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MODELLING SEA LEVEL RISE IMPACTS AND THE MANAGEMENT OPTIONS FOR RICE PRODUCTION: THE EBRO DELTA AS AN EXAMPLE

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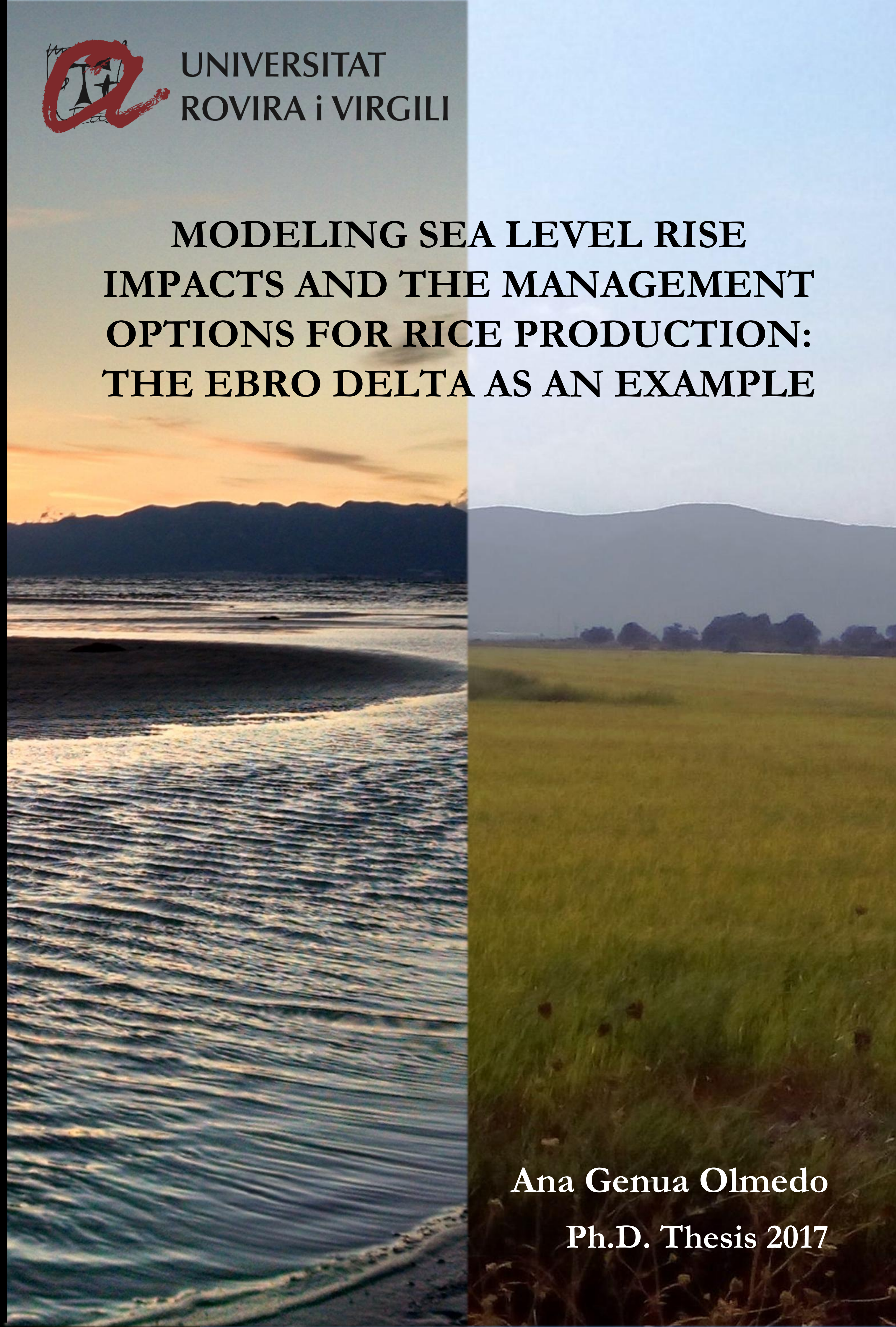

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Doctoral thesis

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WE STATE that the present study, entitled "MODELING SEA LEVEL RISE IMPACTS AND THE MANAGEMENT OPTIONS FOR RICE PRODUCTION: THE EBRO DELTA AS AN EXAMPLE", presented by Ana Genua Olmedo for the award of the degree of Doctor with European mention, has been carried out under my supervision at the Aquatic Ecosystems Program (IRTA).

Tortosa, 30 June 2017

Doctoral Thesis Supervisor/s

Dr. Carles Ibáñez Martí

Dr. Carles Alcaraz Cazorla

A mis padres, mis segundos padres (tía Concha y tío Curro), Luisito y Silvia.

"Delta, un río va.
Delta, sangra hacia el mar.
Delta, eres libertad.
Yo soy el agua que no quiere abandonar tu cauce nunca más.
Iré a morir en esa boca que está llena de verdad.

Delta, remanso de paz.
Delta, sé que un día volarás […]
Delta, es hora de partir.
Será difícil no llorar por ti."

[*] M-Clan (2016). Delta. En Delta [CD]. Nashville, USA: Brad Jones.

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La foto de la contraportada es cortesía de Mariano Cebolla.

Contents

Abstract

The climate is warming and coastal territories have to cope with increasing risks related to sea level rise (SLR). The world's coastal zones are threatened by the increase of mean and extreme sea levels in a variety of ways, such as flooding of shallow areas, coastal erosion, salinization, wetland loss, damage to property, and decreased agricultural and aquaculture production. Among coastal systems, deltas are thought to be highly vulnerable to SLR because of their low elevation, their land subsidence and their dense population. The Ebro Delta (NE Iberian Peninsula) is one of the most valuable coastal systems in the Western Mediterranean, with a total surface of 320 km^2. The Ebro Delta is representative of the vulnerability of coastal areas to SLR, it is a low-lying area characterized by an elevation gradient from a maximum of about 5 m close to the river, down to the coastline, with about 50 % of the total surface below +0.5 m above mean sea level. The delta plain contains a number of ecosystems (*e.g.* coastal lagoons, sand spits, brackish marshes, and fresh water springs) that provide suitable habitats for a diverse and abundant wildlife, and give a high ecological value to the delta, which is protected as Natura 2000 site of the European Union and as Natural Park and Biosphere Reserve (UNESCO). Freshwater and nutrient inputs from the Ebro River allow the development of prosperous fishery and farming activities. Rice cultivation is the main economic activity in the region. Rice fields occupy most of the delta (*ca*. 210 km^2, 66 % of the total surface) and are vulnerable to accelerated SLR and to consequent increase in soil salinity, the most important physical factor affecting rice production. However, literature analysing the impacts of SLR in crops is very scarce, and existing studies only consider the potential damage by flooding but not by salt stress, which is the main remaining impact once adaptation measures to avoid inundation (*i.e.* coastal defenses) are implemented. Thus, it is necessary to analyse the main impacts of SLR, mainly flooding and soil salinization, on the Ebro Delta, and to develop appropriate adaptation measures to preserve its ecological integrity and rice production under future SLR scenarios.

Within this context, we developed different spatial models (resolution of 1 × 1 m) to predict the impacts of SLR on the Ebro Delta. The developed models included: the identification of areas prone to be flooded, the volume of sediment needed to build up land under SLR, soil salinity and rice production loss due to SLR. All models were built by coupling data from Geographic Information Systems with Generalized Linear Models and run under present conditions (reference state) and under different predicted scenarios by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change for 2025 and from 2030 to 2100 with 10-year steps. Finally, we evaluated the feasibility of an innovative nature-based adaptation measure consisting in reintroducing fluvial sediments (retained in the lower basin reservoirs) into the delta plain for balancing the effects of SLR. Different sets of data were obtained from digital imagery, cartography and field data for the lower Ebro River and its delta, and then used to derive new raster datasets. Rice production data were obtained from surveys among farmers.

Our models showed that soil salinity was directly related to distances to the river, to the delta inner border, and to the river old mouth, while clay presence, winter river flow and surface elevation were inversely related to it. Surface elevation was the most important variable in explaining soil salinity. Rice production was negatively influenced by soil salinity, thus the models predicted a decrease from higher elevation zones close to the Ebro River to the shoreline. The model predicted a reduction in normalized rice production index (RPI) subject to the considered SLR scenario. Therefore, the models predicted a RPI reduction from 62.1 % in 2010 to 54.6 % by 2100 in the most conservative scenario (RCP 4.5, SLR = 0.53 m) and to 33.8 % by 2100 in the worst considered scenario (RCP 8.5 modified by Jevrejeva et al. 2014, SLR = 1.8 m), with a decrease of profit up to 300 € per hectare. For the same period and considered SLR scenarios, our flood models predicted that between the 36 and the 90 % of the rice fields will be flooded and lost by 2100, under the most conservative and the worst case scenario, respectively, which means a sediment deficit volume ranging between 130 and 442 million tonnes. The proposed nature-based adaptation measure had a positive effect on rice production, therefore it can be considered as an innovative management option in contrast to classical engineering solution, for maintaining the Ebro Delta ecosystem services although SLR. Our models can be applied to other deltas worldwide, and help rice farmers and stakeholders to identify the most vulnerable areas to SLR impacts, and to develop adequate management plans.

Resumen

El clima del planeta se está calentando y los territorios costeros tienen que hacer frente a los crecientes riesgos relacionados con la subida del nivel del mar (SLR por sus siglas en inglés). Las zonas costeras del mundo están amenazadas por el aumento de los niveles medios y extremos del mar de diversas maneras, como la inundación de áreas poco profundas, erosión costera, salinización, pérdida de humedales, daños materiales y disminución de la producción agrícola y acuícola. Entre los sistemas costeros, los deltas son altamente vulnerables a la SLR debido a la baja elevación que les caracteriza, a la subsidencia, y a la alta densidad de población que habita en ellos. El Delta del Ebro (NE de la Península Ibérica) es uno de los sistemas costeros más valiosos del Mediterráneo occidental, con una superficie total de 320 km^2. El Delta del Ebro es representativo de la vulnerabilidad de las zonas costeras a la SLR, es una zona baja caracterizada por un gradiente de elevación con un máximo de unos 5 m cerca del río, hasta el litoral, con alrededor del 50 % del total de la superficie por debajo de +0.5 m sobre el nivel medio del mar. La llanura deltaica contiene una gran variedad de ecosistemas (por ejemplo, lagunas costeras, playas, barreras de arena, marismas y manantiales de agua dulce) que proporcionan hábitats adecuados para el desarrollo de una fauna y flora diversa y abundante, y dan un alto valor ecológico al delta, el cual está protegido como Natura 2000 de la Unión Europea y como Parque Natural y Reserva de la Biosfera (UNESCO). Las entradas de agua dulce y nutrientes del río Ebro permiten el desarrollo de una próspera actividad pesquera y agrícola. El cultivo de arroz es la principal actividad económica de la región. Los campos de arroz ocupan la mayor parte del delta (aproximadamente 210 km^2, 66 % de la superficie total) y son vulnerables a la SLR y al consiguiente aumento de la salinidad del suelo, el factor físico más importante que afecta a la producción de arroz. Sin embargo, la literatura que analiza los impactos de la SLR en los cultivos es muy escasa y los estudios existentes sólo consideran el daño potencial causado por las inundaciones, pero no por el estrés salino, que es el principal impacto que permanece una vez que se implementan las medidas de adaptación para evitar la inundación. Por lo tanto, es necesario analizar los principales impactos de la SLR, principalmente las inundaciones y la salinización del suelo en el delta del Ebro, y desarrollar medidas de adaptación apropiadas para preservar tanto su integridad ecológica como la producción de arroz bajo futuros escenarios de SLR.

En este contexto, hemos desarrollado diferentes modelos espaciales (con resolución de 1 × 1 m) para predecir los impactos de la SLR en el delta del Ebro. Estos modelos incluyeron: la identificación de áreas propensas a ser inundadas, el volumen de sedimento necesario para mantener la elevación de la superficie a pesar de la SLR, la salinidad del suelo y la pérdida de producción de arroz debido a la SLR. Todos los modelos se construyeron mediante el acoplamiento de datos de Sistemas de Información Geográfica (GIS) con Modelos Lineales Generalizados (GLMz) y funcionan bajo las condiciones actuales (estado de referencia) y bajo diferentes escenarios previstos por el quinto informe de evaluación del Panel Intergubernamental sobre Cambio Climático (AR5 IPCC) para el año 2025 y para el periodo de 2030 a 2100 con intervalos de 10 años. Por último, se evaluó la viabilidad de una medida de adaptación innovadora basada en la naturaleza que consiste en reintroducir sedimentos fluviales (retenidos en los embalses de la cuenca baja) en la planicie de delta para equilibrar los efectos de la SLR. Se obtuvieron diferentes conjuntos de datos a partir de imágenes digitales, cartografía y datos de campo del tramo bajo del río Ebro y su delta, y luego se utilizaron para derivar nuevos conjuntos de datos ráster. Los datos de producción de arroz se obtuvieron a partir de encuestas entre los agricultores.

Nuestros modelos mostraron que la salinidad del suelo estaba directamente relacionada con la distancia al río, la distancia al borde interno del delta y la distancia a la antigua desembocadura del río, mientras que la presencia de arcilla, el caudal fluvial de invierno y la elevación de la superficie estaban inversamente relacionados con ella. La elevación de la superficie resultó ser la variable más importante para explicar la salinidad del suelo. La producción de arroz estaba influenciada negativamente por la salinidad del suelo, por lo que los modelos predijeron una disminución desde las zonas de elevación más altas cerca del río Ebro a la costa. El modelo predijo una reducción en el índice de producción de arroz normalizado (RPI) dependiendo del escenario de SLR considerado. Por lo tanto, los modelos predijeron una reducción de RPI de 62.1 % en 2010 a 54.6 % para el año 2100 en el escenario de SLR más conservador (RCP 4.5, SLR = 0.53 m); y a 33.8 % en 2100 en el escenario más extremo (RCP 8.5 modificado por Jevrejeva et., al 2014, SLR = 1.8 m), con una disminución de los beneficios de hasta 300 € por hectárea. Para el mismo período y dependiendo de los escenarios de SLR, nuestros modelos de inundación predijeron que entre el 36 y el 90 % de los campos de arroz se inundarán y se perderán en 2100, para el escenario más conservador y extremo, respectivamente, lo

que significa un déficit de sedimentos que oscila entre 130 y 442 millones de toneladas. La medida de adaptación propuesta basada en la naturaleza tuvo un efecto positivo en la producción de arroz, por lo que puede considerarse como una opción de gestión innovadora en contraste con la solución basada en la ingeniería clásica, para mantener los servicios ecosistémicos del Delta del Ebro a pesar de que suba el nivel del mar. Nuestros modelos pueden aplicarse a otros deltas del mundo y ayudar a los productores de arroz y a las partes interesadas a identificar las áreas más vulnerables a los impactos de la SLR y a desarrollar planes de gestión adecuados.

General introduction

Sea level rise and climate change

The climate of the planet has changed significantly over the last few decades and global warming due to pollution and greenhouse gases emission has become of concern to the society. Global warming is one of the main factors of climate change leading to excessive flooding due to both Arctic and Antarctic melting, and to the consequent general rise in sea levels (Rahmstorf, 2007). Therefore, understanding the causes and consequences of climate change is a social challenge because help us to predict extreme changes, develop adaptation ad mitigation measures, and to assess climate change impacts on human health and the environment (Nicholls et al., 2007; Small and Nicholls, 2003). In that sense, climate change science has increased substantially since the creation in 1988 of the Intergovernmental Panel on Climate Change (IPCC), the international body par excellence in evaluating climate change causes and consequences. The IPCC regularly prepares comprehensive Assessment Reports (AR) evaluating scientific, technical and socio-economic information concerning climate change, human mediated climate change, effects and consequences, and options for adaptation and mitigation. The Fifth Assessment Report (AR5) published in 2014 provides a clear and up to date view of state of art in climate change science (IPCC, 2017).

The Representative Concentration Pathways (RCPs) is a set of new pathways developed for the climate modeling community as a basis for long-term and near-term modeling experiments (Van Vuuren et al., 2011), and adopted by the IPCC. The main aim of the proposed RCPs is to provide information on possible trajectories for the main forcing agents of climate change by 2100. RCPs projections are based on greenhouse gas (GHG) concentrations (measured in CO_2 equivalents and expressed in Watts per square meter), which assist in modeling and research future climate conditions and their consequences. Four RCPs were selected and defined, based on a literature review, representing a broad range of climate outcomes, RCP 2.6 (stringent mitigation scenario) predicts a peak between 2010 and 2020, with emissions declining substantially hereafter; both RCP 4.5 and RCP 6.0 (intermediate scenarios) assume a peak around

2040 and 2080, respectively, then decline; and RCP 8.5 (scenario with very high emissions) assumes increasing GHG atmospheric concentrations throughout the present century (Church et al., 2013a).

Among other drivers of climate change, the AR5 conducts specific work on sea level rise, which exposes million people living in coastal areas (Nicholls and Cazenave, 2010). During the period 1993-2010, the average SLR was *ca.* 3.0 mm/yr (Hay et al., 2015) and this is projected to increase over the next 100 years depending on the considered RCP. The projected SLR up to 2100 forced by the different RCPs are summarized in Figure 1 and Table 1; in the worst scenario (RCP 8.5), the AR5 IPCC projected a “likely” (*i.e.* 66 % likelihood range) global-average SLR between 0.73 and 0.98 m by 2100 (Figure 1), relative to sea level for the period 1986-2005 (Church et al., 2013b).

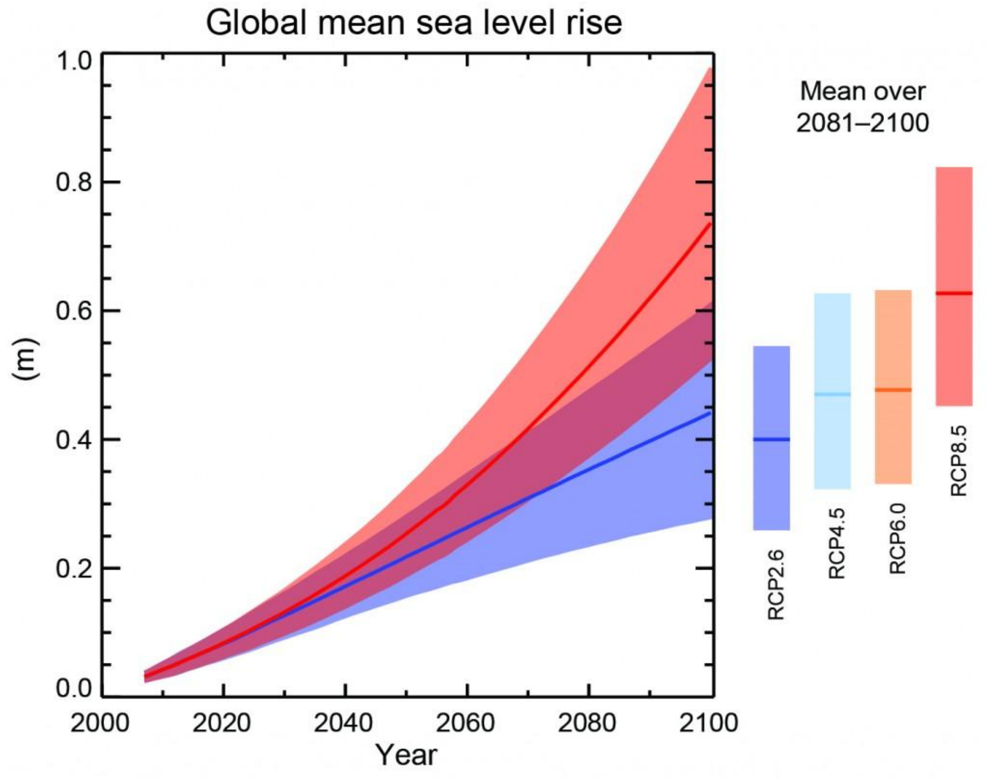

Figure 1. Projections of global mean SLR over the 21st century (relative to 1986–2005) for a low emissions scenario (RCP 2.6), intermediate scenarios (RCP 4.5 and 6.0), and high emissions (RCP 8.5). The assessed likely range is shown as a shaded band. Source: Church et al., (2013b).

The AR5 does not exclude the possibility of higher sea levels which would only occur in the 21st century if the sections of the Antarctic ice sheet were to collapse (Church et al., 2013a). As DeConto and Pollard (2016) predicted, Antarctica has the potential to contribute more than one meter of SLR by 2100 and more than 13 m by 2500. Because of this uncertainty, high-end SLR scenarios should be taken into account when modeling its impacts. On that sense, the upper limit SLR generated by Jevrejeva et al., (2014) (low probability estimates, unlikely to be reached, but which at the same time, cannot be ruled out given paleoclimate observations) estimated higher SLR up to 1.80 m by 2100, with less than 5 % probability, based on the construction of a probability density function for global mean SLR. With this context, the following SLR scenarios have been considered in the present thesis (Table 1):

Table 1. The considered SLR scenarios for the present thesis. RCP 4.5 (intermediate) and RCP 8.5 (increasing radiative forcing) were obtained from the mean and high values of the AR5 IPCC projections, and the upper limit SLR, from Jevrejeva et al., 2014.

	RCP 4.5		RCP 8.5		
Year	Mean SLR	High SLR	Mean SLR	High	Upper Limit
2025	0.103	0.130	0.101	0.129	0.190
2030	0.126	0.159	0.126	0.160	0.240
2040	0.174	0.221	0.182	0.232	0.363
2050	0.228	0.291	0.248	0.317	0.514
2060	0.285	0.369	0.324	0.415	0.697
2070	0.345	0.451	0.411	0.530	0.918
2080	0.407	0.536	0.508	0.660	1.173
2090	0.467	0.622	0.614	0.807	1.468
2100	0.528	0.710	0.731	0.971	1.801

Sea level rise impacts on low-lying coastal areas

Coastal and low elevation populations are at risk from SLR, and other seaward hazards (*e.g.* changes in ocean currents, winds and storms intensity) induced by climate change. Lowland areas are densely populated and continuously growing, making them more vulnerable to threats posed by climate change. The 10 percent of the world's population and the 13 percent of the world's urban population inhabits the area that is less than 10 meters above sea level, which only represents the two percent of the Earth land surface

(McGranahan et al., 2007). Furthermore, the coastal population could grow to 1.8-5.2 billion people by 2080, depending on assumptions about migration (Nicholls et al., 2007). This growing population has led to a widespread conversion of natural coastal landscapes into agriculture, aquaculture, as well as into industrial and residential uses (Valiela, 2006), becoming in highly economically-productive regions. Thus, not only coastal populations but also their socio-economic activities are threatened by SLR. The impacts of SLR on coastal areas include land flooding and storm damage, erosion, saltwater intrusion, rising water tables and wetland loss (Nicholls and Tol, 2006). The inundation of low-lying coastal areas around the world is currently considered one of the most dramatic and immediate effects of SLR (FitzGerald et al., 2008).

Even more dramatic is the situation in river deltas, the largest and low-lying coastal landforms in the world, and although the world’s deltas represent only the one percent of the Earth’s land surface, close to half billion people live in them (Woodroffe et al., 2006). Thus, river deltas are widely recognized as the most vulnerable zones to the impacts of climate change and rising sea level (Zhang et al., 2004). Human development patterns increase deltas vulnerability to the effects of climate change (Day et al., 2016). Currently, most of the world’s deltas are impacted by drastic sediment input reduction (> 80 %) due to entrapment in dams and river flow alterations (Anthony et al., 2014); deltas are also subsiding areas, thus accelerating rates of relative sea level rise above the global average (Nicholls et al., 2007). Ericson et al., (2006) carried out an assessment of 40 deltas based on the effective-SLR impacts (the combination of eustatic SLR, the rate of fluvial sediment deposition and subsidence), showing that the worldwide mean value of effective-SLR is *ca.* 3.9 mm/yr, and conclude that the dominant factor in the effective-SLR for the majority of the studied deltas is the loss of fluvial sediment due to its retention in basin reservoirs (Figure 2).

The world’s deltas are of high ecological and economic importance in terms of wetlands, wildlife habitats, potential for water quality improvement, agriculture, aquaculture, and tourism (Day et al., 1995). Thus, SLR also threats the delta´s ecosystem services, and adds complexity, intensity, and durability to the degradation processes already affecting deltas (Roca and Villares, 2012). For instance the negative impacts of SLR on agriculture have been reported in such different deltas as the Nile, Rhine, and Rhone (Agrawala et al., 2004; Asselman et al., 2003; Poumadère et al., 2008). The main SLR effects are related to crop damage by floods and salt intrusion, one of the most significant factor that constrains crop production (Douglas, 2009; Duan, 2016). Estimations of the global agricultural area vulnerable to SLR varies from 0.65 % to 23.43 % depending on SLR projections (Dasgupta et al., 2009).

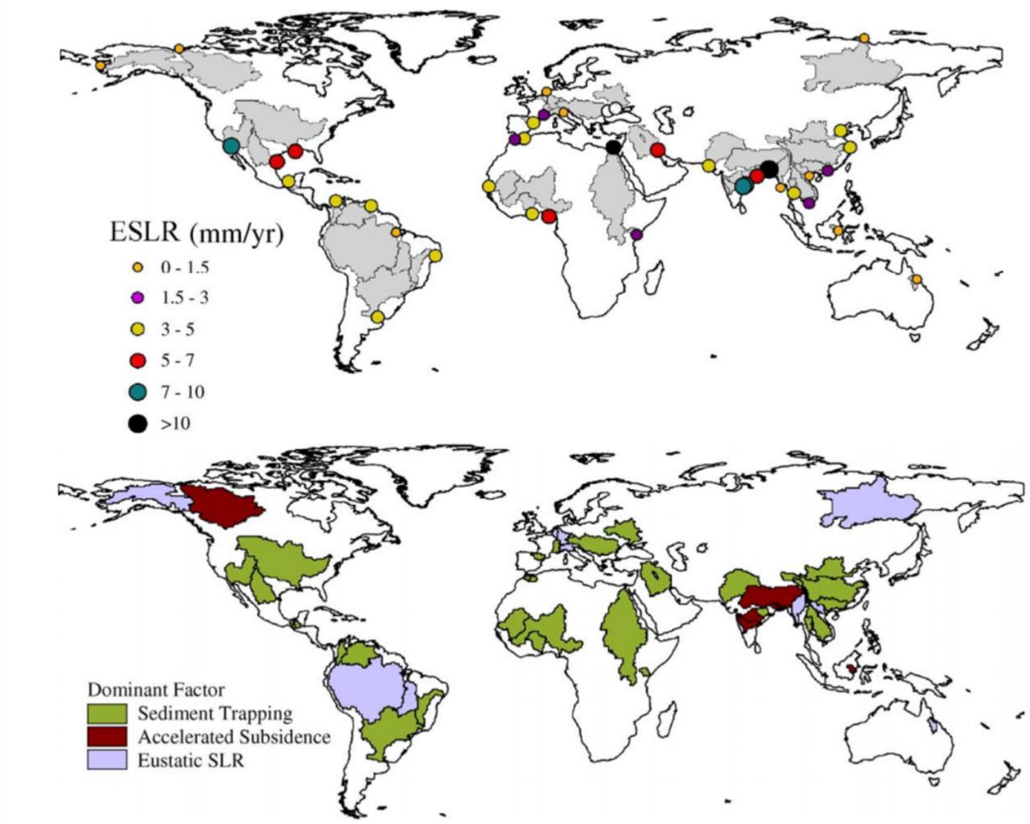

Figure 2. Global distribution of the effective-SLR for 40 deltas. The upstream drainage basin for each delta is highlighted (top); dominant factor in estimate of baseline effective-SLR (bottom). Source: Ericson et al., (2006)

The impacts of SLR are also variable depending on the considered crop type, thus rice (*Oryza sativa*), a crop intensively harvested in low-lying areas such as deltas, is of main concern since it is the most widely consumed staple food for half of the world's population (Chen et al., 2012), and it is the third most important worldwide crop. Global rice production in 2016 was 751.9 million tonnes, being China (145 million tonnes), India (106 million tonnes) and Indonesia (37 million tonnes) the most important producers (FAO, 2017). In the European Union, rice production was 2.87 million tonnes, mainly harvested in Italy (48.26 %), Spain (30.07 %), Greece (9.38 %), Portugal (5.64 %) and France (2.9 %) (FAO, 2017). Rice paddy fields are also home for many species of plants and animals, thus supporting and protecting local biodiversity and ecosystem functioning. In Europe, there are several examples of rice farm areas combined with natural protected areas such as the Po Delta (Italy), La Camargue (France), and the Ebro Delta (Spain) (Serrat Gurrera, 2016). In summary, people inhabiting deltas and their associated activities are already subject to SLR impacts and vulnerable to future SLR projections, thus it is time to develop further methods to adapt to SLR scenarios and to mitigate deltas vulnerability.

Adaptation and mitigation measures to sea level rise impacts

To date, there is little evidence that the international community has seriously considered the implications of SLR for population, infrastructure planning and economic development. There are three important concepts in relation to climate change impacts and the response of both natural and human systems: (i) vulnerability, defined as the threats to a given system, and its susceptibility to the adverse effects of climate change; (ii) adaptation, system ability to adjust and reduce its vulnerability to climate change enhancing resilience to observed and predicted climate change impacts, according to the IPCC is defined as adjustment in natural or human systems to a new or changing environment; and (iii) mitigation are the strategies and actions (*i.e.* policies) applied to reduce GHGs emissions into the atmosphere or reduce their concentration, the IPCC defines mitigation as technological change and substitution that reduce resource inputs and emissions per unit of output with respect to climate change (Cardona et al., 2012; IPCC, 2017; Smith et al., 2001; Watson et al., 1996). Adaptation measures include social and environmental processes modifications, climate risk perception, actions to reduce climate risk and the exploration of new opportunities to cope with the modified environment. Thus, adaptation and mitigation are complementary, for instance, if mitigation measures are effective lesser impacts are expected and consequently lesser adaption is required. Adaptation measures are used to cope with the effects of climate change and SLR, and to reduce the uncertainties associated to their impacts by incrementally planning ahead. They allow stakeholders and policy makers to consider a range of options for choosing the best approach, avoiding to make inappropriate decisions (*i.e.* too little, too much, too soon, or too late), where may inadvertently increase the socioeconomic and environmental SLR impacts (Barnett and O'Neill, 2010). Following IPCC (1990), adaptation to SLR can be undertaken in three stages (Figure 3):

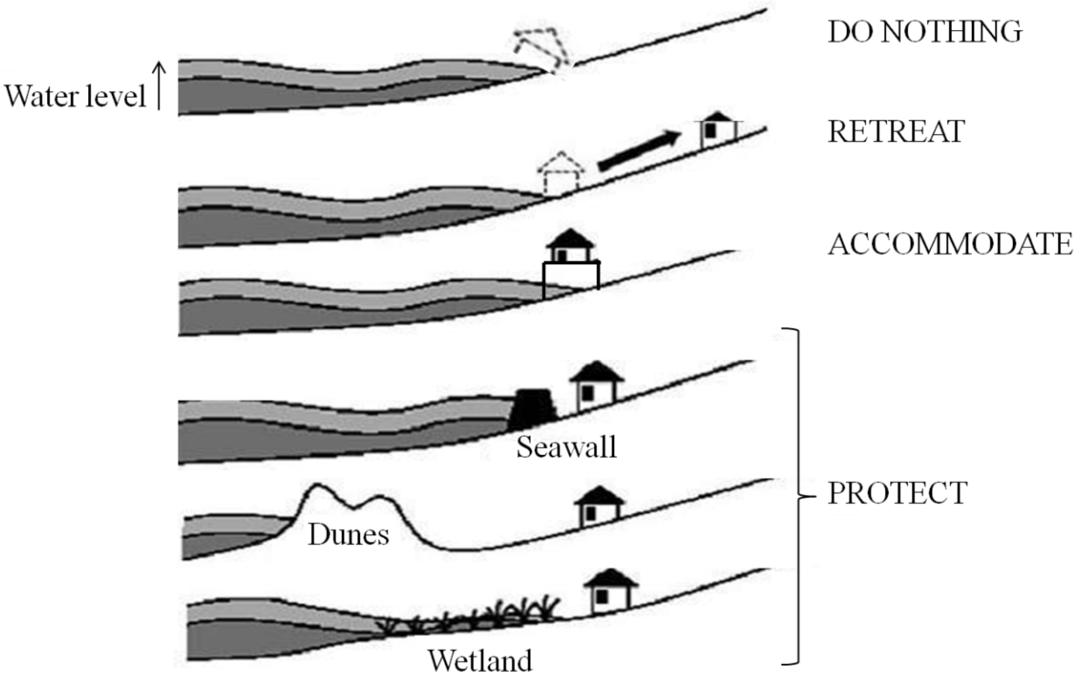

Figure 3. Adaptation strategies of retreat, accommodate and protect (adapted from IPCC 1990).

1- Retreat: "allow the erosion to take place, people and habitats to move landward". It implies to abandon structures in currently developed areas, resettle inhabitants and require that new developments should be set back from the shore.

2- Accommodate: "allow the erosion to take place and accommodate change by changing land-use". It implies to continue occupying vulnerable areas, but accept the greater degree of flooding by changing land use, construction methods and/or improving preparedness by adjusting to the changing environment (either spontaneously, anticipatory or planned).
3- Protect: several options are identified including both hard and soft solutions for SLR. It implies to defend vulnerable areas, especially population centers, economic activities and natural resources, such as by hard (*e.g.* dikes) and soft defenses (*e.g.* wetlands).

In deltas, holding large populations and urban cities, the first type of adaptation measures adopted are often protection and accommodating (Figure 3). Protection has potential longevity (*e.g.* dike levels can be raised) until the SLR is too high and limits on protection are found (Tol et al., 2006) being costly to build and to maintain, and can have adverse impacts, such as changing sediment dynamics. Accommodation strategies (*e.g.* early flood warning systems and retrofitting of buildings) are often more effective in the short-term. In deltas containing wetlands and agriculture areas, the range of options is more focus on accommodation rather than protection (Figure 3), including conversion of crops to salt-tolerant varieties. As sea levels rise, more drastic adaptation options may become necessary (*e.g.* giving up the rural land at the impacted areas or constructing adequate dikes).

The current view is that coastal protection is the best strategy for future SLR up to 5 m, and beyond that retreat would be the best (or the only) strategy. However, for the case of deltas a more functional adaptation strategy can be feasible provided that natural processes and ecosystem functions can be managed to increase system's resilience. The central element of this alternative is the concept of "rising grounds" (vertical aggradation), instead of "rising dikes", but a combination of both can also be foreseen and may be needed in many cases. It has been proposed that "rising grounds" may be the best adaptation strategy in most deltas for high-end scenarios of SLR, though the option of partial retreating may be necessary also in combination with structural and functional measures (Ibáñez et al., 2014).

With these stages in mind, adaptation in the world's deltas is receiving growing attention. Specifically, the studies that argue about the pros of nature-based solutions against the hard-engineering (Chapman and Darby, 2016; Temmerman and Kirwan, 2015). Nature-based solutions help to decrease the vulnerability and enhance the resilience of ecosystems, serving as proactive adaptation options and to mitigate climate change-induced impacts (Kabisch et al., 2016). A good example of nature-base solutions is wetlands restoration to protect ecosystems and the restoration of floodplains into agricultural practices, which are economically more feasible than the classical engineering mainly base on building defenses not efficient in the long-term (Tessler et al., 2015).

Study context: the Ebro Delta

The Ebro River is located in the NE of the Iberian Peninsula (Spain), being 910 km long and with a drainage basin approximately of 85,362 km^2 (Figure 4). It is the Spanish River with the highest mean annual flow and one of the most important tributaries to the western Mediterranean Sea. More than 10,000 km^2 are devoted to crop irrigation, the main land use in the Ebro Basin. The entire basin is strongly regulated by the presence of *ca.* 200 large dams, mainly built for hydroelectric, irrigation and human consumption. In particular, Mequinensa and Riba-Roja reservoirs (*ca.* 100 km upstream from the river mouth) have altered the flow and prevent flood frequency (Rovira et al., 2012). Consequently, present river discharge is *ca.* 30 % lower than original, and the 99 % of the sediment is retained by dams (Rovira and Ibáñez, 2015).

The Ebro River forms a delta, the Ebro Delta (320 km^2), one of the largest deltas in the western Mediterranean (Figure 4). A total of 7,736 ha of the delta are declared protected areas under a National Natural Park, being part of the Natura 2000, including coastal lagoons and freshwater springs. While natural habitats cover only about the 25 % of the total surface, rice fields occupy most of the delta plain (210 km^2), thus representing the main economic activity (Figure 4). The total delta population in 2015 was 62,120 inhabitants, according to the Institute of Statistics of Catalonia (Romagosa and Pons, 2017), and within the active population, an average between 18-27 % is directly working in agriculture (Franquet Bernis, 2012). The total rice production is about 120,000 tonnes/yr, the third most important of the European Union (Day et al., 2006). Rice cultivation generates nearly 98 % of the rice produced in Catalonia, and approximately 13 % in Spain (Zografos, 2017). The Ebro Delta is highly vulnerable to SLR since a significant portion of the delta plain is near or below mean sea level, thus SLR threats the rice production and their associated economic activities.

To date, the considered adaptation measures for preserving both the rice economic activity and the natural habitats of the Ebro Delta under SLR scenarios are explained in Table 2 (Jiménez et al., 2016). A1 is the classical engineering adaptation measure consisting on the construction of coastal defenses to avoid flooding risks. At present, the plan for constructing 1.5 m high defenses along the bays is already elaborated by the Spanish Government, although its implementation has been halted as a consequence of the economic crisis. A2 is considered by stakeholders the most appropriate adaptation option, and can be also combined with A1, depending on the cost of supplying sediments to the delta plain. However, the availability of sediments is considered a limiting factor as well as the lack of support from the Ebro Basin Authority (CHE) and the hydropower company managing the reservoirs. Local or external sediment sources such as dredging and material from public works could be provided. Sediment supply at the local scale is actually a common practice conducted by farmers in order to raise rice fields' grounds and reduce levels of salinity (Ibáñez et al., 2014).

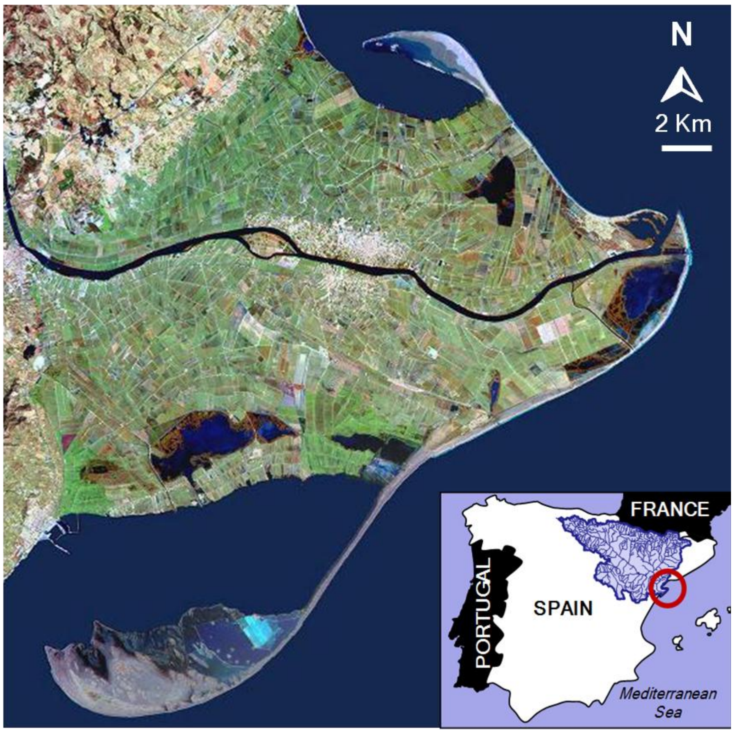

Figure 4. Map of the Ebro Delta showing the distribution of rice fields.

Table 2. Description of business as usual and adaptation measures for the Ebro Delta

Adaptation	Description
BAU	- No protection measures are taken - There are hardly any dikes present - Farmers increase land elevation through sediment supply
A1	- Dikes along the shore of the two bays of the delta. - Dikes of 1.5 m of height planned to be built by the Spanish Government
A2	Rising grounds: - What: Increase land elevation by supplying sediments from the Ebro River - How: Via irrigation channels, including the establishment of a by-pass system in the upstream reservoirs
A3	- Segmentation of the irrigation and drainage network - Isolating low-lying rice drainage system from rice fields above sea level

Both A1 and A2 will help to prevent the inundation of the Ebro Delta but the A2 option will additionally help to reduce salinity intrusion due to ground elevation, minimizing economic losses in rice crops resulting from increased soil salinities. A3 will be dependent on the trends of electricity costs with SLR, which can be partially reduced by isolating the low-lying rice drainage system from rice fields above the sea level that still can be drained by gravity. This will reduce the necessary pumping of freshwater and concentrate the costs in the most affected rice fields adjacent to bays and coasts until they are unsustainable and therefore transformed into wetlands or other land uses.

The Ebro Delta is a very dynamic coastal system where striking a balance between the ecological and agricultural value of the delta is not an easy task. With all this in mind, the analysis of the SLR impacts on rice production and management options to maintain rice production under SLR are the main goal of the present thesis.

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Objectives

The main aims of the PhD thesis, followed by their specific objectives, are:

1. To analyze the impacts of SLR on the Ebro Delta rice production, assessing the associated economic losses for the agricultural sector (*Chapter 1*):
   a) developing a spatial predictive model of soil salinity
   b) assessing the effects of soil salinity on rice production
   c) simulating soil salinity and rice production under different SLR scenarios*

2. To determine the estimation of the volume of sediment needed to build up land under SLR scenarios* and measure the cost and feasibility of introducing fluvial sediments into the delta plain to maintain rice production (*Chapter 2*):
   a) identifying areas prone to be flooded under SLR
   b) calculating the total volume of sediment needed under two modeled scenarios:
      i. to maintain the deltaic surface elevation relative to mean sea level as in the reference state (present topography).
      ii. to raise land only in the flooded areas and just enough to compensate for the SLR.
   c) analyzing the costs and benefits of the proposed nature-based adaptation measure (rising grounds).

* The considered SLR scenarios are common for both Chapter 1 and Chapter 2 and are based on the AR5 IPCC projections up to 2100: RCP 4.5 and RCP 8.5, including the upper limit scenario proposed by Jevrejeva et al., (2014), see Table 1.

Chapter 1

SEA LEVEL RISE IMPACTS ON RICE PRODUCTION: THE EBRO DELTA AS AN EXAMPLE

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Abstract

Climate change and sea level rise (SLR) are global impacts threatening the sustainability of coastal territories and valuable ecosystems such as deltas. The Ebro Delta is representative of the vulnerability of coastal areas to SLR. Rice cultivation is the main economic activity in the region. Rice fields occupy most of the delta (*ca*. 65 %) and are vulnerable to accelerated SLR and consequent increase in soil salinity, the most important physical factor affecting rice production. We developed a model to predict the impacts of SLR on soil salinity and rice production under different scenarios predicted by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change by coupling data from Geographic Information System with Generalized Linear Models. Soil salinity data were measured in agricultural parcels and rice production from surveys among farmers. The correlation between observed and soil salinity predicted values was highly correlated to observed values (Pearson's $r = 0.72$, $P < 0.0001$), thus supporting the predictive ability of the model. Soil salinity were directly related to distances to the river, to the delta inner border, and to the river old mouth, while clay presence, winter river flow and surface elevation were inversely related to it. Surface elevation was the most important variable in explaining soil salinity. Rice production was negatively influenced by soil salinity, thus the models predict a decrease from higher elevation zones close to the river to the shoreline. The model predicts a maximum reduction in rice production from 61.2 % in 2010 to 33.8 % by 2100 in the worst considered scenario (SLR = 1.8 m), with a decrease of profit up to 300 € per hectare. The model can be applied to other deltaic areas worldwide, and help rice farmers and stakeholders to identify the most vulnerable areas to SLR impacts.

Keywords

Climate change, salinization, rice production, SLR, high-end scenarios, deltas.

Introduction

The climate is warming and coastal territories have to cope with increasing risks related to sea level rise (SLR). The world's coastal zones are threatened by the increase of mean and extreme sea levels in a variety of ways, such as flooding of shallow areas, coastal erosion, salinization, wetland loss (Nicholls et al., 2007), damage to property, and decreased agricultural and aquaculture production (Chen et al., 2012). Among coastal systems, deltas are thought to be highly vulnerable to SLR because of their low elevation, their land subsidence and their dense population (Ibáñez et al., 2014; Syvitski, 2008).

The number of works devoted to evaluate the potential socio-economic impacts of SLR has increased exponentially, followed by more recent studies on adaptation measures (*e.g.* Chapman et al., 2016; Day et al., 2005; Giosan et al., 2014). For instance, Hinkel et al., (2014) presented a modelling framework for assessing coastal flood impacts and adaptation costs of future SLR at global scale called DIVA (Dynamic Interactive Vulnerability Assessment), where, apart from the impacts in urban areas, farmlands and other land uses are taken into account. The Fifth Assessment Report (AR5) carried out by the Intergovernmental Panel on Climate Change (IPCC) is the work par excellence in compiling SLR projections, its impacts and adaptation strategies considered. For the highest emission scenario, the IPCC reported a likely range of 0.52 to 0.98 m for SLR projections by 2100 (Church et al., 2013a). AR5 took a moderate position because SLR predictions of the most extreme scenario were assessed with a likely range of 66 %, without considering the possible collapse of Antarctic ice sheet by 2100. The remaining probability (33 %) means that by 2100 SLR may lie outside of the "likely range" (Church et al., 2013b). Because of this uncertainty, some authors consider that larger rates of SLR should be taken into account, including worst case scenarios for sea level with low probability and high impact (DeConto and Pollard, 2016; Hansen et al., 2016). Jevrejeva et al., (2014) constructed the probability density function for the worst SLR scenario and provided an upper limit (with only 5 % likelihood of being exceeded) of 1.8 m by 2100.

Given these SLR projections, the perspective is especially worrying in low-lying coastal regions such as deltas where the risk is exacerbated because of their natural subsidence process and the anthropogenic pressures to which they are subjected. These include changes in farming practices, sediment retention by dams, mining, groundwater or hydrocarbon extraction, and coastal management infrastructures, such as levees or embankments (Day et al., 2005; Syvitski, 2008). Areas at risk of flooding in deltas will grow by 50 % by the turn of the century (Giosan et al., 2014), thus threating the home of millions of people established in deltas, as well as the ecosystem services and the economic activities that support these populations (Brown and Nicholls, 2015).

The Ebro Delta is one of the most valuable coastal systems in the Western Mediterranean. More than 65 % of its surface is devoted to intensive rice cultivation, the main economic activity in the area, with an average production of *ca.* 6,512 kg per hectare (MAGRAMA, 2015). Rice fields provide several ecosystems services such as seasonal habitat for migratory birds, prevention of saline intrusion through fresh water inputs and nutrient removal (Calvo-Cubero et al., 2013). The deltaic system is also threatened by the lack of sediments associated to the construction of upstream dams acting as sediment traps, causing the retreat of the delta coast (Sánchez-Arcilla et al., 2008). This results on wetland and farmland loss, which in combination with eustatic SLR cause soil salinization through subsurface salt intrusion, leading to rice production damage and consequent economic losses.

Rice is the most economically important food crop for half of the world’s population, about 160 million hectares are harvested worldwide producing 730 million tons by year (FAO, 2015). Since rice is primarily cultivated in lowland areas, SLR threats rice production in a great percentage of the most productive rice-land in deltas, such as the Mekong and Ganges Delta in Asia, and Mississippi Delta in North America (Teixeira et al., 2013; Wassmann et al., 2004). The Ebro Delta is a good example of rice production area, with a mean surface elevation of 0.87 m is highly sensitive to SLR, and thus, it can be used as a model of rice response to SLR. While most studies concerning SLR impacts in deltaic areas focus on wetlands (Geselbracht et al., 2015; Pont et al., 2002), only a few deal with agriculture in general, or rice in particular (Chen et al., 2012; Wassmann et al., 2004). Moreover, literature analyzing the impacts of SLR in crops is very scarce, and existing studies only consider the potential damage by flooding but not by salt stress (*e.g*. Lázár et al., 2015), which is the main remaining impact once adaptation measures to avoid inundation (*i.e.* coastal defenses) are implemented. The aim of this study is to model the main impact of SLR on the effect of soil salinization due to SLR on the Ebro Delta rice fields, with the following specific objectives: (1) to develop a spatial predictive model of soil salinity, (2) to assess the effects of soil salinity on rice production; and (3) to simulate soil salinity and rice production under different SLR scenarios up to 2100, according to AR5 IPCC projections and also including the upper limit scenario proposed by Jevrejeva et al., (2014).

Materials and methods

Study area

The Ebro River is one of the most important tributaries of the Mediterranean Sea, being 910 km long and with a drainage area of 85,362 km^2. It is the river with the highest discharge in Spain (426 m^3/s of mean annual flow), but shows a marked variability between dry (118 m^3/s) and wet (569 m^3/s) years. The lower Ebro River has suffered important changes in the last decades due to industrial pollution, water abstraction and damming (*e.g.* Alcaraz et al., 2011; Ibáñez et al., 2012; Rovira et al., 2012). Thus, present river flow is significantly lower than originally (*ca*. 40 % decrease). The environmental variability is modulated by the presence of *ca.*190 large dams in the catchment, mainly built for hydroelectric and irrigation purposes. The construction of two large dams in the lower Ebro River (*ca.* 100 km upstream the mouth, see Figure 1a) by the end of the 60's prevent sediment transport along the river, thus leading to a reduction in sediment deposition in the delta plain.

The Ebro Delta (Figure 1a) is one of the largest (320 km^2) deltas in the north-western Mediterranean Basin. It is a low-lying area characterized by an elevation gradient from a maximum of about 5 m close to the river, down to the coastline (Figure 1b), with about 50 % of the total surface below +0.5 m above mean sea level. The delta plain contains a number of ecosystems (*e.g.* coastal lagoons, sand spits, brackish marshes, and fresh water springs) that provide suitable habitats for a diverse and abundant wildlife, and give a high ecological value to the delta, which is protected as Natura 2000 site of the European Union and as Natural Park and Biosphere Reserve (UNESCO). Fresh water and nutrient inputs from the river allow the development of prosperous fishery and farming activities. Agriculture is important in the Ebro Delta, because 210 km^2 of the delta plain are devoted to rice production (Figure 1c). Soil salinity distribution in the Ebro Delta at the year 2010 (reference state, hereafter) is shown in Figure 1d, and rice production distribution across the delta is shown in Figure 1e.

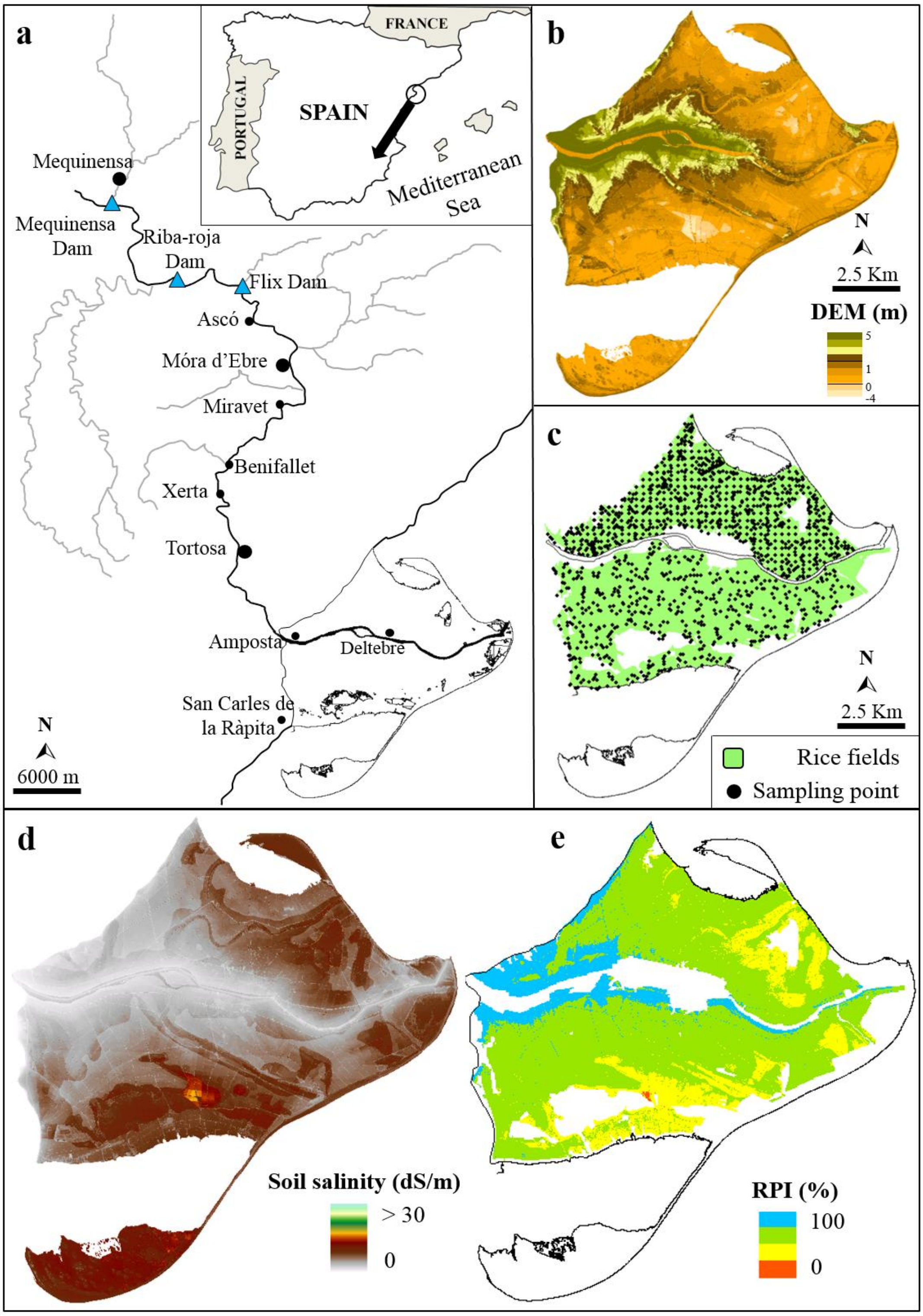

Figure 1. Location of the Ebro Delta (**a**); Ebro Delta Digital Elevation Model (DEM) map (**b**); distribution of rice fields along with soil salinity sampling points (**c**); soil salinity (**d**); and rice production index maps (**e**) in the reference state (2010).

Data collection

Different sets of data were obtained from sources such as digital imagery, cartography and field data for the lower Ebro River and its delta. The cartographic information on delta water bodies (*e.g.* the river course, old mouth locations, and lagoons) and delta contour (*e.g.* inner border and shoreline) were obtained from the Cartographic and Geological Institute of Catalonia (ICGC). This information was also used to derive new raster datasets, such as the Euclidean distance to the Ebro River, distance to the current mouth, distance to the old mouth, distance to the inner border and distance to the shoreline. This set of distances had a spatial grid resolution of 1×1 m. Soil geology data was obtained from geological maps at 1:50000 scale (ICGC, 2006; sheets number 522, 523, 547 and 548) and were utilized to produce new raster datasets defined as presence/absence of each soil-type category. Surface elevation was obtained from a Digital Elevation Model (DEM) with a spatial grid resolution of 1×1 m and a height accuracy of 15 cm (Figure 1b). The DEM was built from a topographic database obtained by the ICGC using LIDAR methodology; elevation data was referred to mean sea level in Alicante datum.

Soil salinity was obtained from 1,400 different rice fields (Figure 1c) sampled in the winter season (*i.e*. before flooding fields); 500 of them were obtained from a previous study during 1994-1996 (see Casanova et al., 2002), and 900 of them from field data of the "Agrupacions de Defensa Vegetal of Catalonia" during 2003-2007. Soil salinity was measured through electromagnetic induction at various depth intervals, and averaged over the soil profile to calibrate the electromagnetic sensor. When EM is used in the horizontal mode, 75 % of the signal response is estimated to come from the top 1 m of soil, while in the vertical mode 75 % of the signal is estimated to come from the top 1.8 m (Bennett et al., 1995). Soil salinity was expressed as the electrical conductivity of the saturated soil paste extract (EC_e, expressed in dS m^{-1}), a more reliable indicator for soil salinity than $EC_{1:5}$ (Casanova 1998), which is performed in the field or in the laboratory by mixing 1 part soil with 5 parts of distilled water. EC_e and $EC_{1:5}$ have a linear relationship (see Equation 1) independent of the soil textural class (Casanova et al., 1999).

Equation 1: $$EC_e = -1.62 + 7.75 \times EC_{1:5};\ R^2 = 0.92,\ n = 55$$

Rice production data (718 parcels in total) were directly obtained from records of nine rice farmers of the Ebro Delta for the period 1997-2014. Finally, hydrological data (*e.g.* river flow), water quality and meteorological data (*e.g.* precipitation and temperature) were obtained from the Ebro Water Authority (www.chebro.es) and the Tortosa meteorological station (Station Id. 9981A, located at 47 m above sea level).

Soil salinity model

The relationship between soil salinity (dependent variable) and independent variables (see list of variables in Table 2 in Supplementary material) was analyzed with Generalized Linear Models (GLMz). An information-theoretic approach was used to find the best approximating models following the methodology described by Burnham and Anderson (2002). GLMz were built including all possible combinations of independent variables, but excluding interactions, due to the large number of variables considered. The degree of support of each candidate model was assessed with the second order Akaike Information Criterion (AICc); and then AICc was rescaled to obtain ΔAICc values (ΔAICc = $AICc_i$ – minimum AICc). Candidate models were defined following two additional criteria: models with a variance inflation factor of > 5 were not considered, to avoid multicollinearity effects in regression models (Brockwell and Davis 2002); and only those models performing significantly better than the null model (*i.e.* the model including only the intercept), by a likelihood-ratio test, were considered (Maggini et al., 2006).

For the current analysis we examined in detail the set of models with ΔAICc ≤ 7, since models with ΔAICc > 7 have essentially no support and might be omitted from further consideration. Then, the relative plausibility of each candidate model was assessed by calculating Akaike's weights (w_i); w_i ranges from 0 to 1, and can be interpreted as the probability that a given model is the best model in the candidate set. Because no model was clearly the best one (*i.e.* $w_i \geq 0.9$), we calculated model-average regression coefficients (β_i) by weighing selected models coefficients by model w_i. The relative importance of each variable was also calculated by the sum of w_i for all models in which a given variable occurs, which estimates the importance of an independent variable for differentiating the response variable (see Burnham and Anderson, 2002). Finally, model-averaged estimates were compared with regression coefficients from the full model to assess the impact of model selection bias on parameter estimates

(Whittingham et al., 2005). For all of the candidate models the full model residuals were tested for normality through the Shapiro-Francia normality test; the residuals of all models were normally distributed ($P \geq 0.20$). Previously to analysis, quantitative variables were log-transformed to improve linearity and homoscedasticity.

Model calibration and validation

The performance criterion of the soil salinity model consisted in a graphical assessment of the relationship between observed and predicted values; and model efficiency were measured with Pearson's correlation coefficient (r) between both values. The calibration process mostly consisted in optimizing regression (GLMz) models by introducing and deleting different model parameters (*i.e.* independent variables) in order to maximize the relationship between observed and predicted values (Pearson's r). Optimization of the fit to the soil salinity data eliminated most of the over-prediction. Model selection, soil salinity estimation and calibration (Figure 2a) were done with 75 % of the data, and the remaining data (25 %) was used for model validation.

Rice production model

Several studies have shown that rice production decreases with soil salinity (*e.g.* Asch et al., 1995). We used in situ measures of soil salinity and rice production of 26 experimental parcels from the Ebro Delta (see Casanova et al., 2002; Català and Fosch, 1997) to establish the statistical relationship between soil salinity and rice production at local level. Data from farmers (kg ha^{-1}) were normalized in a rice production index (RPI) because rice production varies year by year due to environmental factors outside of the scopes of the analysis (*e.g.* meteorology). Therefore, observed rice production (kg ha^{-1}) were normalized to the maximum production value of the given year. RPI ranged from 0 (minimum productivity) to 100 (maximum productivity). Minimum and maximum observed productivity values were, respectively, 5,814 and 10,073 kg ha^{-1}. In the calibration process, different regression fits were tested (*e.g.* linear, logarithmic, exponential, etc.) and a negative exponential function was the best one to predict rice production for the given values of soil salinity, following the criterion of maximization of Pearson's correlation coefficient (r) between soil salinity and rice production:

Equation 2: $$RPI = (0.9486 \times e^{-0.082 \times ECe}) \times 100; \; r = 0.69, \; n = 26$$

,where EC_e is the soil salinity (dS m^{-1}) and RPI, the rice production index given in percentage. RPI equation was validated with the rice farmers data (Figure 2b).The estimated profit in € ha^{-1} was calculated for each of the modeled scenarios. For a given scenario, the rice production index was multiplied by the maximum observed value of rice production (kg ha^{-1}), and then converted to profit by multiplying by 0.28 €, the price per kilogram of rice paid to farmers in the Ebro Delta (data provided by the Ebro Delta rice farmers).

Sea level rise scenarios

The spatial distribution of soil salinity and rice production in the Ebro Delta was modeled under several SLR scenarios. The scientific community established a common set of scenarios referred as Representative Concentration Pathways (RCPs) which provide information on possible development trajectories for the main forcing agents of climate change (for full details see Van Vuuren et al., 2011). Two different scenarios were selected for the modeling exercise, namely RCP 4.5 (stabilization) and RCP 8.5 (increasing radiative forcing). The first is a mitigation scenario (mean global temperature +2.4 ºC; mean SLR average over 2081 to 2100 +0.47 m), and the second is a ‘business as usual’ scenario (mean global temperature +4.3 ºC; mean SLR average over 2081 to 2100 +0.63 m) (Church et al., 2013a).

Following Jevrejeva et al., (2014) we also included a worst case scenario (upper limit hereafter), with a 5 % probability of being exceeded (see Table 1). The Ebro Delta protection plan includes the construction of dikes (1.5 m height) along the inner bay shores, thus we assumed that soil salinization was mediated by saline intrusion. For a given scenario i, surface elevation (DEM_i) was calculated as the difference between the surface elevation in the reference state and SLR_i (Table 1). The model was calibrated and validated for the reference state and then model simulations were obtained for 2025 and from 2030 to 2100 with 10-year steps.

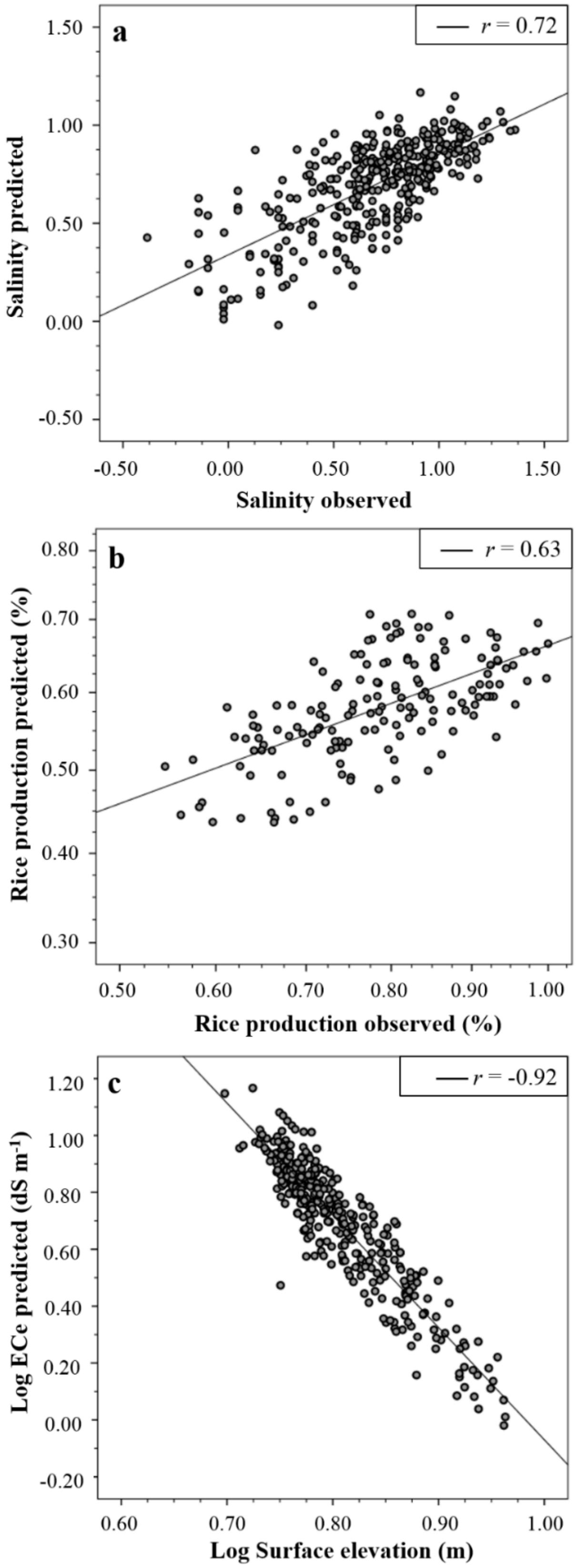

Figure 2. Relationship between the observed and predicted soil salinity values (dS m^{-1}) by the Generalized Linear Models (GLMz) averaged through an Information-Theoretic approach (**a**). Relationship between the observed and predicted rice production values by the regression analysis (**b**). Relationship between predicted soil salinity and surface elevation (m) (**c**). Pearson's correlation coefficient (*r*) is also shown.

Table 1. SLR projected values of the simulated years for the selected scenarios: RCP 4.5 (stabilization) and RCP 8.5 (increasing radiative forcing). Values of mean and high scenarios were obtained from AR5 IPCC and the upper limit of SLR was obtained from Jevrejeva et al., 2014.

	RCP 4.5		**RCP 8.5**		
Year	Mean SLR (m)	High SLR (m)	Mean SLR (m)	High SLR (m)	Upper Limit SLR (m)
2025	0.103	0.130	0.101	0.129	0.190
2030	0.126	0.159	0.126	0.160	0.240
2040	0.174	0.221	0.182	0.232	0.363
2050	0.228	0.291	0.248	0.317	0.514
2060	0.285	0.369	0.324	0.415	0.697
2070	0.345	0.451	0.411	0.530	0.918
2080	0.407	0.536	0.508	0.660	1.173
2090	0.467	0.622	0.614	0.807	1.468
2100	0.528	0.710	0.731	0.971	1.801

Results

Soil salinity

The correlation between observed and predicted values was significant (Pearson's r = 0.716, $P < 0.0001$), supporting the predictive ability of the model (Table 2, Figure 2a). The AICc-based model selection indicated that only 2 models could be considered as plausible models (*i.e.* AICc ≤ 7) to explain soil salinity variation. Out of the 21 independent variables initially included in the model (see Supplementary Table 2), only six were selected. The model with best AICc contained the following variables: clay presence, distance to the Ebro River, distance to the delta inner border, winter river flow and surface elevation (Table 2). Distance to the old river mouth was only included in one of the selected models and had the weakest relationship with soil salinity (Table 2). Parameter bias, namely the difference between the averaged regression coefficient estimates and the full model regression coefficients, was lower than 0.05 (Table 2), which supports the importance of each selected variable in estimating soil salinity. When analyzing the model averaged coefficients, it was found that all the selected distance variables (*i.e.* distances to the Ebro River, to the inner border, and to the old mouth) were positively related to soil salinity (Table 2). In contrast, winter river flow and surface elevation were inversely related to it. Surface elevation had the highest model averaged coefficient in absolute value (-2.609), and thus, it could be considered the most important variable in predicting soil salinity (Figure 2c).

Table 2. Results from the Generalized Linear Models (GLMz) analysis to predict soil salinity (EC_e) in the Ebro Delta. Model-averaged regression coefficients (*β*) are averaged by model weight across all candidate models (*i.e.* AICc ≤ 7). Model variables are chosen according to the selection probability (SP), indicating the importance of each independent variable. Bias is the difference between the averaged estimates and the full model coefficients. The number (*N*) of candidate models (AICc ≤ 7) is also shown. Individual model coefficients and information necessary to estimate soil salinity values are provided in Supplementary Table 1.

Model parameter	***N* = 2**		
	β	**SP**	**Bias**
Intercept	2.175		0.043
Clay presence	-0.119	1.000	-0.028
Distance to the Ebro River (m)	0.109	1.000	-0.029
Distance to the inner border (m)	0.070	1.000	-0.036
Distance to the old mouth (m)	0.005	0.310	< 0.001
Winter flow ($m^3\ s^{-1}$)	-0.214	1.000	0.003
Surface elevation (m)	-2.609	1.000	0.020

[a] Best model showed an AICc weight (w_i) of 0.69; 15 variables were excluded (*e.g.* distance to the shoreline or sand presence).

Response of soil salinity to sea level rise scenarios

Results on soil salinity, RPI, and profit for modeled scenarios (both RCP 4.5 and RCP 8.5) are summarized in Tables 3 and 4, whereas results on predicted soil salinity across the delta are shown in Figure 3. The spatial distribution of soil salinity shows a clear gradient in all scenarios, with the lowest values along the Ebro River bank and the highest nearby the shoreline and coastal lagoons directly connected to the sea. In the southern delta, the saltiest values are found in a specific area characterized by its low surface elevation, between 0.5 m and -0.87 m (Figure 1b), becoming the most vulnerable area to SLR. As general trend, the increase of soil salinity is similar for all scenarios except for the upper RCP 8.5 scenario, where a larger increase is observed (Figure 4a). In the RCP 4.5 scenario, soil salinity increases from a mean value of 5.53

dS m^{-1} in 2010 (Figure 1d) to 7.09 dS m^{-1} and 7.76 dS m^{-1} by 2100, for the mean and high SLR scenarios, respectively. However, this increment is much higher in the RCP 8.5 scenario, reaching values of 7.84 dS m^{-1}, 8.88 dS m^{-1} and 14.36 dS m^{-1} (mean, high and upper SLR scenarios, respectively) in the year 2100 (Table 4). For all scenarios, most of the delta plain ranges from 5 to 8 dS m^{-1} in 2050, with maximum values of 26.6 dS m^{-1} for mean RCP 4.5 and 32.4 dS m^{-1} for the upper RCP 8.5 in the areas with the lowest surface elevation. These areas show the highest increase in salinity reaching maximum values beyond 35 dS m^{-1} (Table 4). Thus, soil salinity in the Ebro Delta rice fields will increase about three times if SLR reaches 1.80 m, which is the worst considered scenario by the end of the present century.

Table 3. Model predicted values of soil salinity (EC_e, dS m^{-1}) and Rice Production Index (RPI, %) for the RCP 4.5 (stabilization) SLR scenarios. Mean and maximum EC_e, mean RPI, and mean profit (€ ha^{-1}) values are shown.

	RCP 4.5							
	Mean SLR scenario				**High SLR scenario**			
	EC_e		RPI	Profit	EC_e		RPI	Profit
Year	Mean	Max			Mean	Max		
2025	5.80	24.5	60.0	2,343.43	5.87	25.0	59.7	2,339.85
2030	5.86	24.9	59.7	2,339.85	5.95	25.4	59.3	2,335.08
2040	5.99	25.7	59.1	2,332.69	6.12	26.5	58.6	2,326.73
2050	6.14[a]	26.6[a]	58.5[b]	2,325.54	6.33	27.8	57.7	2,316.04
2060	6.31	27.7	57.8	2,317.19	6.56	29.3	56.1	2,296.92
2070	6.49[a]	28.8[a]	57.0[b]	2,307.65	6.83	31.0	55.1	2,284.99
2080	6.68	30.1	56.2	2,298.11	7.12	32.9	54.5	2,277.84
2090	6.88	31.4	55.4	2,288.57	7.42	35.1	53.2	2,263.53
2100	7.09[a]	32.8[a]	54.6[b]	2,279.03	7.76	37.4	52.0	2,248.03

Reference State (year 2010): Mean EC_e = 5.53 dS m^{-1}; Max EC_e = 23.0 dS m^{-1}; Mean RPI = 61.2 %; Mean Gross Profit: 2,359.38 € ha^{-1}

a: corresponds to Figure 3; *b*: corresponds to Figure 5.

Table 4. Model predicted values of soil salinity (EC_e, dS m^{-1}) and Rice Production Index (RPI, %) for the RCP 8.5 (increasing radiative forcing) SLR scenarios. Mean and maximum EC_e, mean RPI, and mean profit (€ ha^{-1}) values are shown.

	RCP 8.5											
	Mean SLR scenario (50 % probability of being exceeded)				**High SLR scenario (33 % probability of being exceeded)**				**Upper Limit SLR scenario (5 % probability of being exceeded)**			
	EC_e				EC_e				EC_e			
Year	Mean	Max	RPI	Profit	Mean	Max	RPI	Profit	Mean	Max	RPI	Profit
2025	5.79	24.5	60.0	2,343.43	5.87	25.0	59.7	2,339.85	6.03	26.0	58.9	2,330.31
2030	5.86	24.9	59.7	2,339.85	5.95	25.5	59.3	2,335.08	6.18	26.8	58.3	2,323.15
2040	6.01	25.8	59.0	2,331.50	6.15	26.7	58.4	2,324.35	6.54	29.2	56.8	2,305.27
2050	6.20	27.0	58.2	2,321.96	6.40	28.3	57.4	2,312.42	7.04[a]	32.4[a]	54.8[b]	2,281.42
2060	6.42	28.4	57.2	2,310.04	6.71	30.2	56.1	2,296.92	7.71	37.1	52.2	2,250.41
2070	6.70	30.2	56.1	2,296.92	7.09	32.8	54.5	2,277.84	8.64[a]	44.0[a]	48.9[b]	2,211,06
2080	7.02	32.3	54.8	2,281.42	7.57	36.1	52.7	2,256.37	9.91	54.4	44.8	2,162.16
2090	7.40	34.9	53.3	2,263.53	8.15	40.3	50.6	2,231.33	11.72	71.3	39.8	2,102.54
2100	7.84	38.0	51.7	2,244.45	8.88	45.9	48.1	2,201.52	14.36[a]	100.3[a]	33.8[b]	2,030.99

Reference State (year 2010): Mean EC_e = 5.53 dS m^{-1}; Max EC_e = 23.0 dS m^{-1}; Mean RPI = 61.2 %; Mean Gross Profit: 2,359.38 € ha^{-1}

a: corresponds to Figure 3; *b*: corresponds to Figure 5

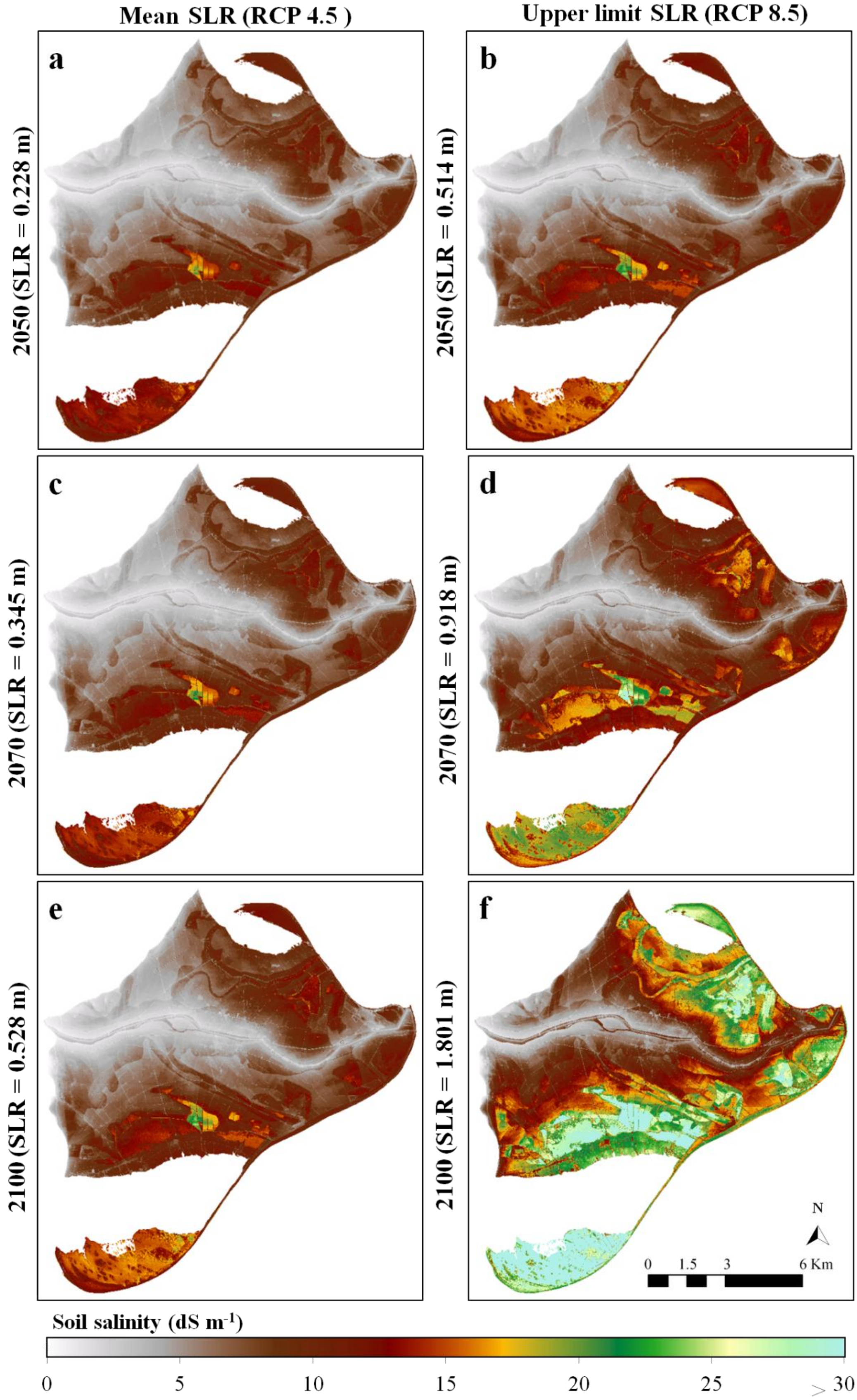

Figure 3. Distribution of estimated soil salinity in the Ebro Delta under different SLR scenarios. The modeled scenarios shown in the figure are the mean RCP 4.5 and the upper RCP 8.5. The remaining scenarios and years are shown in Supplementary Figure 1.

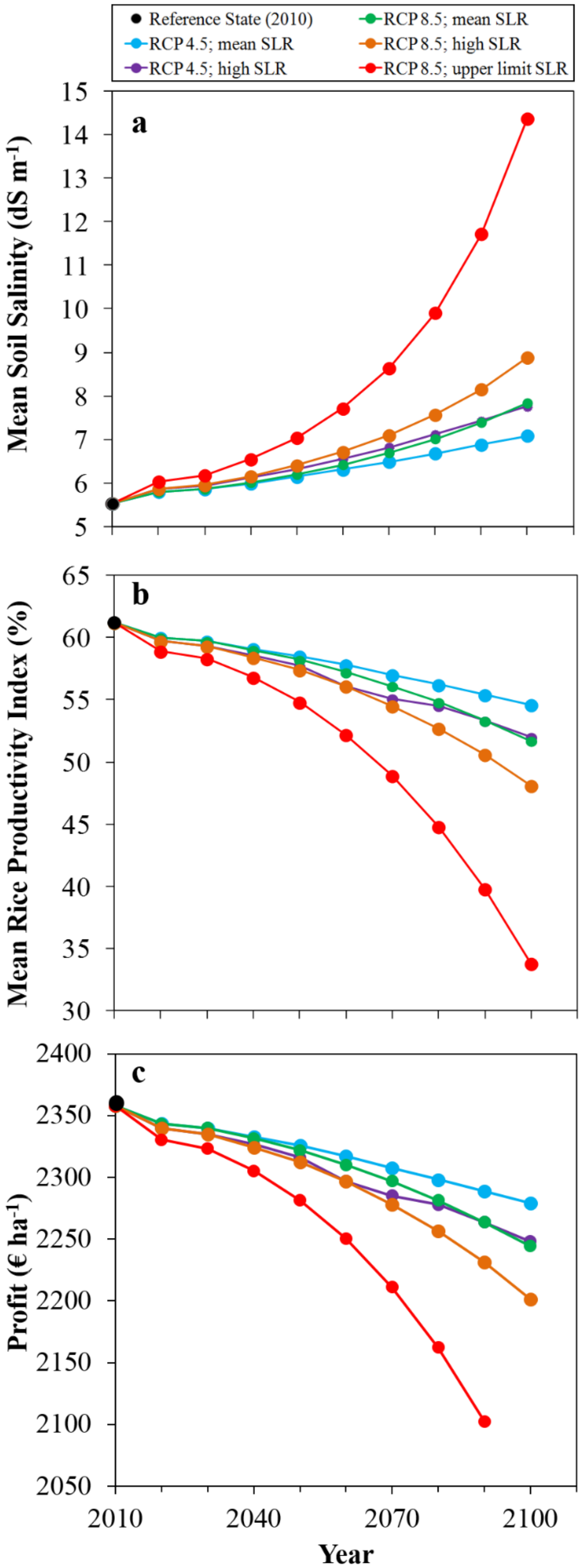

Figure 4. Estimated mean value of soil salinity (**a**); mean RPI (**b**); and mean profit (**c**) along the 21st century under the simulated SLR.

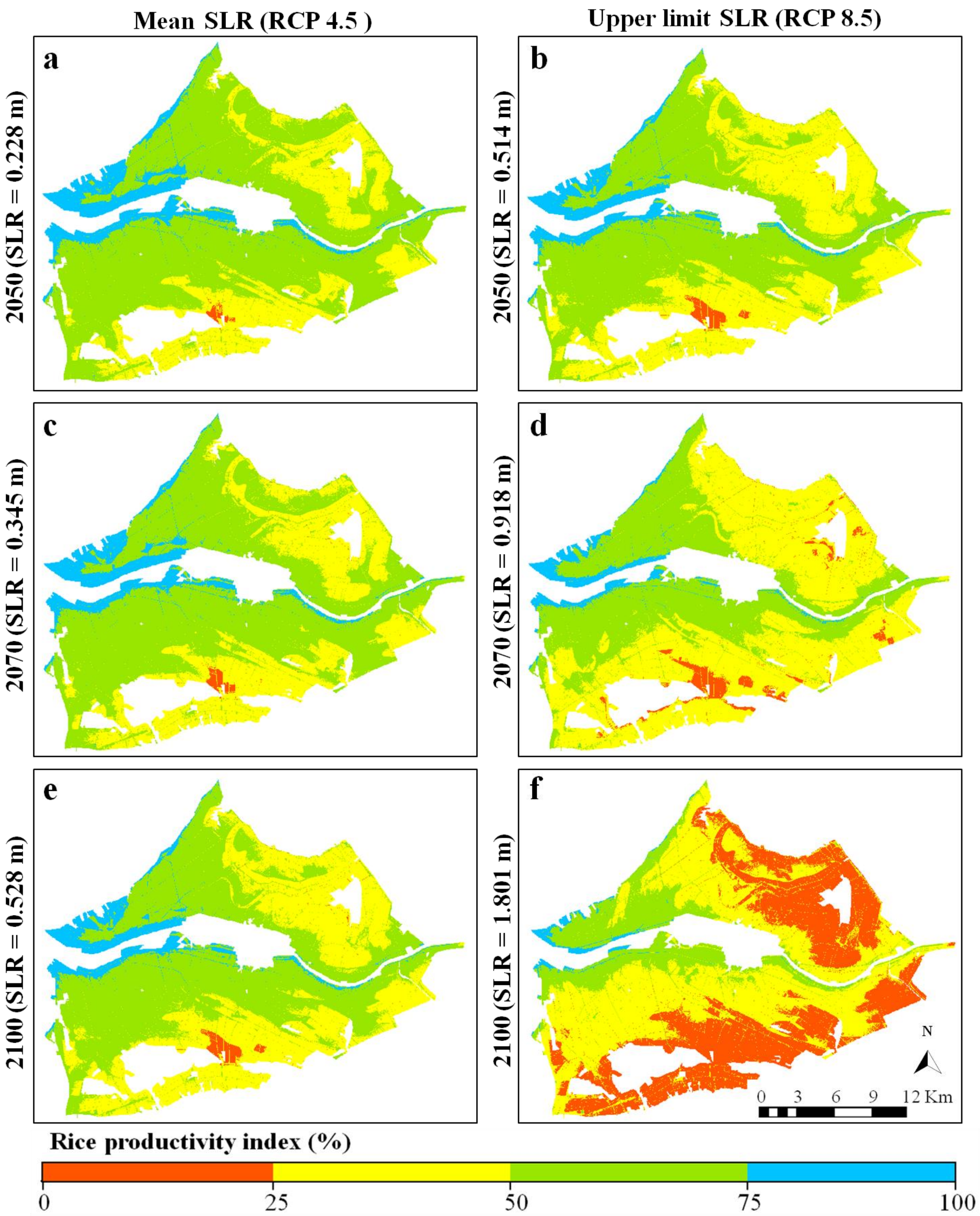

Figure 5. Distribution of estimated RPI in the Ebro Delta rice fields under the different SLR scenarios. The modeled scenarios shown are the mean RCP 4.5 and the upper limit RCP 8.5. The remaining scenarios and years are shown in Supplementary Figure 2.

Response of rice production to sea level rise scenarios

Table 3 and Table 4 show results of rice production for RCP 4.5 and RCP 8.5, respectively. Results of estimated rice production across the delta under SLR scenarios are shown in Figure 5. All simulated scenarios show a clear production gradient, from the most productive areas along the Ebro River to the lowest values along the shoreline and the surroundings of salty coastal lagoons. The RPI gradient is opposite to soil salinity, with maximum values attained in areas of low soil salinity. Consequently, the common trend in all scenarios is a decrease of rice production following the increment in soil salinity (Figure 4b). Compared to the reference state (Figure 1e), by 2100, the mean RPI is reduced from 61.2 % to 54.6 % and 52.0 % for the mean and high SLR scenarios (RCP 4.5), respectively. In the RCP 8.5 scenarios the reduction is greater with RPI values of 51.7 %, 48.1 % and 33.8 % for mean, high and upper SLR scenarios, respectively (Table 4) by 2100. The lowest values of productivity, 0-25 %, are located in the southern hemidelta; these values are not found in the northern hemidelta until SLR increases half a meter. Hence, the southern hemidelta is more vulnerable to SLR whereas the northern shows more resilience due to a higher land elevation. In the worst considered scenario (Figure 5f), about 30 % of the rice fields can be highly impacted by saline intrusion.

Discussion

Responses of soil salinity and rice production to sea level rise scenarios

Six variables out of 21 were significantly affecting soil salinity and rice production according to the statistical analysis. Surface elevation was the most influent variable in determining soil salinity which allows simulating SLR scenarios. This is the case for most of deltas because of their topography, since fresher habitats are usually located close to the river banks (which are the highest areas) and saltier habitats are at sea level and close to the sea or coastal lagoons. In the Ebro Delta, clay soils presented lower salinity values, and it is well stablished that finer soil are more resilience to salt intrusion than coarser soils (Casanova, 1998). Therefore, topsoils of deltaic areas tend to be permeable due to their high sand content; this together with their low elevation allows underground (subsurface) salt intrusion to advance rapidly and reach the root zone of the rice plant. Under a SLR scenario, rice plants respond negatively, since the interface of the salt wedge goes up and the rice plant undergoes stressful conditions leading to lower productivity (Casanova et al., 1999).

The winter flow of the Ebro River was also an influencing variable (but weaker than elevation) in terms of impact on soil salinity. The inverse relationship found between the winter flow and soil salinity may be linked to the management conditions of most temperate rice fields in deltas. Farmers dry up rice paddies in winter and reduce water table to prepare the land for the next season, often with the use of pumping stations, thus allowing salt intrusion to penetrate underground from the estuary. The situation is even worse if river flow is not high enough to prevent salt wedge incursion. Results also show that an increase in soil salinity leads to a decrease in rice production, in accordance with the existing literature (Khan et al., 1992; Lazar et al., 2015). Asch et al., (1995) found a physiological explanation to this negative relationship in the rice plant: the high soil electrical conductivity reduces stem base water potential, and this is followed by the release of root-borne abscisic acid to the xylem eventually resulting in stomatal closure. In the Mekong Delta, seasonal impacts of SLR often push salinity beyond the physiological limits of the rice plant (Wassmann et al., 2004); in the Nile Delta salt-crusted sabkhas form in most of delta plain, comprising about 63 % of agricultural area (Eladawy et al., 2015); and the Rhone Delta undergoes similar salt stress as the Ebro Delta, with the need to supply large fresh water inputs to the rice fields to keep soil salinity low (Poumadère et al., 2008).

Model results predict a significant decrease in productivity as sea level increases. This loss of productivity reaches 30 % in 2100 for the most pessimistic scenario (RCP 8.5, upper limit). In the most impacted areas, rice production could become economically unfeasible before the end of this century, even if the present European Union subsidies that rice farmers receive are continued. The economic loss due to the impact of SLR on rice production will be larger in the areas with lower surface elevation and higher soil salinity. From a mean gross profit of 2,359.38 € ha^{-1} in the reference state, by 2100 the profit decreases to 2,279.03 € ha^{-1} in the RCP 4.5 mean scenario, and to 2,030.99 € ha^{-1} in the RCP 8.5 upper limit scenario (Figure 4c). Temporal patterns of mean soil salinity, rice production, and its consequent decrease in profits through time show that under extreme scenarios there would be an acceleration of impacts at the second half of the century (when SLR reaches more than 0.5 m), and this change of dynamics could be considered a tipping point (*i.e.* the critical point that leads to a new and irreversible situation) both for impacts and adaptation, thus the rise of sea level above 0.5 m can be established as a threshold in the management of the Ebro Delta rice fields.

Model limitations and further improvements

One of the model gaps is that the subsidence process has not been considered due to the lack of reliable data across the Ebro Delta, though some general estimates are available (Ibáñez et al., 1997). In that sense, we are developing a subsidence model based on satellite elevation data measured in the last 30 years. On the other hand, the model has not included the loss of delta surface by sea flooding, which can be relevant in the future in case that coastal defense are not built or upgraded.

A relevant improvement of the model that is under development is the simulation of the introduction of fluvial sediments into the rice fields via the irrigation network to promote vertical accretion and elevation gain. This elevation capital (*i.e.* the stock of natural resources that permits the stability and resilience of a system) is a way to increase resilience of coastal habitats against SLR (Cahoon et al., 2010). According to IPCC projections changes in meteorological variables than could affect river flow are expected, for instance the regional precipitation pattern and drought duration and severity. Thus a detailed analysis of meteorological parameters can enhance winter flow predictions, and thus improving model predictions. The model also includes geographic variables such as distance to the shoreline or to the river and results show that soil salinity and rice production are sensitive to those variables.

Given the nature of rice production and the Ebro Delta, model results can be extrapolated to other deltaic areas worldwide and site specific models can be developed, by obtaining digital imagery information, soil salinity data and rice production information from farmers.

Implications for adaptation and management

The following adaptation measures are being applied or considered to reduce the impacts of SLR on soil salinity and rice production in the Ebro Delta (see Alvarado-Aguilar et al., 2012; Cardoch et al., 2002; Ibáñez et al., 2010; Rovira and Ibáñez, 2007; Sánchez-Arcilla et al., 2008): (1) increasing water pumping and turnover to avoid high water level and salt stress in the rice fields, (2) building coastal defenses to avoid flooding (but not salt intrusion) during high sea level periods, (3) delivery of fluvial sediments to increase soil elevation (vertical accretion) and to prevent salt stress, and, (4) habitat restoration: convert the most impacted rice fields (low elevation) into wetlands, as rice production becomes unsustainable in those areas. For instance, wetlands have been recently created in the Ebro Delta in rice fields located below sea level.

Agricultural adaptation to salinity stress will be necessary in most of the world's deltas so results from the present research can be of interest to other similar areas. In the coast of Bangladesh, Clarke et al., (2015) proposed to develop salt tolerant varieties of some crops like rice, and this is something that is also being investigated in the Ebro Delta (Català et al., 2013). In recent years, advances in agronomical molecular biology have obtained achievements related to rice genome mapping for the development of new varieties more suitable for salty soils (Ferrero 2007).

The recovery of sediment fluxes from the Ebro River to the delta in order to increase vertical accretion in the rice fields is another adaptation measure, which actually was used in the past by farmers to promote soil fertility and reduce salinity (Ibáñez et al., 2014). However, to undertake such a measure under present conditions a system to by-pass sediments trapped in the reservoirs would be required, since more than 99 % of the sediment flux is retained in the Ebro basin reservoirs (Rovira and Ibáñez, 2007). In the Mississippi Delta controlled diversions of river floods are currently carried out to deliver suspended sediment in order to enhance wetland accretion to face salt intrusion in the delta plain (Day et al., 2011).

Future SLR is expected to have major consequences on coastal crops even with adaptation measures, and as rice is the world's number one stapler crop, it will be relevant in economic terms. This is especially significant for the case of pessimistic scenarios of SLR corresponding to extreme scenarios of climate change. Interestingly, this would also allow modelling the response of soil salinity and rice production to coastal retreat (which is occurring in most of deltas) and to changes in the river course.

Conclusions

We developed a soil salinity model to forecast the impacts of SLR on the Ebro Delta rice fields by the end of the 21st century under different scenarios. This is the first work investigating the response of rice fields to SLR that is based on salt intrusion rather than on crop inundation. In order of importance, results indicated that surface elevation was the most influencing variable in soil salinity, followed by winter flow, clay presence, distance to the river, distance to the delta inner border and distance to the river old mouth

Our model predicts a reduction in rice production, with its consequent economic loss, related to an increase in soil salinity due to an elevation loss, which is larger in areas near the coast and lower near the Ebro River. This decrease in rice production is similar in all the simulated scenarios, except for the upper limit (SLR = 1.8 m), where the larger reduction is observed. Soil salinity is expected to increase by three-fold in the worst considered scenario by the end of this century. It is clear that some adaptation measures will be necessary to cope with SLR, such as the construction of dikes or the supply of fluvial sediments to increase rice fields' elevation.

The model presented here can help to provide a better understanding of how rice fields will be impacted by SLR, being useful for rice farmers and decision makers. Despite model limitations, we show that soil salinity and rice production across the Ebro Delta as a consequence of future SLR can be simulated in a realistic way, and a GIS-statistical model combination is a helpful tool for detecting the most sensitive areas to SLR impacts.

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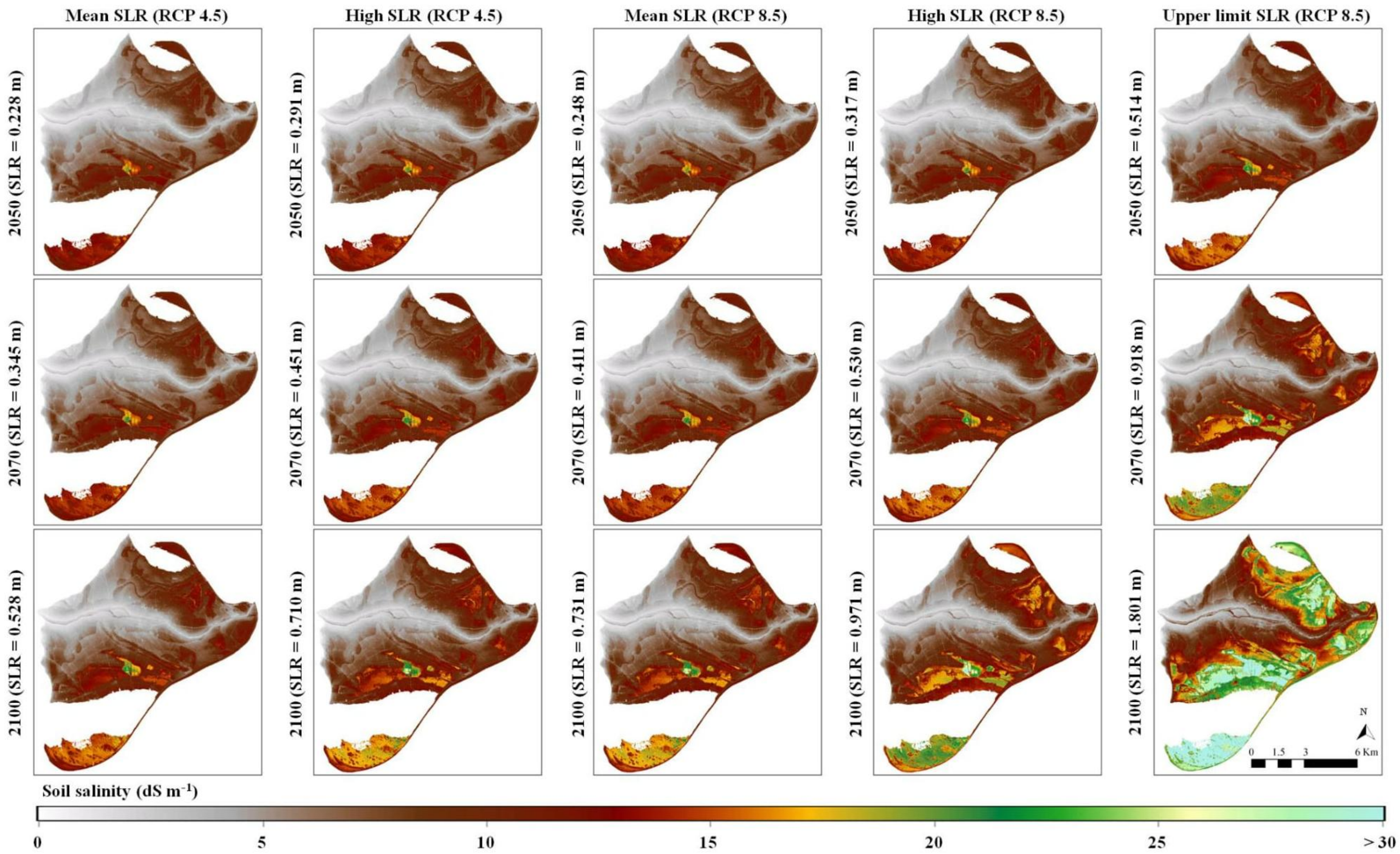
Supplementary Table 1. Soil salinity (EC_e) equation parameters obtained from the Generalized Linear Models (GLMz) for the two candidate models. Average-predicted values are obtained by weighting each component model predictions by AICc weight (***w***$_i$). All models variables were log-transformed prior the analysis. See methods for more details on model averaging procedures.

	Regression coefficients (β)	
Model Parameter	$w_i = 0.69$	$w_i = 0.31$
Intercept	2.218	2.082
Clay presence	0.117	0.122
Euclidean distance to the Ebro River (m)	0.108	0.112
Euclidean distance to the inner border (m)	0.069	0.073
Euclidean distance to the old mouth (m)	Not selected	0.005
Winter flow (m3 s-1)	0.215	0.214
Surface elevation (m)	2.618	2.561

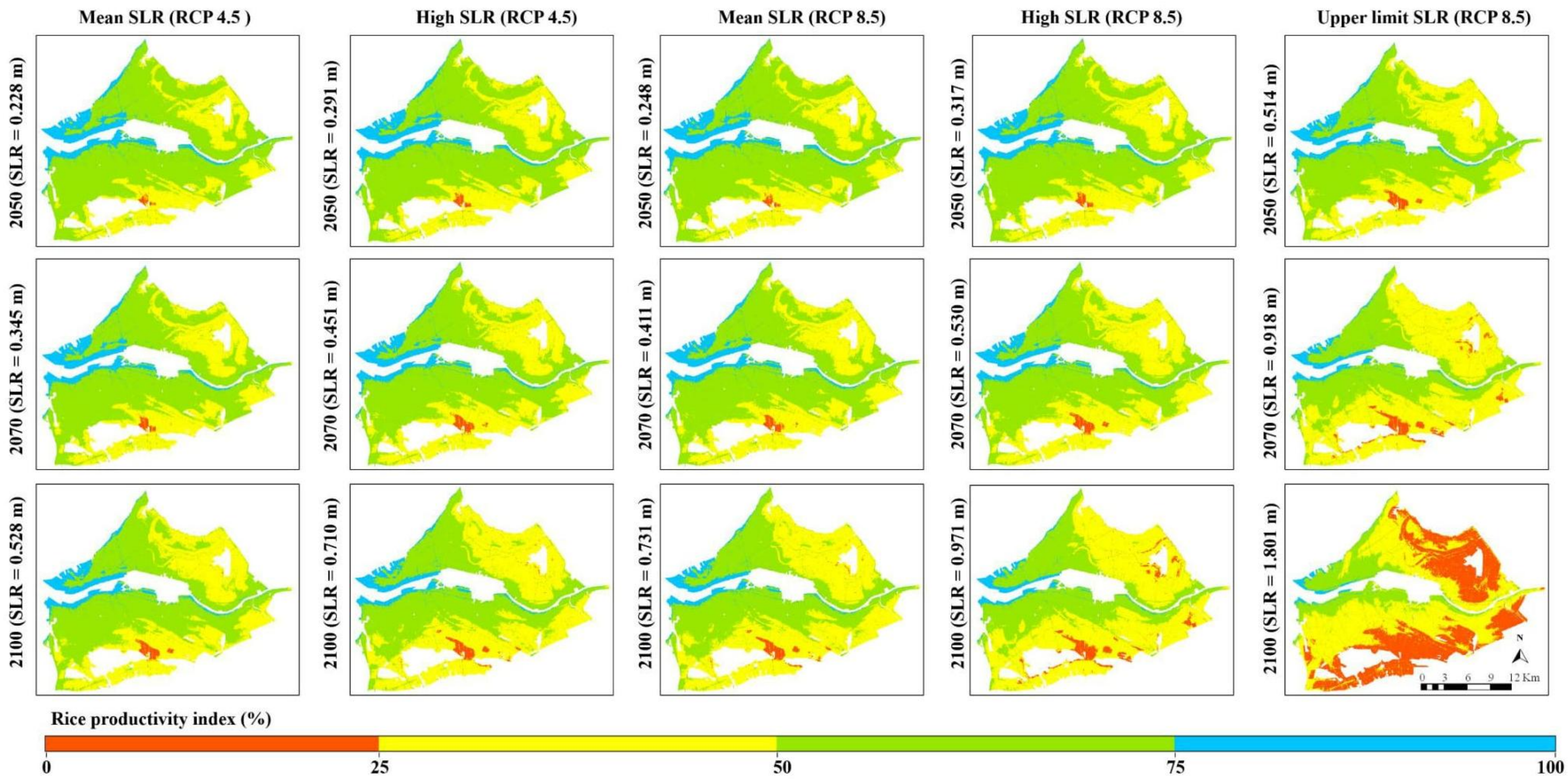
Supplementary Table 2. Full list of the variables initially included in the soil salinity model obtained from the Generalized Linear Models (GLMz). Quadratic and cubic components of all continuous variables were also included in the model.

Variables initially included in the model
1- Location of the sample point (north, south)
2- Surface elevation in 2010 (m)
3- Surface elevation in 2010 (interpolated) (m)
4- Distance to the Ebro River (m)
5- Distante to the mouth (m)
6- Distance to the old mouth (m)
7- Distance to the shoreline (m)
8- Distance to the northern border (m)
9- Distance to the southern border (m)
10- Distance to the inner border (m)
11- Distance to nearest coastal lagoon (m)
12- Winter flow ($m^3 s^{-1}$)
13- Winter precipitation (mm)
14- Clay presence
15- Silt presence
16- Sand presence
17- Gravel presence
18- Organic matter presence
19- Peat presence
20- Block presence
21- Pebbles presence

Supplementary Figure 1. Distribution of predicted soil salinity in the Ebro Delta for the RCP 4.5 and RCP 8.5 SLR scenarios. All scenarios obtained from the AR5 IPCC, except the upper limit scenario obtained from Jevrejeva et al. 2014.



Supplementary Figure 2. Distribution of predicted RPI in the Ebro Delta for the RCP 4.5 and RCP 8.5 SLR scenarios. All scenarios obtained from the AR5 IPCC, except the upper limit scenario, obtained from Jevrejeva et al. 2014.



Chapter 2

EVALUATING NATURE-BASED ADAPTATION OPTIONS TO SEA LEVEL RISE AND BENEFITS TO AGRICULTURE IN THE EBRO DELTA

Genua-Olmedo et al., 2017. Evaluating nature-based adaptation options to sea level rise and benefits to agriculture in the Ebro Delta (*in preparation*).

Abstract

Sea level rise (SLR) is threatening low-lying coastal areas such as deltas by increasing the risks of flooding, coastal retreat, and salt intrusion. The Ebro Delta is representative for coastal systems that are particularly vulnerable to SLR, due to significant sediment retention (up to 99 %) behind dams in the upstream river catchment, thereby dramatically reducing the capacity for deltaic sediment accretion with SLR. 66 % of the delta area is used for rice production, the main economic activity, which is negatively affected by SLR because of flooding and soil salinization. Therefore, it is necessary to develop appropriate adaptation measures to preserve rice production and the delta's morphological and ecological integrity. We coupled data from Geographic Information Systems with Generalized Linear Models to predict the impacts of SLR on the Ebro Delta, which zones are prone to flooding and increased soil salinity, and the so-called sediment deficit, that is the amount of sediment that would be needed to raise the land in order to compensate this flooding and soil salinization. We modeled different SLR scenarios considered by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, and analyzed the feasibility of reintroducing fluvial sediments, retained in the lower basin reservoirs, into the delta plain rice fields to maintain land elevation and rice production. We made a simplified economic analysis, by estimating the costs related to different sediment reintroduction measures and their benefits in terms of avoided loss of income from rice production. Our flood model predicted that between 36 and 90 % of the rice field area will be flooded in the best and worst SLR scenarios considered (SLR = 0.52 m and 1.8 m by 2100, respectively), corresponding to a sediment deficit ranging between 130 and 442 million tonnes by 2100 (with annual rates ranging from 1.4×10^6 to 4.9×10^6 tonnes per year in the best and worst scenarios, respectively). The proposed nature-based adaptation measure (rising grounds) would also have a positive effect on rice production and can be considered as an innovative management option for maintaining Ebro Delta ecosystem services under SLR.

Keywords: climate change; sediment deficit; rice production; wetlands; flooding; coastal adaptation.

Introduction

Global warming causes polar ice to melt and consequently sea level to rise. This increase in sea level will continue and accelerate through the 21st century and beyond, but their magnitude remains uncertain (Nicholls and Cazenave, 2010). Sea level rise (SLR) poses a serious threat to low-lying coastal areas, which are home to ten percent of the world's population (McGranahan et al., 2007). The situation is especially dramatic in river deltas (Giosan et al., 2014; Tessler et al., 2015), which are inhabited by more than 500 million people worldwide (Rogers et al., 2013) and which are major centres of agriculture (Pont et al., 2002) and other highly valuable economic activities. The physical impacts of SLR are well known (Nicholls et al., 2007), and are associated to increasing risks for flooding, coastal retreat, saltwater intrusion into groundwater, and reduction of wetlands due to habitat changes. These impacts are exacerbated by human-driven changes in the river basin (Day et al., 2016; Syvitski et al., 2009), such as river channelization, river water diversion for irrigation, and river damming, which have altered deltaic environments (Anthony et al., 2014; Nicholls and Cazenave, 2010). The reduction of sediment supply to river deltas, mainly due to upstream river damming and therefore blockage of downstream sediment transport causes coastal erosion and reduces vertical build up of the delta plain (Anthony et al., 2014; Syvitski et al., 2005) with rising sea level.

Nature-based solutions involve the facilitation of sediment supply and deposition to the delta plain are increasingly recognized as a potential strategy to adapt and mitigate to SLR (Chapman and Darby, 2016; Ibáñez et al., 2014; Giosan et al., 2014). This concept arose from previously proposed management actions to adapt to SLR in deltas such as the Mississippi and Mekong (Day et al., 2005; MDP, 2013). In the Mississippi Delta, large wetlands area are submerging due to relative sea level rise and sediment supply reduction to the deltaic wetlands. Here, adaptation is based on the use of dredged sediments for wetlands restoration and nourishment, on pumping the sediments over long distances despite the associated high financial and energy costs, and on diverting sediment-rich river water again into the deltaic wetlands (CPRA, 2012). In other large deltas such as the Mekong Delta, nature-based solutions have not yet been systemically evaluated because they may conflict with other local non-adaptation oriented objectives, such as achieving maximum short-term agricultural production and flood protection (Chapman and Darby, 2016).

The aim of this paper is to evaluate nature-based adaptation options to SLR based on fluvial sediment supply, for the specific case of the Ebro Delta (Spain). Existing studies have analyzed the feasibility of implementing adaptation strategies based on introducing fluvial sediments into the Ebro Delta plain (*i.e.* Martín-Vide et al., 2004; Rovira and Ibáñez, 2007), but yet there is no information available about the specific quantity of sediment required across the delta and over time to maintain the Ebro Delta elevation under different SLR scenarios. The principal aims of this paper are: (1) to identify areas at risk of flooding due to different SLR scenarios; (2) to calculate the volume of sediment that would be needed to build up land under SLR assuming the following two considerations: the first is maintaining the Ebro Delta elevation relative to mean sea level as in the current state (2010); and the second is only raising land in the flooded areas and just enough to compensate for the SLR; and (3) to analyze the costs and benefits (in terms of agricultural income) of the proposed sediment management measures, and the economic feasibility of implementing them. SLR scenarios up to 2100 are selected according to AR5 IPCC projections (Church et al., 2013), as well as the upper limit scenario proposed by Jevrejeva et al., (2014) has been also included.

Materials and methods

Study area

The Ebro River (910 km long) is located in the NE Iberian Peninsula and drains an area of *ca.* 85,362 km^2. With a mean annual discharge of 426 m^3/s, it is the river with the highest discharge in the Iberian Peninsula. The river flow and sediment transport are modulated by the presence of *ca.* 200 large dams, mainly built for hydroelectric and irrigation purposes. In the lower Ebro River the construction of two large dams in the 1960s, Mequinensa and Riba-Roja (*ca.* 100 km upstream from the river mouth, Figure 1), have modified the river flow and prevent sediment transport. Consequently, present river discharge is *ca.* 30 % lower than original, and 99 % of the sediment is retained by dams (Rovira and Ibáñez, 2015). Hence, this leads to a dramatic reduction in sediment deposition in the delta plain, which mostly consists of rice fields that are irrigated by the Ebro River. Thus, the delta is no longer able to grow seaward and vertically, and suffers from an intense reshaping of the coastline by wave erosion (Sánchez-Arcilla et al., 2008). The Ebro Delta is one of the largest deltas in the NW Mediterranean Sea, with a surface area of about 320 km^2. It is a low-lying area characterized by an elevation gradient that ranges from *ca.* +5 m close to the river bank, to an elevation of 0.5 m down the coastline (50 % of the delta, Figure 1). The Ebro Delta supports a high diversity of ecosystems (*e.g.* wetlands and lagoons), waterfowl and wildlife, and socio-economic activities such as tourism, fishing and aquaculture. Wetland area has been reduced due to the conversion to agriculture. Rice is the predominant crop (*ca.* 210 km^2 of the total deltaic surface, Figure 1), with an average production of *ca.* 6339 kg per hectare (MAGRAMA, 2017). Fresh water from the Ebro River is diverted to the rice fields by gravity from a weir located 60 km upstream of the river mouth (Figure 1), and is transferred to the delta plain by two irrigation channels that run parallel to the river course and branch into a network of irrigation channels spreading out over the delta plain (Figure 1).

Flood model

The Ebro Delta areas at risk of flooding due to SLR were determined by analyses in a Geographical Information System (GIS) using a Digital Elevation Model (DEM) based on elevation data from 2010 (hereafter referred as the reference state). The DEM (Figure 1), with a spatial resolution of 1×1 m and a height accuracy of 15 cm, was developed by the Cartographic and Geological Institute of Catalonia (ICGC) using LIDAR methodology. Elevation data were referred to mean sea level in Alicante datum. Cartographic databases were also used to identify the delta areas connected to water bodies (*e.g.* sea/river/lagoons), and the Ebro Delta habitats were classified according to the CORINE Land Cover Mapping (Bossard et al., 2000) (Figure 1). The Ebro Delta habitats were then reclassified in two categories: (1) rice fields (covering up to 66 % of the delta), and (2) other deltaic areas including wetland vegetation (*e.g. Phragmites spp* and *Salicornia spp*), arable and woody crops, beaches, and dunes.

Every cell elevation located below mean sea level was initially classified in two categories: (1) below mean sea level with direct connection to water bodies; and (2) below mean sea level with no direct connection to water bodies. For modeling purposes, both categories were merged since in unconnected cells below mean sea level, flooding due to rise of groundwater is expected and the number of unconnected cells was negligible compared to those from the first category. Tidal effects were not considered since the Ebro Delta is a micro-tidal environment, with an average tide of 16 cm (Cacchione et al., 1990).

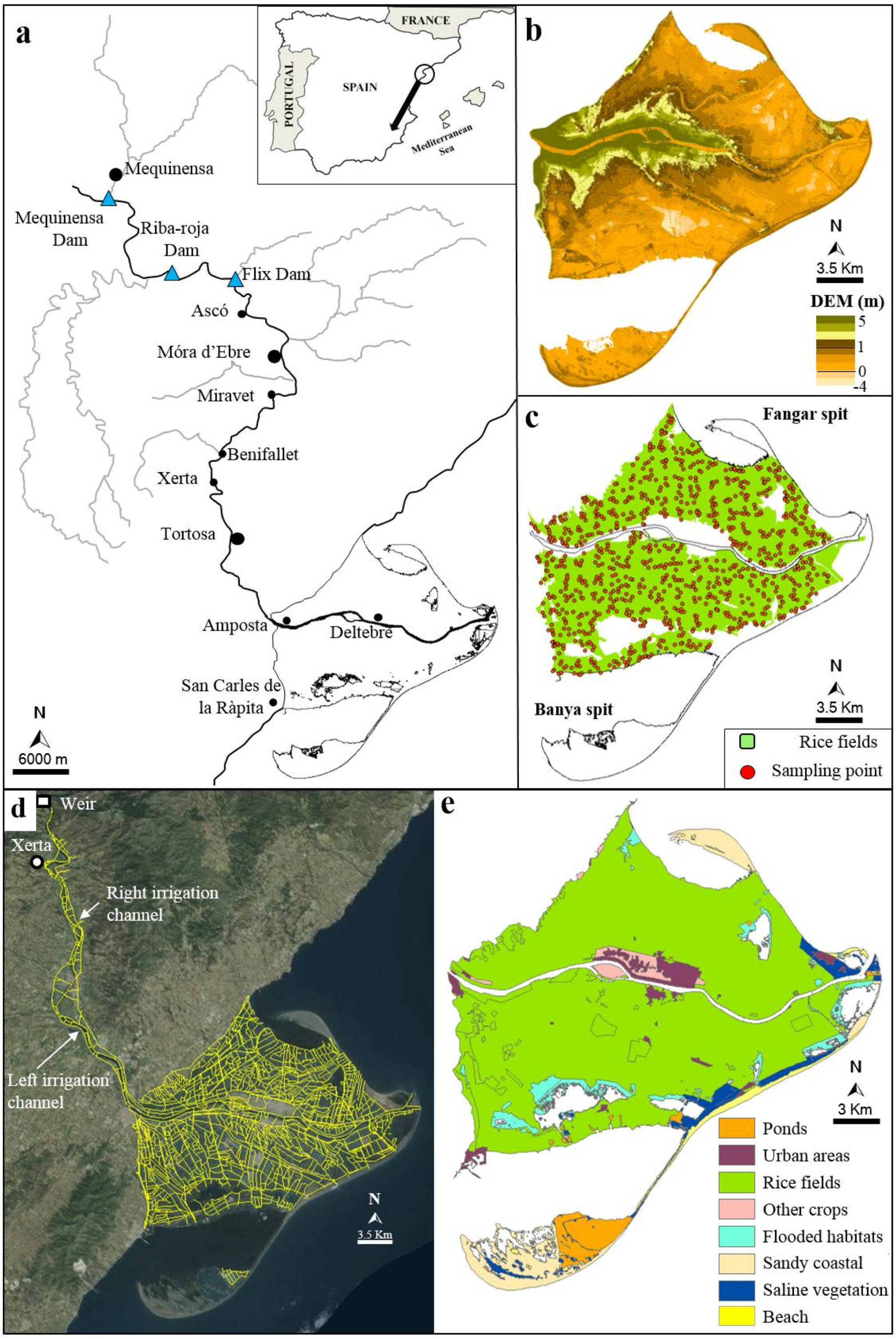


Figure 1. Location of the Ebro Delta (**a**); the Digital Elevation Model (DEM, m relative to mean sea level) (**b**); distribution of the rice fields along with organic matter sampling points (**c**); irrigation channels network (**d**); and habitats distribution (**e**).

Estimation of the sediment deficit volume

The volume of sediment that would be needed to build up land with SLR (further referred to as the sediment deficit volume, m^3) was spatially calculated in the Ebro Delta. Two different scenarios were modeled for the estimation of the sediment deficit volume: Scenario 1 (SC1) considered the total volume needed to maintain the deltaic surface elevation relative to mean sea level as in the reference state; and Scenario 2 (SC2) considered the total volume needed to raise land only in the flooded areas and just enough to compensate for the SLR. This sediment deficit volume is calculated as follows:

for SC1: $V_i = SLR_i \times A$

for SC2: $V_i = (SLR_i - Zpixel_{i-1}) \times A$ for $Zpixel_{i-1} \leq SLR_i$

, where V is the sediment deficit volume (m^3), *i* is a given modeled time step, thus *i*-1 is the previous time step, SLR is the sea level rise (m) at time *i*, A is the pixel area (m^2), and Zpixel is the pixel elevation (m) from the Digital Elevation Model.

Economic analysis

The economic analysis was based on the estimated costs of carrying out the proposed sediment management measure versus the benefits in terms of maintenance of rice production in the Ebro Delta. The economic costs, in €/m^3 of sediment deficit volume, included the costs of extraction and transport of the sediment from the Riba-Roja reservoir to the Ebro Delta. Different techniques of transport (Table 1) summarized in Martín-Vide et al., (2004) were considered. The economic impact on rice production were assessed following the models developed by Genua-Olmedo et al. (2016). Briefly, authors established a statistical relationship between soil salinity (that was related to SLR) and rice production in the Ebro Delta. Then, because rice production (in kg ha^{-1}) varies year by year due to environmental factors such as meteorology; rice production data were normalized in a rice production index (RPI). RPI ranged from 0 (minimum observed production, 5814 kg ha^{-1}) to 100 (maximum observed production, 10,073 kg ha^{-1}), and it was validated with the rice farmers data. The estimated income (€ kg ha^{-1}) for a given scenario was calculated by multiplying the RPI by the maximum rice production observed and 0.28 €, the price per kilogram of rice paid to farmer.

Table 1. Costs of sediment extraction and transport from the Riba-Roja Reservoir to the Ebro Delta. Cost considers the cheapest (minimum) and the most expensive (maximum) sum of the different costs. Data were obtained from Martín-Vide et al., 2004.

Method	Extraction cost (€/m^3)	Transport cost (€/m^3)		Additional cost (€/m^3)	Min. cost (€/m^3)	Max. cost (€/m^3)
Mechanic dredging	7.2-8.3	Boat	2.3	3.1-8.3	12.6	28.8
		Road	12.	3.1-8.3	12.6	28.8
Suction dredging	3.1-13	Pipe	1.4	3.1-8.3	7.6	22.7
Flusing	0.54		0	0	0.54	0.54

Bulk density and organic matter estimation

For a better interpretation of the results, the sediment deficit volume (V, m^3) was converted to sediment deficit mass (S, kg) by using the following equation: S = V × BD, where BD is the bulk density (g/cm^3). Several studies have shown that bulk density is highly related to organic matter content of sediments (Curtis and Post 1964; Périé and Ouimet, 2008), thus we used data of bulk density and organic matter content from 25 rice fields sampled between 2015 (15) and 2016 (10), and 35 wetlands sampled in 2009 (11) and 2015 (24). Different published regression fits were tested (see Supplementary Table 1), and a modified logarithmic function from Perie and Ouimet (2008) was selected. Selection was done following the criterion of maximization of Pearson's correlation coefficient between observed and predicted values of bulk density (Figure 2a). 75 % of the data were used in the calibration process, and 25 % in the validation. The selected regression equation was:

$BD = -0.970 + 1.033 \times OM - 0.912 \times \ln(OM) - 0.095 \times [\ln(OM)^2]$; Pearson's $r = 0.86$, $N = 125$, $P < 0.0001$

, where BD is the bulk density (g/cm^3), and OM is the organic matter content (g/g soil).

In order to build a spatial distribution model of the OM, we obtained data from 900 different rice fields (Figure 1), sampled by the "Agrupacions de Defensa Vegetal of Catalonia" during the 2003–2007 period. The relationship between OM and soil descriptors (see Supplementary Table 2) was analyzed with Generalized Linear Models (GLMz). An information-theoretic approach was used to find the best approximating models following the methodology described by Burnham and Anderson (2002). GLMz were built including all possible combinations of independent variables, excluding interactions, due to the large number of variables included. Two additional criteria were used to define the best candidate models: (1) only those models performing significantly better than the null model (*i.e.* the model including only the intercept), by a likelihood-ratio test, were considered, and to avoid multicollinearity effects (2) models with a variance inflation factor of > 5 were not selected (Brockwell and Davis, 2002; Maggini et al., 2006). The degree of support of each candidate model was assessed with the second order Akaike Information Criterion (AICc); and then AICc was rescaled to obtain ΔAICc values ($\Delta AICc = AICc_i$ – minimum AICc). For the current analysis we examined in detail the set of models with $\Delta AICc \leq 4$, since models with $\Delta AICc > 4$ have less support and might be omitted from further consideration. Then, the relative plausibility of each candidate model was assessed by calculating Akaike's weights (w_i); w_i ranges from 0 to 1, and can be interpreted as the probability that a given model is the best model in the candidate set. Because no model was clearly the best one (*i.e.* $w_i \geq 0.9$), we calculated model-average regression coefficients (β_i) by weighing selected model coefficients by model w_i. The relative importance of each variable was also calculated by the sum of w_i for all models in which a given variable occurs, which estimates the importance of an independent variable for differentiating the response variable (see Burnham and Anderson, 2002). Finally, model-averaged estimates were compared with regression coefficients from the full model to assess the impact of model selection bias on parameter estimates (Whittingham et al., 2005). For all of the candidate models the full model residuals were tested for normality through the Shapiro-Francia normality test; the residuals of all models were normally distributed ($P \geq 0.20$). Prior to analysis, quantitative variables were log-transformed to improve linearity and homoscedasticity. All statistical analyses were performed with R software version 3.4.0 (R Core Team 2016); MuMIn 1.15.6 was used for multi-model inference analysis; car 2.1-4 was used for variance inflation factor analysis of each of the candidate models; and Nortest 1.0-4 was used for normality test analysis.

Model efficiency was quantified with Pearson's correlation coefficient between observed and predicted values. The calibration process mostly consisted in optimizing regression models (GLMz) by introducing and deleting different model parameters (see Supplementary Table 2) to maximize Pearson's *r* values. Optimization of the fit eliminated most of the over-prediction. Model selection and calibration (Figure 2b) were done with 75 % of the data, and the remaining data (25 %) was used for model validation.

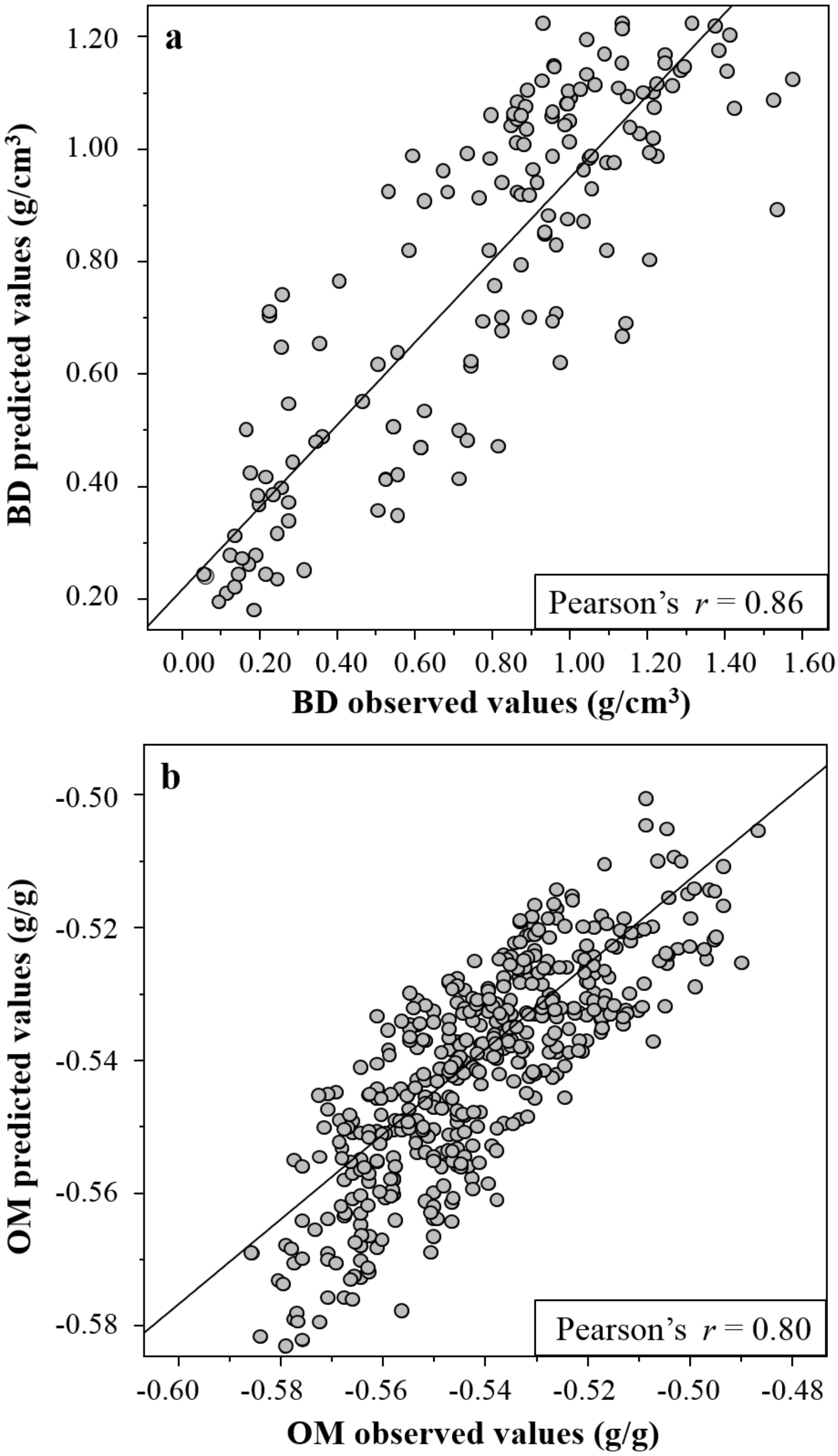


Figure 2. Relationship between predicted and observed values of soil bulk density (BD) (**a**), and soil organic matter content (OM) (**b**). Data were log-transformed and refer to the calibration process.

Sea level rise scenarios

The flooded area, sediment deficit volume and associated benefits of maintenance of rice production and costs of sediment supply were modeled under different SLR scenarios based on the projections of the Fifth Assessment Report (AR5) carried out by the IPCC, the Intergovernmental Panel on Climate Change (Church et al., 2013). Representative Concentration Pathways (RCPs) are different greenhouse gas (GHG) concentration trajectories adopted by the IPCC for AR5 modelling and used for climate change research. RCPs provide a quantitative description of concentrations of GHG emissions measured in CO_2 equivalents in the atmosphere over time, as well as their radiative forcing up to 2100 (Van Vuuren et al., 2011). Two RCPs were selected: the RCP 4.5 (stabilization) and RCP 8.5 (increasing radiative forcing). The former is a mitigation scenario, with an emissions peak around 2040 and then declining resulting in a mean global temperature increase o +2.4 ºC and mean SLR average over 2081 to 2100 of +0.47 m. The latter is a 'business as usual' scenario with emissions continuing to rise through the 21st century, resulting in a mean global temperature increase of +4.3 ºC and mean SLR average over 2081 to 2100 of +0.63 m (Church et al., 2013). Following Jevrejeva et al., (2014) we also included a worst case SLR scenario (called upper limit, hereafter), with a 5 % probability of being exceeded, resulting in a mean SLR by 2100 of +1.80 m. Model simulations were obtained for 2010 (reference state), 2025 and from 2030 to 2100 in 10-year steps (Supplementary Table 3).

Results

Flood model

The flood simulations identified the Ebro Delta areas prone to be flooded under the considered SLR scenarios if no adaptation measures are implemented. As expected a progressive inundation of the rice fields and wetlands was predicted up to 2100 (Figure 3; Supplementary Figure 1). In both SLR scenarios the inundation process started in lowland areas connected to water bodies (*e.g.* sea/river/lagoons), whereas the last flooded areas were those located along the river, characterized by higher elevations (Figure 3; Supplementary Figure 1). For the RCP 4.5 scenario, the flooded area showed a progressive increase over time reaching a maximum of 140 km^2 or 44 % of the total delta surface by 2100. For the RCP 8.5 inundation process was faster and the flooded area varied between 145 and 240 km^2 (or 45 and 75 % of the delta area) for the mean and upper limit SLR scenario, respectively (Figure 3). By 2100, the potential loss of rice field area (rice fields below mean sea level) ranged between 40-90 percent depending on the considered scenario (Supplementary Figure 1; Supplementary Table 4). Results also showed that for the mean and high SLR RCP 4.5 scenario, 50 percent of the rice fields would be below sea level by 2080 and 2050, respectively. For the mean, high and upper limit SLR RCP 8.5 scenario, it would happen in 2070, 2060 and 2050, respectively (Supplementary Table 4). In relation to the other deltaic areas (*e.g. Phragmites spp*, wetlands and beaches) the relative area loss up to 2100 was between 37-66 % depending on the considered scenario. The period in which 25 percent of the deltaic areas would be flooded was reached in 2060 and 2070 for both RCPs 4.5 scenarios, and in 2060, 2050 and 2040 for RCPs 8.5 scenarios (Supplementary Table 4).

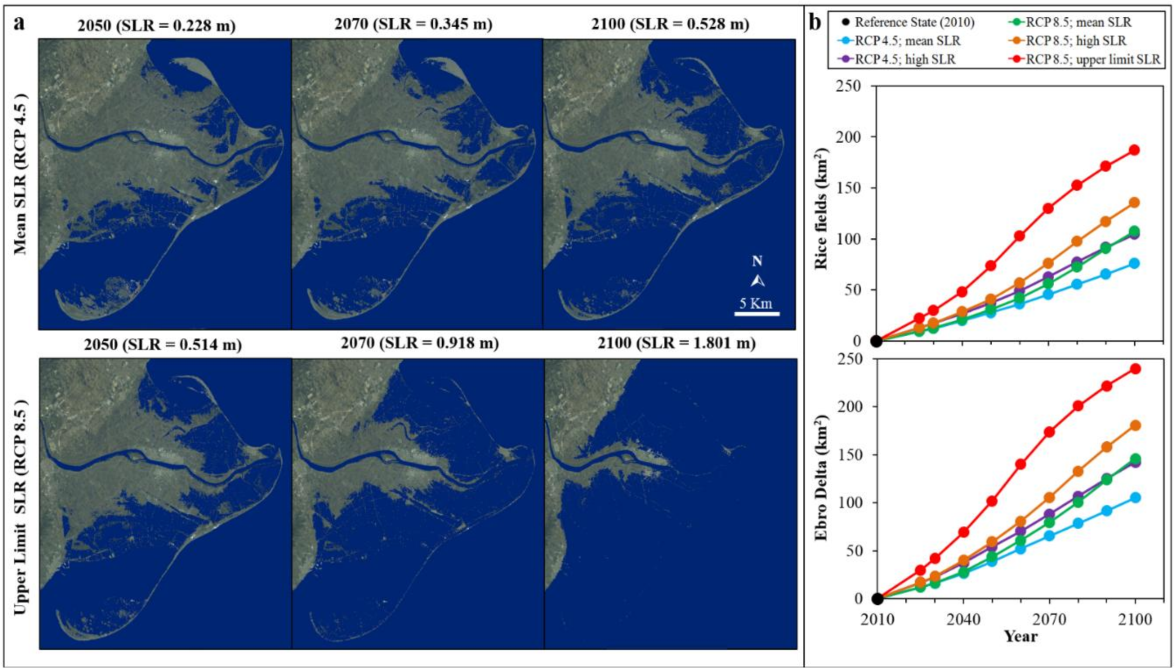


Figure 3. Simulation of Ebro Delta flooding under mean RCP 4.5 and upper limit RCP 8.5 SLR scenarios (**a**). Flooded area of Ebro Delta and rice fields under SLR scenarios (**b**). See Supplementary Figure 1 for complementary information.

Bulk density and organic matter

Bulk density (BD) showed a spatial distribution within the Ebro Delta, having the highest values close to the shoreline and along the Ebro River bank (Supplementary

Figure 2a). Lower values were found around the coastal lagoons and the freshwater springs. The mean value of BD over the whole delta was 1.00 g/cm^3, being 0.93 g/cm^3 in rice fields, with a range from 0.69 to 1.15 g/cm^3. Wetlands showed a smaller mean BD of 0.74 g/cm^3, but with a larger range of variation between 0.07 and1.6 g/cm^3. BD was strongly negatively related to organic matter (OM) (Supplementary Figure 2b).

The results of the information-theoretic analysis provided predictive models of the effect of the analyzsed variables on OM spatial distribution (Table 2). The correlation between observed and predicted values was statistically significant (Pearson's r = 0.80, N = 455, P < 0.0001), supporting the predictive ability of the model (Figure 2b). According to the AICc selection process (*i.e.* ΔAICc $\leq$ 4) only one model was considered as plausible (Table 2). Among the variables in the model (Supplementary Table 2), only six of the variables initially included were selected: Euclidean distance to the inner border, Euclidean distance to the mouth, surface elevation, the quadratic component of Euclidean distance to the coast, soil salinity and surface elevation (Table 2). The mean value of OM in the delta was 0.03 g/g soil, with a range of 0.01-0.07 g/g soil in rice fields, and 0.01-0.25 g/g soil in wetlands.

Table 2. Results from the information-theoretic framework analysis to predict organic matter content in the Ebro Delta. Model regression coefficients (β) are shown, bias is the difference between the AICc selected model and the full model coefficients. All models variables were log-transformed prior to the analysis. See Supplementary Table 2 for a detailed list of variables initially included.

Model parameters	$\boldsymbol{\beta}$	**Bias**
Intercept	-0.610	-0.473
Euclidean Distance to the inner border (m)	-0.009	-0.029
Euclidean Distance to the mouth (m)	0.031	0.035
Surface elevation (m)	-0.010	3.753
Quadratic soil salinity (dS/m)	0.032	0.127
Quadratic Euclidean distance to the coast (m)	0.005	-0.017
Quadratic surface elevation (m)	-0.148	-2.863

Estimation of sediment deficit volume

Results of the SC1 approach (maintaining surface elevation relative to mean level as in the reference state) showed that the total average sediment deficit volume in the Ebro Delta rice fields (for the period 2010-2100) ranged between 122×10^6 m^3 and 418 $\times10^6$ m^3 according to the considered SLR scenarios, while in the total delta area was between 156×10^6 m^3 and 534 $\times10^6$ m^3 (Figure 4; Supplementary Table 4). In the SC2 approach (sediment volume needed to raise flooded land just enough to compensate the SLR), the sediment deficit showed a spatial gradient with the lower values along the river and the highest nearby the coastline and coastal lagoons (Figure 4) following the delta elevation gradient. Based on the considered SLR scenarios, in the rice fields the range of total sediment deficit volume for the period 2010-2100 was between 24.8×10^6 m^3 and 227×10^6 m^3, while in the total delta area was between 33.6×10^6 m^3 and 300 $\times10^6$ m^3 (Supplementary Table 4). In both SC1 and SC2 approaches, the sediment deficit volume showed a non-linear increase over time, following a sigmoidal trend that was more apparent in the upper limit SLR scenario (Figure 5). The difference of total sediment deficit volume between SC1 and SC2 in the rice fields ranged between 97.2×10^6 m^3 and 191×10^6 m^3 by 2100, depending on the considered SLR scenarios, whereas in the entire delta ranged between 122×10^6 m^3 and 236 $\times10^6$ m^3 (Supplementary Table 4). In SC1, by 2050, the annual rate for the entire delta was 1.69×10^6 m^3 while by 2100 was 5.93×10^6 m^3. In SC2 the annual rate was 0.17×10^6 m^3 and 3.30×10^6 m^3 by 2050 and 2100, respectively.

Economic analysis

The economic effects of SLR on rice production were modeled following Genua-Olmedo et al., (2016). In SC1 the mean normalized rice production index (RPI) by 2100 was 61.2 % with a mean income of 2,359 €/ha/yr; the same values as in the reference state are obtained given that land elevation is maintained, thus not varied along the 21st century (Figure 4). In SC2 a progressive soil salinization was predicted leading to a reduction in RPI and consequently in income. The RPI decreased from 61.2 % to a range from 56.7 to 52.6 % by 2100, depending on the SLR scenarios, representing an economic loss (income reduction) ranging from 59 €/ha to 104 €/ha by 2100, depending on the SLR scenarios (Figure 6; Supplementary Table 4). Compared with SC1, SC2 implied a total income decrease in the rice field area by 2100 of 104 €/ha, amounting a total of 2,184,000 €.

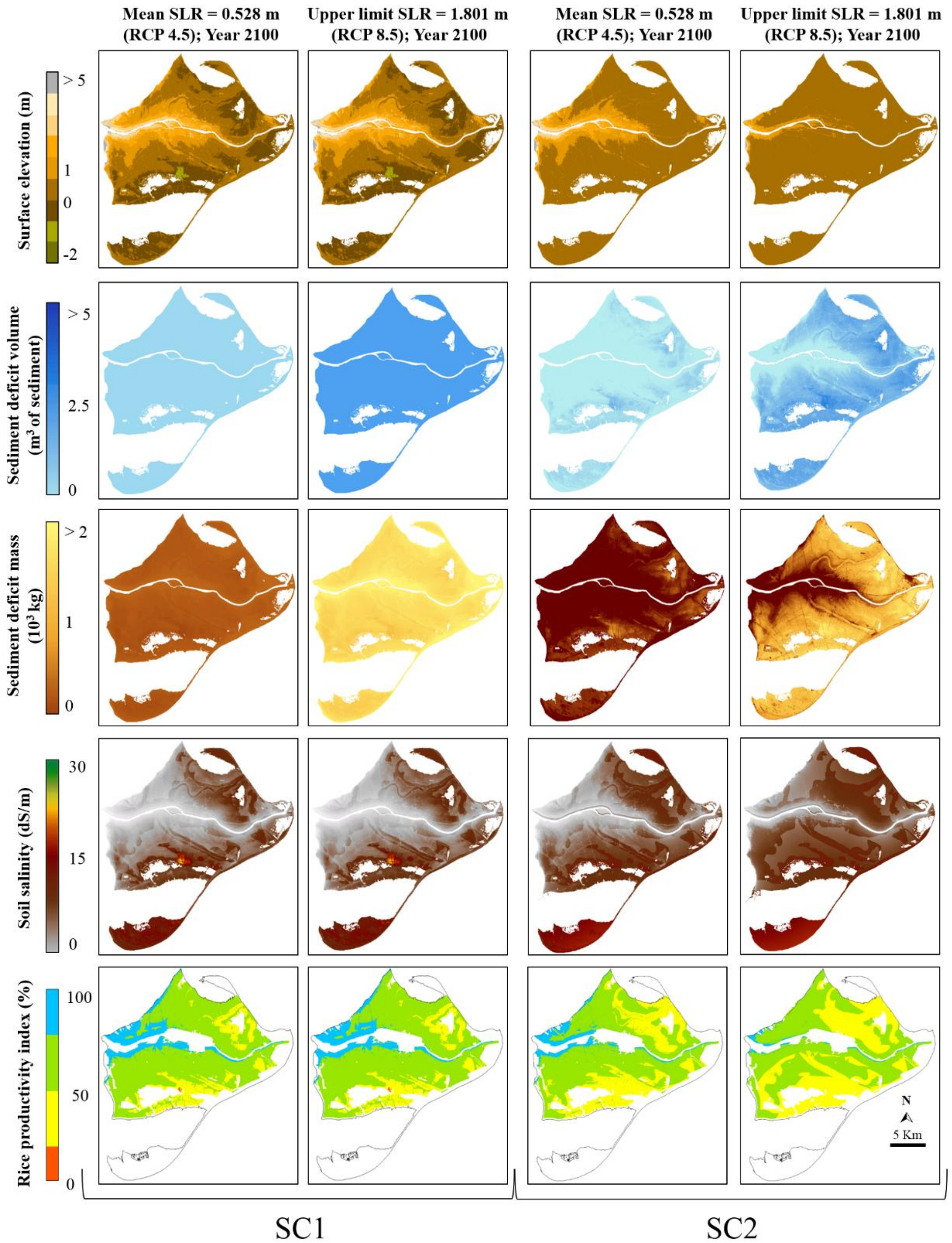


Figure 4. Spatial distribution of surface elevation (m relative to mean sea level), sediment deficit volume (m^3/m^2), sediment deficit mass (kg/m^2), soil salinity (dS/m) and rice production index (%) under mean RCP 4.5 and upper limit RCP 8.5 SLR scenarios in 2100 for both SC1 and SC2. SC1 considers the total sediment volume needed to maintain deltaic surface elevation relative to mean sea level as in the reference state, and SC2 considers the total sediment deficit volume needed to raise inundated areas just enough to compensate the SLR.

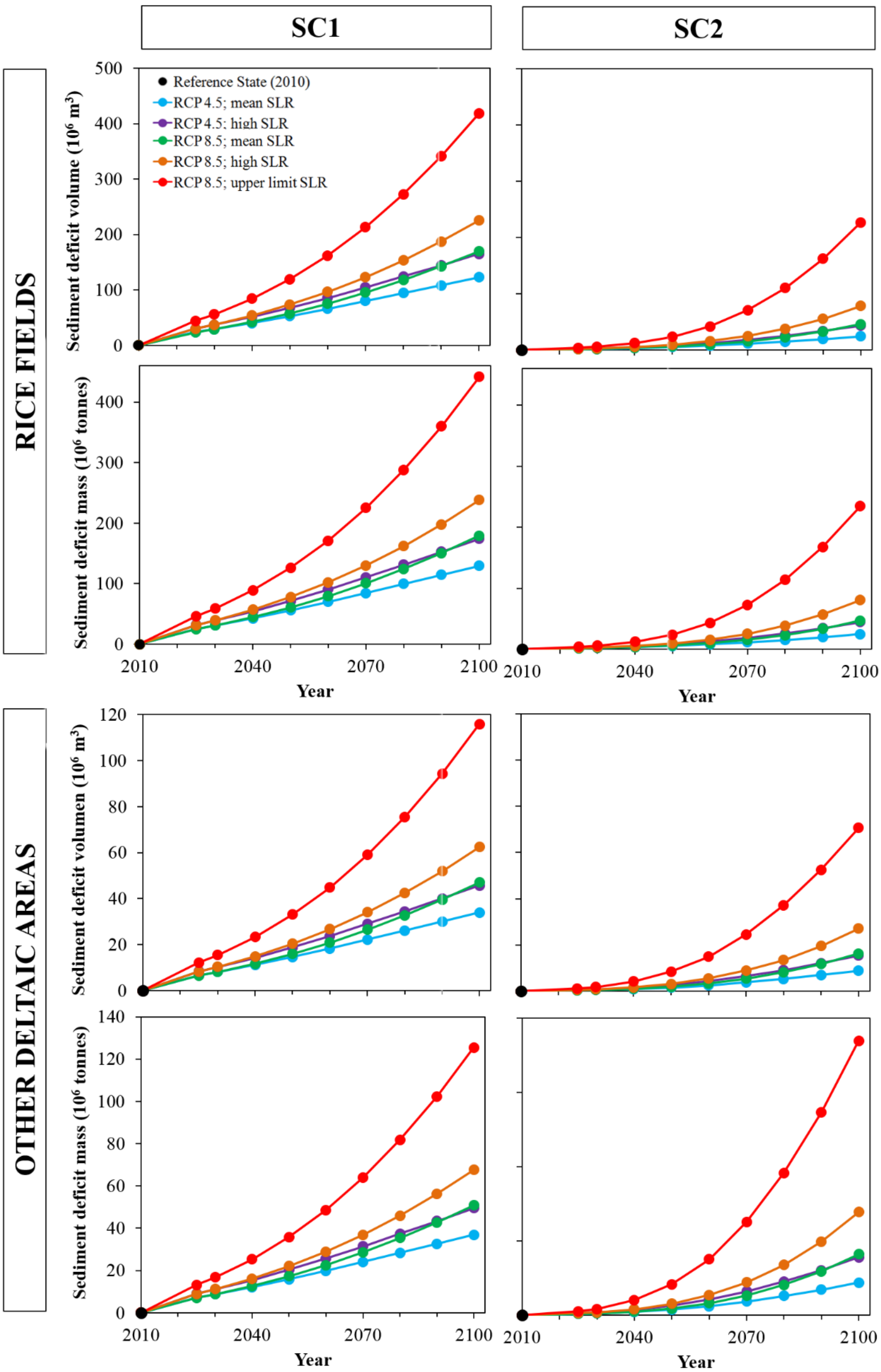


Figure 5. Evolution of sediment deficit volume and equivalent mass during the 21 st century for the considered SLR scenarios. SC1 considers the total sediment deficit volume needed to maintain deltaic surface elevation relative to mean sea level as in the reference state, and SC2 considers the total sediment deficit volume needed to raise inundated areas just enough to compensate the SLR.

Among the three considered techniques to by-pass the sediment (*i.e.* mechanic dredging, suction dredging and flushing, see Table 1), flushing was by far the cheapest with a variation of cost in SC1 by 2100 from 84 millions € (for RCP 4.5 mean SLR scenario) to 290 millions € (for the RCP 8.5 upper limit SLR scenario). In SC1, by 2050, the annual rate for the entire delta for the flushing was 922,500 €/yr whereas in SC2 was 95,000 €/yr (for the mean SLR RCP 4.5). And by 2100, the annual rate was 933,333 €/yr and 202,222 €/yr for SC1 and SC2, respectively. For the upper limit RCP 8.5 scenario, in SC1, by 2050, the annual rate was 2 millions €/yr while was 0.43 million €/yr in SC2. By 2100 was 3.21 millions €/yr and 1.75 million €/yr, respectively. By contrast, the mechanic dredging was the most expensive, the cost range was 4,500-15,380 millions €, respectively, according to the considered SLR scenarios (using the maximum cost value; Figure 7; Supplementary Table 5). In SC2, by 2100, for the same SLR scenarios, the cost range of flushing was 18.2-160 millions €, whereas the cost range of mechanic dredging was 970-8,560 millions € (Figure 7; Supplementary Table 5). Compared with SC1, SC2 involved less volume of sediment and consequently lower costs.

Discussion

Assessment of flooding with SLR and model limitations

Our modeling approach allows to identify the areas within the Ebro Delta that are prone to flood risks induced by the different SLR scenarios, essentially accounting for the spatial variations in soil surface elevation change within the delta plain. Depending on the considered SLR scenario, between 36 and 89 % of the rice field area (which covers today 210 km^2) would be below mean sea level by 2100 if the sea level rises up to 0.5 m and 1.8 m, respectively. This not means that rice cultivation would stop in areas below sea level (some rice fields in the Ebro Delta are indeed cultivated below sea level), but increasing costs of maintenance and decreasing rice production could make economically unfeasible the crop in the lowest areas.

One of the model limitations is that the delta subsidence process has not been included due to the lack of reliable data. Although different average estimates of *ca.* 3 mm/year are available for the entire delta, there are no spatially explicit data available yet. As such, one could say that model results are conservative. On the other hand, we included extreme SLR scenarios up to 1.8 m by 2100 (Jevrejeva et al., 2014). Currently, we are developing a spatially-explicit subsidence model based on satellite data measured during the last 30 years.

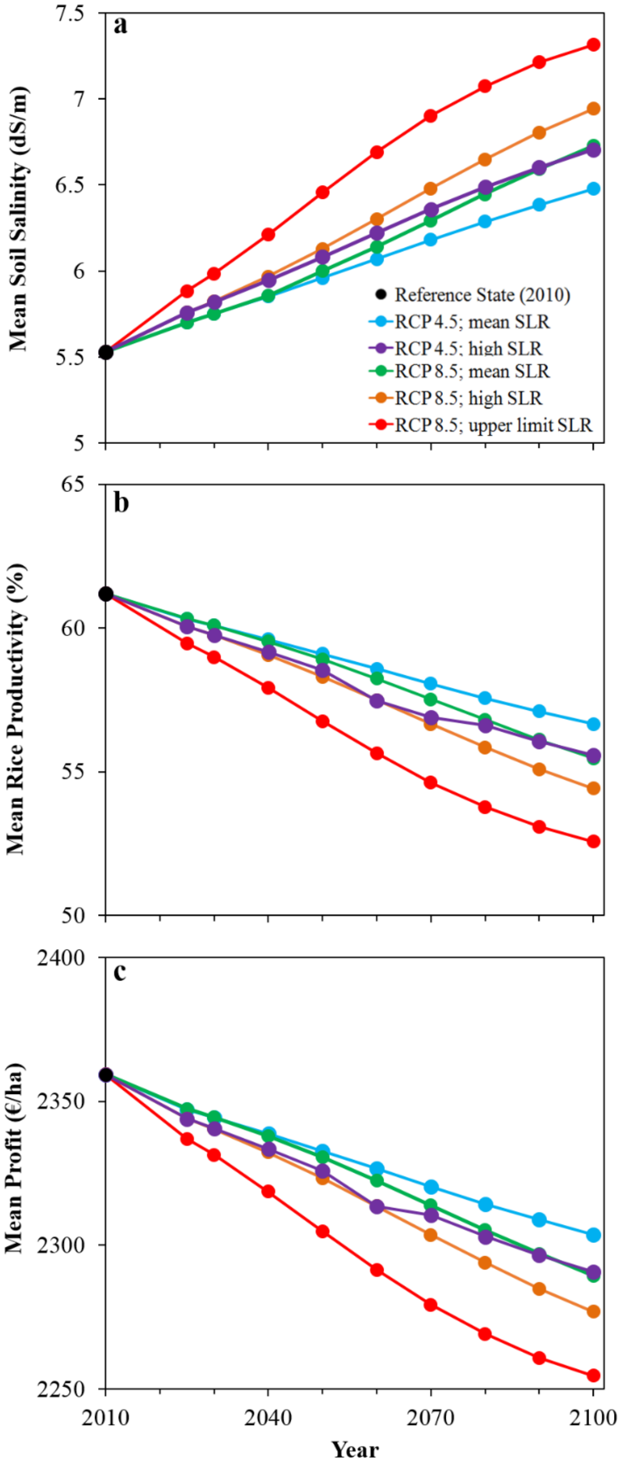


Figure 6. Evolution of mean value of soil salinity (**a**), rice production index (**b**), and income (**c**) during the 21 st century under the simulated SLR along the 21st century under the simulated SLR scenarios. SC1 is not shown because remains constant over time, as in the reference state (mean soil salinity = 5.53 dS/m; mean rice production = 61.2 %; mean income = 2,359.38 €/ha).

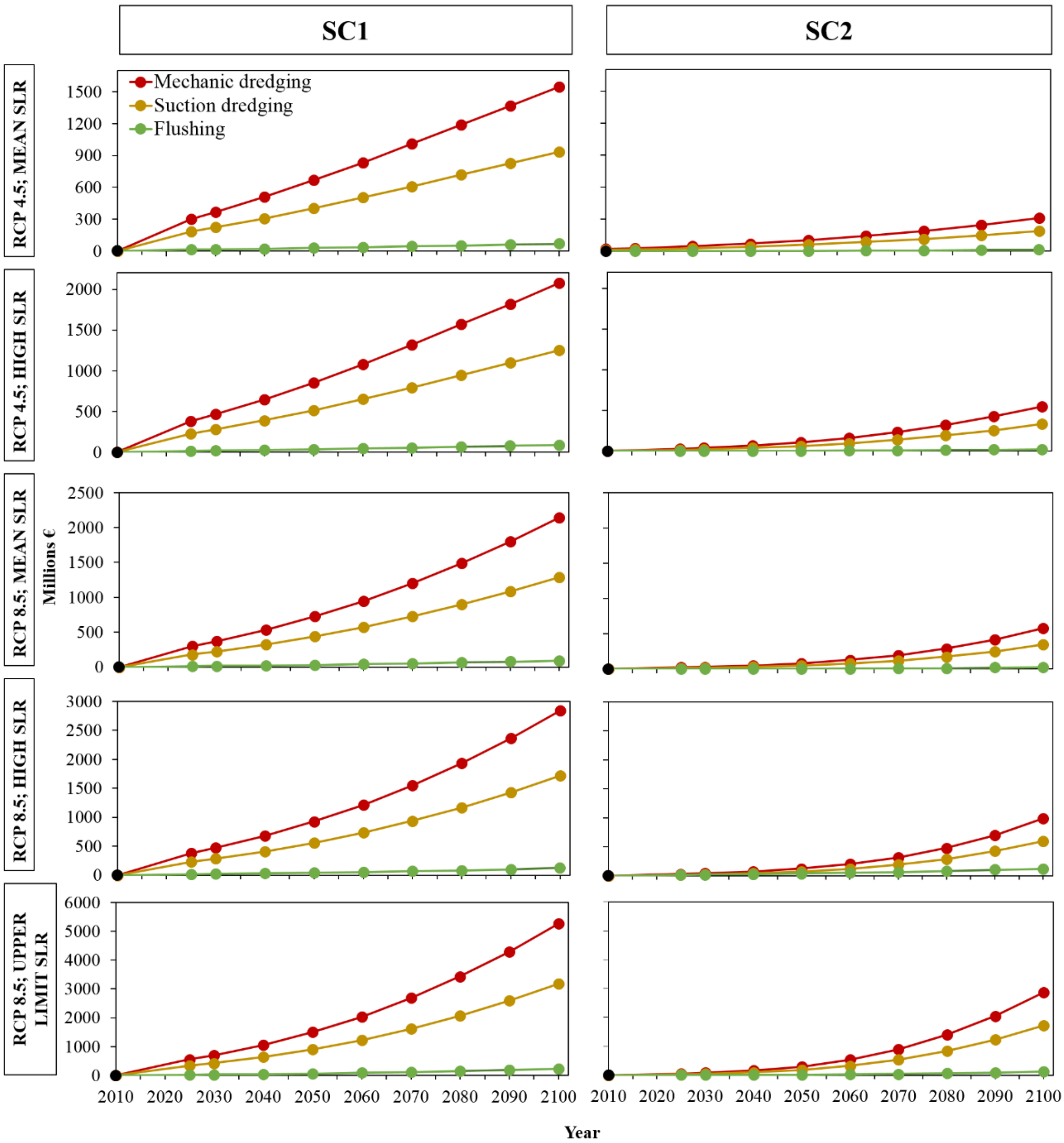


Figure 7. Estimated minimum costs associated to sediment extraction and transport for mechanic dredging, suction dredging and flushing methods, under the simulated SLR scenarios.Cost values refer to raising only rice fields considering the minimum cost shown in Table 1. SC1 considers the total sediment deficit volume needed to maintain deltaic surface elevation relative to mean sea level as in the reference state, and SC2 considers the total sediment deficit volume needed to raise inundated areas just enough to compensate the SLR.

Another limitation is that our modeling approach does not account for the natural capacity of deltaic habitats, such as beaches and wetlands, to adapt their elevation to SLR by enhanced sediment accretion (Gedan et al., 2011; Kirwan et al., 2016; Temmerman et al., 2013).In this respect, the loss of rice fields depends on the distance to the coast because, assuming the dynamic nature of the coastal response to SLR, beaches and dunes can serve as protective barriers against flooding since they have a certain capacity to maintain their elevation relative to the rising sea level through natural processes of sand accretion (Warren and Niering, 1993). However, most of the sandy coastal zone surrounding the Ebro deltaic plain is currently retreating (Sánchez-Arcilla et al., 2008), which is aggravated by the dominance of sediment transport by waves due to the reduction of sediment supply by the river discharge (Jiménez and Sánchez-Arcilla, 1993). Nevertheless, there are rice fields located along the inner bays (see Figure 1), where beaches are absent, and cannot count on the protection by beaches and dunes. In these rice fields, rice cultivation may become unsustainable and a conversion into wetlands is expected (Fatorić and Chelleri, 2012). Such wetlands could trap sediments and improve water quality coming from the rice fields, and as such build up land with the rising sea level and serve as natural protective barriers for the more inland located rice fields (Kirwan and Megonigal, 2013; Temmerman and Kirwan, 2015). This type of constructed wetlands have already been set up in the Ebro Delta (see http://www.lifeebroadmiclim.eu/en/), but their capacity for vertical accretion, carbon sequestration and nutrient removal is still being assessed. In the Ebro Delta, previous results on vertical accretion in constructed wetlands have been obtained in small experimental plots, with accretion rates higher than 1 cm/yr (Calvo-Cubero et al., 2013).

Dealing with the sediment deficit

The volume of the estimated sediment deficit by 2100 in SC1 (the scenario considering the volume needed to maintain deltaic surface elevation relative to mean sea level as in the reference state) varied for the entire delta between 156×10^6 m^3 in the most conservative scenario (mean RCP 4.5, SLR = 0.53 m), and 534×10^6 m^3 in the worst case scenario (upper limit RCP 8.5, SLR = 1.80 m). These values decreased in the SC2 (considering the total volume needed in the inundated areas, just enough to compensate the SLR) to 34×10^6 m^3 and 298×10^6 m^3 in the most conservative and worst case scenario, respectively. The annual rate of sediment deficit by 2100 for a SLR of 0.5 m. was 1.85×10^6 tonnes/yr and 0.38×10^6 in SC1 and SC2, respectively. These findings seem to be consistent with previous studies that have estimated sediment loss ranging from 1.3-2.1$\times10^6$ tonnes/yr under relative SLR of 0.70 m (Ibáñez et al., 1997). However, the annual rate ranges between 4.1 and 7.6×10^6 tonnes/yr in our estimations for a SLR of 1.8 m. This range is higher due to the more than one meter of SLR difference in comparison with the more conservative SLR considered in the mentioned study.

To compensate the sediment deficit in the Ebro Delta, the following adaptation measure is being considered: restoring part of the sediment flux of the lower Ebro River through by-passing sediments in the Riba-Roja reservoir, and transfer the sediment to the delta plain through controlled river floods, delivering the sediment to the rice fields via the irrigation network. Different technical measures with different associated costs have been considered for transferring the sediment: mechanic dredging and transfer of sediment by road or boat, suction dredging, and generation of flushing floods. Flushing floods are the cheapest option and according to previous work is the most suitable measure in mobilizing the sediment. Successful removal of reservoir sediment has been applied worldwide (see Kondolf et al., 2014 for an extensive review) such as in reservoirs of Cachí, Costa Rica (Jansson and Erlingsson, 2000); Halligan, United States (Wohl and Cenderelli, 2000); and Hengshan and Zhuwo, China (Wang and Chunhong, 2009). Similar techniques have also been applied in deltaic areas such as the Mississippi Delta, where controlled diversions of river water are used to deliver sediments to the deltaic wetlands and such to contribute to wetland sedimentation and elevation gain (Day et al., 2003), but in this case no sediment by-pass is needed since the Mississippi River still carries a significant amount of sediment.

In our study, we only have considered the rice fields as an ecosystem service, showing a positive effect of the application of the adaptation measure on rice production, and thus on economic income. Comparing SC2 with SC1, by 2100, the loss of income is *ca.* 55 €/ha more for SC2 than for SC1. Thus, considering the 21,000 ha of rice fields, represent a total of 1,155,000 € by 2100 in the most conservative scenario (RCP 4.5, SLR = 0.5 m), while in the most extreme scenario (RCP 8.5, SLR = 1.8 m) the income losses are 48 €/ha more for SC2 than for SC1, *i.e.* 1.008,000 € more. Compared with a scenario of no adaptation to SLR (Genua-Olmedo et al., 2016), the considered adaptation measure reduces soil salinity, thus minimizing the loss of rice production and economic income. Our results show that the cost of applying the considered adaptation measure is high but has a positive effect on the economic feasibility of rice farming, as well as on ecosystem services provided by rice fields.

Rice fields and wetlands offer numerous ecosystem services and hence maintaining them by supplying sediment to the delta plain delivers multiple benefits to society.Apart from the direct economical income from rice production, rice fields prevent salt intrusion through fresh water irrigation, they contribute to nutrient removal, biodiversity, ecotourism, and fisheries (Natuhara, 2013). Wetlands offer ecosystem services associated to buffering against coastal flood risks, being a natural capital substitute for conventional flood protection investments such as dykes (Boyd and Banzhaf, 2007; Cheong et al., 2013; Temmerman et al., 2013). Moreover, wetlands work as a sediment trap and deltaic wetland sedimentation efficiently helps to compensate for SLR and subsidence (Temmerman and Kirwan, 2015; van der Deijl et al., 2017). The preservation of the Ebro Delta rice fields and wetlands is also perceived as important by local stakeholders for cultural, economic and ecological reasons. Moreover, the measure of “rising grounds” is supported by delta’s inhabitants, including rice farmers (Ibáñez et al., 2014), which are –in face of climate change and SLR – mainly concerned about the conservation of the delta’s natural heritage (Romagosa and Pons, 2017b), and the survival of rice cultivation.

The measure of “rising grounds” has other indirect benefits like the improvement of the maintenance of the dam capacity (Martín-Vide et al., 2004), and others associated to the increase of turbidity in the river water, such as the reduction of the widespread macrophyte cover and the invasive black-fly (Ibáñez et al., 2012), and zebra mussel population (Alcaraz et al., 2011) in the lower Ebro River. On the other hand, there are also arguments against applying this measure of “rising grounds” using sediment by-passing from river dam reservoirs; for example, flushing operations may negatively impact hydropower companies (Martín-Vide et al., 2004), and may impact the irrigation system. Therefore, all advantages and disadvantages need to be fully considered before applying this measure, and in this respect, our study is a first step to further studies, also with regard to the quality of sediment and grain size stored in Riba-Roja reservoir.

The considered measure to adapt to SLR is an innovative alternative to classical grey infrastructures (Rovira and Ibáñez, 2007) such as building flood defense structures which have limitations in the long-term and does not solve the sediment deficit problem. The evaluation of the sediment deficit under different SLR scenarios can also help the development of sustainable sediment management plans for the Ebro River and its delta.

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Supplementary Table 1. Published functions considered to assess the relationship between soil bulk density (BD, g/cm^3) and organic matter (OM, g/g soil).

Functions	References*
$\ln(BD) = -2.31 - 1.079 \times \ln(OM) - 0.113 \times [\ln(OM)^2]$	Federer (1983)
$\ln(BD) = -2.39 - 1.316 \times \ln(OM) - 0.167 \times [\ln(OM)^2]$	Huntington et al., (1989)
$\ln(BD) = -1.81 - 0.892 \times \ln(OM) - 0.092 \times [\ln(OM)^2]$	Prevost (2004)
$BD = (1.111 \times 1.450) / (1.450 \times OM) + 0.111 \times (1 - OM)$	Federer et al. (1993)
$BD = (1.244 \times 1.640) / (1.640 \times OM) + 0.244 \times (1 - OM)$	Post and Kwon (2000)
$BD = (1.120 \times 1.400) / (1.400 \times OM) + 0.120 \times (1 - OM)$	Tremblay et al. (2002)
$BD = (1.159 \times 1.561) / (1.561 \times OM) + 0.159 \times (1 - OM)$	Prevost (2004)
$BD = (1.111 \times 1.767) / (1.767 \times OM) + 0.111 \times (1 - OM)$	Périé and Ouimet (2008)
$BD = -1.977 + 4.105 \times OM - 1.229 \times \ln(OM) - 0.103 \times [\ln(OM)^2]$	Périé and Ouimet (2008)
$BD = -0.970 + 1.033 \times OM - 0.912 \times \ln(OM) - 0.095 \times [\ln(OM)^2]$	This study: modified from Périé and Ouimet (2008)

*References:

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Supplementary Table 2. Full list of variables initially included in the organic matter model. The quadratic component of all continuous variables was also included.

Variables initially included in the model	Source
22- Location of the sample point (north, south)	GIS database
23- Surface elevation of 2010 (m) 24- Surface elevation of (interpolated) (m)	DEM 2010
25- Distance to the Ebro River (m) 26- Distante to the mouth (m) 27- Distance to the old mouth (m) 28- Distance to the coastline (m) 29- Distance to the northern border (m) 30- Distance to the southern border (m) 31- Distance to the inner border (m) 32- Distance to the nearest coastal lagoon (m)	GIS database
33- Predicted soil salinity (dS/m)	Genua-Olmedo et al., (2016)
34- Clay presence 35- Silt presence 36- Sand presence 37- Gravel presence 38- Peat presence 39- Block presence 40- Pebbles presence	ICGC, 2006; 1:50,000 scale sheets number 522-523, 547-548

Supplementary Table 3. SLR scenarios modeled (m): RCP 4.5 (stabilization) and RCP 8.5 (increasing radiative forcing) were obtained from the mean and high values of the AR5 IPCC projections, and the upper limit SLR, from Jevrejeva et al., 2014.

	RCP 4.5		**RCP 8.5**		
Year	Mean SLR	High SLR	Mean SLR	High	Upper Limit
2025	0.103	0.130	0.101	0.129	0.190
2030	0.126	0.159	0.126	0.160	0.240
2040	0.174	0.221	0.182	0.232	0.363
2050	0.228	0.291	0.248	0.317	0.514
2060	0.285	0.369	0.324	0.415	0.697
2070	0.345	0.451	0.411	0.530	0.918
2080	0.407	0.536	0.508	0.660	1.173
2090	0.467	0.622	0.614	0.807	1.468
2100	0.528	0.710	0.731	0.971	1.801

Supplementary Table 4. Estimated flooded areas, sediment deficit volume and mass, mean soil salinity (ECe), mean rice productivity index (RPI) and mean income under the simulated SLR, in rice fields (210 km^2) and in the other deltaic areas (80 km^2). The table continues in next page.

		Flooded area * (km^2)		Sediment deficit volume (10^6 m^3) Scenario 1		Sediment deficit volume (10^6 m^3) Scenario 2		Sediment deficit mass (10^6 tonnes) Scenario 1		Sediment deficit mass (10^6 tonnes) Scenario 2		Scenario 2**		
	Year	Rice fields	Deltaic areas	Rice fields	Deltaic areas	Rice fields	Deltaic areas	Rice fields	Deltaic areas	Rice fields	Deltaic areas	ECe (dS/m)	RPI (%)	Income (€/ha)
RCP 4.5 Mean SLR	2025	9.26	2.84	23.9	6.62	1.72	0.41	25.2	7.17	1.70	0.40	5.70	60.3	2347
	2030	12.3	3.87	29.2	8.09	2.26	0.55	30.8	8.76	2.23	0.54	5.75	60.1	2345
	2040	19.7	6.60	40.5	11.21	3.65	0.94	42.7	12.1	3.63	0.92	5.85	59.6	2339
	2050	27.8	11.0	53.0	14.66	5.61	1.56	55.9	15.9	5.60	1.53	5.96	59.1	2333
	2060	36.1	16.2	66.2	18.32	8.15	2.51	69.8	19.8	8.18	2.46	6.07	58.6	2327
	2070	45.4	20.1	80.2	22.20	11.4	3.79	84.6	24.0	11.4	3.73	6.18	58.1	2320
	2080	55.4	23.3	94.5	26.16	15.3	5.30	99.7	28.3	15.4	5.24	6.29	57.6	2314
	2090	65.4	26.2	108	30.03	19.7	6.97	114	32.5	19.9	6.92	6.39	57.1	2309
	2100	76.0	29.3	122	33.99	24.8	8.86	130	36.8	25.3	8.83	6.48	56.7	2304
RCP 4.5 High SLR	2025	12.9	4.06	30.1	8.35	2.36	0.58	31.8	9.04	2.34	0.57	5.76	60.0	2344
	2030	17.2	5.60	36.9	10.2	3.16	0.80	38.9	11.1	3.14	0.78	5.82	59.8	2341
	2040	26.9	10.4	51.4	14.2	5.34	1.47	54.3	15.4	5.34	1.44	5.95	59.2	2333
	2050	37.1	16.7	67.7	18.7	8.47	2.63	71.4	20.3	8.51	2.58	6.08	58.5	2326
	2060	49.1	21.4	85.6	23.7	12.8	4.34	90.4	25.7	12.9	4.28	6.22	57.5	2313
	2070	62.7	25.5	105	29.0	18.4	6.50	111	31.4	18.7	6.44	6.36	58.0	2320
	2080	77.4	29.6	125	34.5	25.5	9.11	131	37.4	26.0	9.08	6.49	56.6	2303
	2090	91.6	33.7	144	40.0	33.9	12.1	153	43.3	34.6	12.1	6.60	56.1	2297
	2100	104	37.7	165	45.7	43.6	15.5	174	49.5	44.7	15.6	6.71	55.6	2291

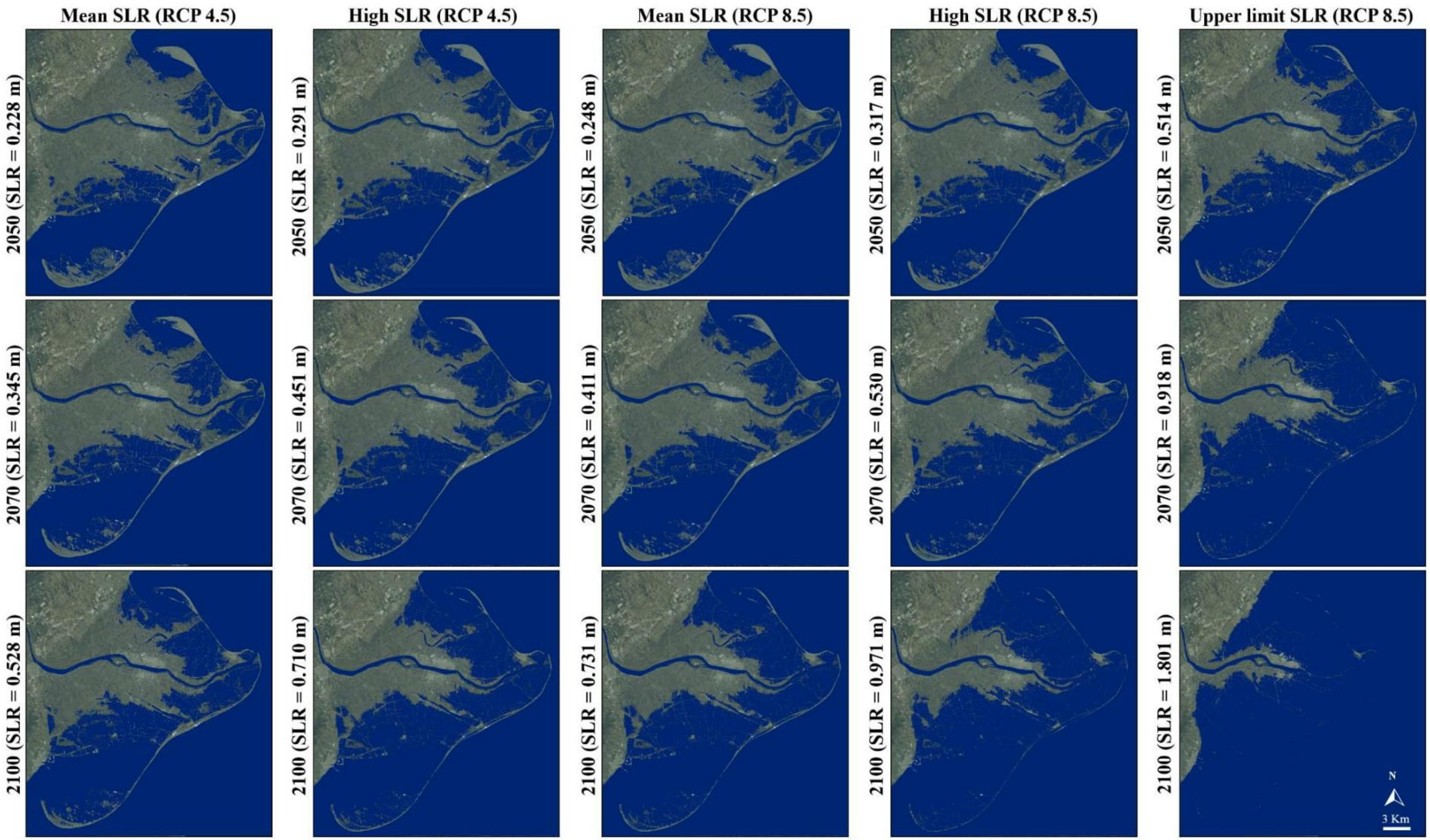
		Flooded area* (km^2)		Sediment deficit volume (10^6 m^3)				Sediment deficit mass (10^6 tonnes)				Scenario 2**		
				Scenario 1		Scenario 2		Scenario 1		Scenario 2				
	Year	Rice fields	Deltaic areas	Rice fields	Deltaic areas	Rice fields	Deltaic areas	Rice fields	Deltaic areas	Rice fields	Deltaic areas	ECe (dS/m)	RPI (%)	Income (€/ha)
RCP 8.5 Mean SLR	2025	9.14	2.80	23.5	6.52	1.69	0.40	24.8	7.06	1.66	0.39	5.70	60.3	2347
	2030	12.4	3.92	29.3	8.11	2.27	0.56	30.9	8.79	2.24	0.54	5.75	60.1	2344
	2040	20.9	7.15	42.4	11.7	3.91	1.02	44.7	12.7	3.89	1.00	5.76	59.5	2338
	2050	30.9	13.0	57.6	16.0	6.45	1.86	60.8	17.3	6.46	1.82	6.00	58.9	2330
	2060	41.9	18.9	75.2	20.8	10.2	3.31	79.4	22.6	10.2	3.25	6.14	58.2	2322
	2070	56.1	23.5	95.5	26.4	15.5	5.42	101	28.6	15.7	5.35	6.29	57.5	2314
	2080	72.4	28.2	118	32.6	23.0	8.20	124	35.4	23.4	8.16	6.45	56.8	2305
	2090	90.4	33.4	143	39.5	33.0	11.8	151	42.8	33.8	11.8	6.59	56.1	2297
	2100	107	38.5	170	47.0	46.1	16.3	179	50.9	47.3	16.5	6.73	55.5	2289
RCP 8.5 High SLR	2025	12.9	4.06	30.0	8.3	2.34	0.58	31.6	8.99	2.31	0.56	5.76	60.1	2344
	2030	17.5	5.71	37.2	10.3	3.21	0.82	39.3	11.2	3.18	0.80	5.82	59.7	2340
	2040	28.5	11.5	53.9	14.9	5.77	1.62	56.9	16.2	5.77	1.59	5.97	59.1	2332
	2050	40.8	18.4	73.5	20.4	9.8	3.15	77.6	22.1	9.8	3.10	6.13	58.3	2323
	2060	56.9	23.7	96.4	26.7	15.8	5.53	102	28.9	16.0	5.46	6.30	57.5	2314
	2070	76.2	29.3	123	34.1	24.9	8.90	130	36.9	25.4	8.87	6.48	56.7	2304
	2080	97.4	35.5	153	42.4	37.9	13.5	162	46.0	38.8	13.6	6.65	55.8	2294
	2090	117	41.2	187	51.9	55.7	19.6	198	56.2	57.2	19.9	6.81	55.1	2285
	2100	135	45.3	226	62.4	78.6	27.1	238	67.6	80.9	27.8	6.94	54.4	2277
RCP 8.5 Upper Limit SLR	2025	22.0	7.66	44.1	12.2	4.17	1.10	46.5	13.2	4.15	1.07	5.88	59.5	2337
	2030	29.7	12.2	55.8	15.4	6.11	1.74	58.9	16.7	6.11	1.70	5.98	59.0	2331
	2040	48.1	21.0	84.2	23.3	12.4	4.20	88.9	25.3	12.5	4.14	6.21	57.9	2319
	2050	73.4	28.5	119	33.0	23.5	8.39	126	35.8	23.9	8.36	6.46	56.8	2305
	2060	103	37.2	162	44.8	42.1	14.9	171	48.6	43.2	15.1	6.69	55.6	2291
	2070	130	44.1	213	59.0	70.8	24.6	225	63.9	72.8	25.1	6.90	54.6	2279
	2080	153	48.4	272	75.4	111	37.1	288	81.7	114	38.4	7.07	53.8	2269
	2090	171	50.7	341	94.4	162	52.5	360	102.3	168	54.7	7.21	53.1	2261
	2100	187	52.9	418	116	227	70.6	442	125.5	235	73.9	7.32	52.6	2255

* Surface: Ebro Delta = 320 km^2, rice fields = 210 km^2, other deltaic areas = 80 km^2.
** Scenario 1 refers to the reference state (year 2010): ECe = 5.53 dS/m; RPI = 61.2 %; income = 2359.38 €/ha

Supplementary Table 5. Estimated costs of the sediment needed to face SLR impacts along the 21 st century under the simulated SLR in the rice fields (210 km^2) and in the other deltaic areas (80 km^2). Results show different values of cost using minumum and maximum cost value in rice fields and in deltaic area according to Table 1. The table continues in next page.

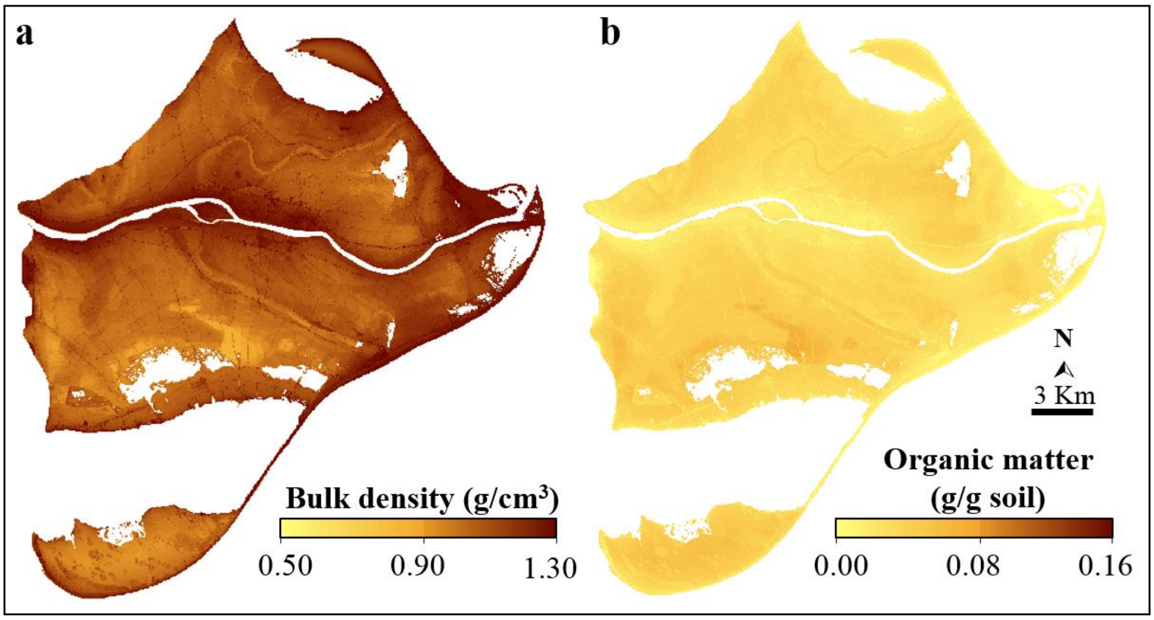
		Mechanic dredging (Millions €)								Suction dredging (Millions €)								Flushing (Millions €)			
		Scenario 1				Scenario 2				Scenario 1				Scenario 2				Scenario 1		Scenario 2	
		Rice fields		Deltaic areas		Rice fields		Deltaic areas		Rice fields		Deltaic areas		Rice fields		Deltaic areas		Rice fields	Deltaic areas	Rice fields	Deltaic areas
	Year	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Unique			
RCP 4.5 Mean SLR	2025	301	688	83	191	22	50	5.2	11	182	543	50	150	13	39	3.1	9.4	13	3.6	0.9	0.2
	2030	368	842	102	233	29	65	7.0	16	222	663	61	184	17	51	4.2	13	16	4.4	1.2	0.3
	2040	510	1166	141	323	46	105	11	27	308	919	85	254	28	83	7.2	21	22	6.1	2.0	0.5
	2050	667	1525	185	422	71	161	19	45	403	1202	111	333	43	127	12	35	29	7.9	3.0	0.8
	2060	834	1905	231	528	103	235	31	72	503	1502	139	416	62	185	19	57	36	9.9	4.4	1.4
	2070	1010	2309	280	639	143	327	47	109	609	1820	169	504	86	258	29	86	43	12	6.1	2.0
	2080	1190	2721	330	753	192	439	66	1528	718	2144	199	594	116	346	40	120	51	14	8.2	2.9
	2090	1366	3123	378	865	248	566	87	200	824	2462	228	682	149	446	53	158	59	16	10.6	3.8
	2100	1546	3535	428	979	313	714	111	255	933	2786	258	771	189	563	67	201	66	18	13.4	4.8
RCP 4.5 High SLR	2025	380	868	105	240	30	68	7.3	17	229	684	63	190	18	54	4.4	13	16	4.5	1.3	0.3
	2030	465	1062	129	294	40	91	10	23	280	837	78	232	24	72	6.1	18	20	5.5	1.7	0.4
	2040	648	1481	179	410	67	154	19	42	391	1167	108	323	41	121	11	33	28	7.7	2.9	0.8
	2050	853	1949	236	540	107	244	33	76	514	1536	142	425	64	192	20	60	37	10	4.6	1.4
	2060	1079	2465	299	683	161	368	55	125	651	1943	180	538	97	290	33	99	46	13	6.9	2.3
	2070	1319	3014	365	835	232	530	82	187	795	2376	220	658	140	418	49	148	57	16	9.9	3.5
	2080	1569	3586	434	993	321	734	115	262	946	2827	262	783	194	579	69	207	67	19	13.8	4.9
	2090	1820	4160	504	1152	427	975	152	348	1098	3279	304	908	257	768	92	274	78	22	18.3	6.5
	2100	2078	4749	575	1315	550	1256	195	445	1253	3743	347	1036	332	991	117	351	89	25	23.6	8.3

		Mechanic dredging (Millions €)								Suction dredging (Millions €)								Flushing (Millions €)			
		Scenario 1				Scenario 2				Scenario 1				Scenario 2				Scenario 1		Scenario 2	
		Rice fields		Deltaic areas		Rice fields		Deltaic areas		Rice fields		Deltaic areas		Rice fields		Deltaic areas		Rice fields	Deltaic areas	Rice fields	Deltaic areas
	Year	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Unique			
RCP 8.5 Mean SLR	2025	296	865	82	188	21	49	5.1	12	179	534	50	148	13	38	3.1	9.2	13	3.5	0.9	0.2
	2030	369	1077	102	234	29	65	7.0	16	223	665	62	184	17	51	4.2	13	16	4.4	1.2	0.3
	2040	534	1558	148	338	49	113	13	29	322	962	89	266	30	89	7.8	23	23	6.3	2.1	0.6
	2050	726	2119	201	460	81	186	23	54	438	1308	121	362	49	146	14	42	31	8.6	3.5	1.0
	2060	948	2766	262	600	128	293	42	95	572	1707	158	473	77	231	25	75	41	11	5.5	1.8
	2070	1203	3511	333	761	196	448	68	156	726	2167	201	600	118	353	41	123	52	14	8.4	2.9
	2080	1486	4336	411	940	290	662	103	236	896	2676	248	741	175	522	62	186	64	18	12.4	4.4
	2090	1797	5246	498	1138	416	952	148	339	1084	3238	300	897	251	750	90	267	77	21	17.8	6.4
	2100	2138	6241	592	1353	581	1328	205	470	1290	3852	357	1067	350	1047	124	370	92	25	24.9	8.8
RCP 8.5 High SLR	2025	378	863	105	239	29	67	7.3	17	228	680	63	188	18	53	4.4	13	16	4.5	1.3	0.3
	2030	469	1072	130	297	40	92	10	24	283	845	78	234	24	73	6.2	19	20	5.6	1.7	0.4
	2040	679	1553	188	430	73	166	20	47	410	1224	113	339	44	131	12	37	29	8.1	3.1	0.9
	2050	927	2118	257	586	123	281	40	91	559	1669	155	462	74	222	24	72	40	11	5.3	1.7
	2060	1215	2777	336	769	199	456	70	159	733	2189	203	606	120	359	42	125	52	14	8.5	3.0
	2070	1551	3545	429	982	314	718	112	256	935	2794	259	774	189	566	68	202	66	18	13.5	4.8
	2080	1931	4414	535	1222	478	1092	170	388	1165	3479	323	963	288	861	102	306	83	23	20.5	7.3
	2090	2362	5398	654	1495	702	1604	246	563	1425	4255	394	1178	423	1264	149	444	101	28	30.1	11
	2100	2841	6495	787	1798	990	2263	341	781	1714	5119	475	1418	597	1784	206	615	122	34	42.4	15
RCP 8.5 Upper Limit SLR	2025	556	1270	154	352	53	120	14	32	335	1001	93	277	32	95	8.3	25	24	6.6	2.3	0.6
	2030	703	1606	195	445	77	176	22	50	424	1266	117	351	46	139	13	39	30	8.3	3.3	0.9
	2040	1061	2425	294	672	156	357	53	121	640	1912	177	529	94	282	32	95	45	13	6.7	2.3
	2050	1504	3437	416	952	296	677	106	242	907	2709	251	750	179	534	64	191	64	18	12.7	4.5
	2060	2040	4663	565	1291	531	1214	188	430	1231	3676	341	1018	320	957	114	339	87	24	22.8	8.1
	2070	2686	6139	744	1700	892	2040	310	708	1620	4839	449	1340	538	1608	187	558	115	32	38.2	13
	2080	3433	7847	951	2173	1392	3182	468	1069	2071	6185	573	1713	840	2508	282	843	147	41	59.7	20
	2090	4296	9819	1190	2719	2046	4677	662	1513	2591	7739	718	2143	1234	3686	399	1192	184	51	87.7	28
	2100	5271	12047	1459	3336	2856	6529	889	2033	3179	9496	880	2629	1723	5146	536	1602	226	63	122.4	38



Supplementary Figure 1. Evolution of the flooded area for all the simulated SLR scenarios in 2050, 2070 and 2100: mean and high RCP 4.5, and mean, high and upper limit RCP 8.5. See materials and methods for RCR description.

Supplementary Figure 2. Soil bulk density (**a**) and soil organic matter content (**b**) distribution maps in the Ebro Delta. To convert BD g/cm^3 units to kg/m^3, multiply by 1000.



Conclusions

1. Lowlands-lying areas, such as the Ebro Delta, are highly sensitive and vulnerable to climate change and consequent sea level rise (SLR).

2. The Ebro Delta rice production is threatened by SLR and the associated increase in soil salinity, the main limiting factor of rice growth.

3. A Geographic Information Systems (GIS)-based model coupled with Generalized Linear Models (through model averaging tools) showed a good predictive capability of soil salinity and rice production in the Ebro Delta.

4. The model selected six variables, out of the 21 initially included, as the most important ones for soil salinity prediction: surface elevation was the most influential, followed by clay presence and winter flow (inversely related to soil salinity), distance to the river, distance to the delta inner border and distance to the old mouth (positively related soil salinity.

5. Rice production was closely and negatively related to soil salinity. Up to 2100, a decline in rice production as consequence of an increase in soil salinity is predicted and will be larger in areas near the coast and lower along the Ebro River, following the Ebro Delta elevation gradient.

6. For the mean RCP 8.5 scenario, the predicted rice production loss is up to 10 % by 2100, and 13 % for the high RCP 8.5 SLR scenario, in relation to the reference state (2010).

7. If RCP 8.5 high scenario projections are exceed (upper limit SLR scenario of 1.8 m, 5 % of probability) the predicted reduction in rice production is near 30 % when compared to the reference state, and is associated to an increase in soil salinity up to three times the reference condition and to an income reduction of about 300 € per hectare.

8. Without adaptation measures by 2100, the potential loss of rice field surface due to SLR flooding ranges between the 40 and the 90 % depending on the considered SLR scenario.

9. The nature-based adaptation measure (rising grounds), consisting in reintroducing fluvial sediments into the delta plain to maintain land elevation and rice production is considered a feasible innovative management option for balancing the effects of SLR in the Ebro Delta.

10. Two sediment supply scenarios were considered: SC1, considered the total sediment deficit volume needed to maintain deltaic surface elevation relative to mean sea level as in the reference state, and SC2, considered the total sediment deficit volume needed to raise inundated areas just enough to compensate the SLR. In SC1, for the worst case scenario, the sediment deficit volume was 420 million m^3 of sediment by 2100, whereas in SC2 it was 220 million m^3.

11. The considered adaptation measure has a positive effect in rice production because also reduce soil salinity, thus increasing rice production. For SC1 the rice production index was 61.2 % with a income of 2,359 €/ha, the same values as in the reference state, thus not varied along the 21st century. For SC2 there was a progressive reduction of rice production, with a range from 56.7 % to 52.6 % by 2100, depending on the SLR scenarios, representing an economic loss ranging from 2,300 €/ha to 2,255 €/ha by 2100.

12. Our models help to provide a better understanding of how rice fields will be impacted by SLR, being useful for rice farmers and decision makers, as well as to implement adaptation such as the development of sustainable sediment management plans for the Ebro River and its delta.