast of Spain very close to Albufera de Adra surrounded by Mediterranean ecosystems. Both wetlands, Nueva Lagoon and Punta Entinas (focus on salt marsh and marshland) have species in common, for instance *A. halimus, S. vermiculata,S. maritimus, J. maritimus, J. acutus, P. australis, N. oleander, P. pectinatus* and *D. chlorelloides*[57]*)*, amounting to 50% of the species included in the EF for Albufera de Adra. Therefore, we might consider the EF to be applicable for the marshland of Punta Entinas.

Characterization Factor

According to Equation 1 the CF for Nueva Lagoon is 3.16×10^{-1} with a standard error of $\pm 1.84 \times 10^{-1}$ $PAF \cdot m^3 \cdot yr \cdot m^{-3}$, and a 95% confidence interval of 8.30×10^{-2}–7.83×10^{-1} $PAF \cdot m^3 \cdot yr \cdot m^{-3}$.

Impact Score

The impact score is calculated as a product of the characterization factor (CF) developed for Nueva Lagoon ($3.16 \times 10^{-1} PAF \cdot m^3 \cdot yr \cdot m^{-3}$) and the crop evapotranspiration (ET_{crop}) (Equation 10). Crop evapotranspiration was obtained from "Las Palmerillas" experimental station close to Albufera the Adra (constructed to improve the efficiency in agricultural production)[30]and was converted to $m^3 \cdot yr^{-1}$ taking into account the cultivation area from the study[21] close to Adra. Table 3 shows the Impact Score ($m^3 \cdot PAF \cdot yr$) for each crop per unit of area and per tonne of production ($m^3 \cdot PAF \cdot tonne^{-1} \cdot yr$) considering the local productions in that area.[23]

$$IS = CF \cdot ET_{crop} \qquad \textbf{Equation 10}$$

Table 3: Characteristics and impact scores for the 8 main crops in the area of study: greenhouse area (GH_{Area}), crop evapotranspiration (ET_{crop}), impact score per area ($IS_{1,per}$area)and its assigned percentage ($IS_{1,\%}$), crop's yield (Y_c) and Impact Score per tonne ($IS_{2,tonne}$) .

Crops	GH_{Area}	ET_{crop}	$IS_{1, per\ area}$	$IS_{1,\%}$	Y_c	$IS_{2,tonne}$
	Ha	$m^3 \cdot ha^{-1}$	$m^3 \cdot PAF \cdot yr$	%	$tonne \cdot ha^{-1}$	$m^3 \cdot PAF \cdot tonne^{-1} \cdot yr$
Tomato	216.1	$3.47x10^{+03}$	$7.49x10^{+04}$	29.6	100.6	$3.44\ x10^{+00}$
Pepper	180.5	$3.78x10^{+03}$	$6.81x10^{+04}$	26.9	61.7	$6.12\ x10^{+00}$
Cucumber	95.1	$1.61x10^{+03}$	$1.53x10^{+04}$	6.0	87.0	$1.85\ x10^{+00}$
Zucchini	97.9	$2.81x10^{+03}$	$2.75x10^{+04}$	10.9	54.5	$5.15\ x10^{+00}$
Watermelon	101.1	$1.79x10^{+03}$	$1.81x10^{+04}$	7.1	69.6	$2.57\ x10^{+00}$
Melon	115.0	$2.98x10^{+03}$	$3.42x10^{+04}$	13.5	36.0	$8.27\ x10^{+00}$
Aubergine	33.7	$2.84x10^{+03}$	$9.57x10^{+03}$	3.8	72.6	$3.91\ x10^{+00}$
Green bean	59.7	$8.69x10^{+02}$	$5.19x10^{+03}$	2.1	15.3	$5.68\ x10^{+00}$

For the cultivated area considered, tomato is the crop that shows the highest impact score, with approximately 30% of the overall impact, because tomato is the most produced crop in the province, whereas green bean shows the smallest impact with around 2% due to a relatively small cultivated area. However, when we consider the total impact score per tonne of production, we obtain different results due to different crop yields. The low yield of melon leads to the highest impact per tonne, while cucumber with a higher yield leads to the lowest impact score per tonne for the crops studied.[22]

Application in LCA studies. This work derived the first CF for salinity impacts in a coastal wetland defined as the change in the Potentially Affected Fraction (PAF) of species due to a change in salinity related to the extraction of groundwater for crop irrigation. This case study takes the expectation away that this is a fully applicable approach for the whole world and it proved to be very relevant indeed. The impacts on wetland biodiversity due to the irrigation of the existing crops close to the study area, were calculated using the proposed CF.

A comparison between the salinity impacts of the main crops tomato, cucumber, zucchini, melon and aubergine with other impact categories was carried out in order to investigate the relative importance of salinity impacts. For this comparison we used the endpoints of several categories within the area of protection "ecosystem quality" of the ReCiPe methodology[54]. Experimental data for these crops were adapted from Stoessel et al.[60] taking into account a local yield (Table 3) in Adra greenhouses. The crop-specific impact scores presented in Table 3 (PAF·m^3·yr·tonne^{-1}) were converted into species·yr·kg^{-1}considering the recommended freshwater species density [54] (7.89×10^{-10} species·m^{-3}) and the conversion[54] dPDF/dPAF = 1 (Table 4).

Table 4. Endpoint Impacts (*species·yr·kg^{-1}*) according to the ReCiPe methodology and the contribution of each category to the total ecosystem quality impact. No data was available for green beans and watermelon, and thus these crops are neglected in this comparison.

Category impact	Tomato		Cucumber		Zucchini		Melon		Aubergine	
Unit	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%
Salinity impact due to water use	2.72 x10-12	0.31	1.46 x10-12	0.18	4.06 x10-12	0.08	6.53 x10-12	0.35	3.09E-12	0.02
Climate change	6.16 x10-10	69.6	5.85 x10-10	73.1	1.96 x10-9	37.4	7.07 x10-10	38.2	3.67 x10-9	70.4
Terrestrial acidification	2.32 x10-12	0.26	2.12 x10-12	0.26	9.88 x10-12	0.19	3.38 x10-12	0.18	1.43 x10-11	0.28
Freshwater eutrophication	3.85 x10-13	0.04	3.46 x10-13	0.04	5.63 x10-13	0.01	3.82 x10-13	0.02	2.56 x10-12	0.05
Terrestrial ecotoxicity	2.40 x10-11	2.70	2.10 x10-12	0.26	4.73 x10-12	0.09	3.08 x10-12	0.17	7.38 x10-11	1.42
Freshwater ecotoxicity	2.59 x10-14	0.00	1.10 x10-14	0.00	1.39 x10-13	0.00	7.65 x10-14	0.00	1.14 x10-13	0.00
Marine ecotoxicity	1.21 x10-16	0.00	4.86 x10-17	0.00	1.86 x10-16	0.00	8.28 x10-17	0.00	5.33 x10-16	0.00
Agricultural land occupation	2.15 x10-10	24.3	1.82 x10-10	22.7	3.12 x10-09	59.5	1.08 x10-9	58.4	1.25 x10-9	24.1
Urban land occupation	8.11 x10-12	0.91	1.29 x10-11	1.61	4.48 x10-11	0.86	2.18E x10-11	1.18	7.62 x10-11	1.46
Natural land transformation	1.68 x10-11	1.90	1.52 x10-11	1.89	9.87 x10-11	1.88	2.72 x10-11	1.47	1.20 x10-10	2.30
Total	8.84 x10^{-10}	100	7.99 x10^{-10}	100	5.24 x10^{-9}	100	1.84 x10^{-9}	100	5.21 x10^{-9}	100

The results for all crops show that, if the generic freshwater species density from ReCiPe is used (Table 4), the impact of salinity (due to water use) for the total damage to ecosystems is in the range of terrestial acidification for tomato (2.72x10^{-12} species·yr·kg^{-1}), cucumber (1.46x10^{-12} species·yr·kg^{-1}) and melon (6.53x10^{-12} species·yr·kg^{-1}), in the range of terrestial ecotoxicity for zucchini (4.06x10^{-12} species·yr·kg^{-1}) and in the range of freshwater eutrophication aubergine (3.09x10^{-12} species·yr·kg^{-1}). The relative contribution to the total impact score is dominated by climate change for all the crops with approximately 70% in tomato, cucumber and aubergine and around 40% in zucchini and melon. The climate change ecosystems impact category considers fertilizing (ammonium nitrate, single superphosphate and potassium sulphate) and electricity consumption for the irrigation system, which is the highest contributing impact when capital goods are not considered.

Note that if a specific freshwater species density (9.47 x10^{-5} species·m^{-3}) from the wetland had been used instead of generic freshwater species density from ReCiPe, the salinity impact for the total damage to ecosystems would represent in all studied crops the major contribution (98-99%) between all categories impact (tomato 3.26x10^{-07} species.yr·kg^{-1}, cucumber 1.75x10^{-07} species.yr·kg^{-1}, zucchini 4.87x10^{-07} species.yr·kg^{-1}, melon 7.84x10^{-07} species.yr·kg^{-1} and aubergine 3.71x10^{-07} species.yr·kg^{-1}). Hence, the difference between them shows that taking a global average value can be misleading since local species richness can be very different.

Outlook. Future efforts should be undertaken in order to further methodological development and make global characterization factors available. It is a broader approach (exploratory case study) with a more global perspective shall be developed. This will close an important gap in the LCIA methodology regarding the relevant impacts on coastal wetlands.

In this work we used the freshwater species density from the ReCiPe model, acknowledging that freshwater species density can greatly vary depending on local conditions (e.g. the freshwater species density in Albufera de Adra is 9.47×10^{-5} species·m^{-3}). Hence, further improvements in LCIA endpoint methodologies could be considered given that species density for freshwater was shown to be higher than terrestrial species density[61], in contrast to estimates proposed by ReCiPe.

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Supporting information. Details on the fate and effect factor and further results are available free of charge via the Internet at http://pubs.acs.org.

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