



Impacts of Climate Change on Wetland Ecosystems

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Abstract

Wetlands cover a heterogeneous spectrum of aquatic habitats, widely recognized as biodiversity hotspots and key components of the global carbon budget. They provide a wide range ecosystem goods (e.g. food, drinking water) and services (e.g. water purification, climate regulation, flood regulation, coastal protection, etc.) to human welfare. Wetlands are highly dependent on water levels, and so changes in climatic conditions (e.g. hydrological cycle, i.e. the nature and variability of the wet and dry seasons, and the number and severity of extreme events) will highly influence its structure and functioning. There is a widespread and ongoing degradation and loss of wetlands. Direct non-climatic anthropogenic impacts (e.g. drainage, water withdrawal, habitat fragmentation, eutrophication, etc.) have been more noteworthy than impacts directly attributed to climate change. Climatic and non-climatic drivers are expected to act synergistically on wetlands resulting in abrupt and large changes that can be difficult, expensive, or impossible to reverse. Ecosystems are hierarchical and climate change is projected to change their structure and functioning by affecting the abiotic and the biotic components (from individual organisms, populations, to communities). The overall impact will depend on the ecosystem resilience and the rate and magnitude of change in several critical climate drivers such as temperature and water availability (in inland wetlands), and, in addition, the sea level and storm surges (in coastal and low-lying wetlands). Temperature will affect both the abiotic (e.g. physical mixing, water quality, etc.) and the biotic compartments (e.g. throughout physiology, specie range shifts, overall community metabolism, etc.). Changes in the hydrological cycle together with a rising sea level and increasing storm surges will result in enhanced erosion of coastal habitats, salinization of groundwater aquifers and estuaries, altered tidal ranges, changes in sediment inputs and nutrient loadings, increased flooding and, consequently in a decrease of freshwater availability for humans and ecosystems. Predictions about the extent and direction of climate change on species and ecosystems are associated with varying degrees of confidence, which arise from uncertainties about how regional climate will change, the influence of non-climatic drivers and how complex ecological systems will respond. Indeed, as climate change alters ecosystem metabolism and species composition, unforeseen ecological changes are expected (e.g. harmful algal blooms or invasive alien species) that may threaten the goods and services these systems provide to humans.

Key words: climatic drivers, coastal wetlands, ecosystem functioning, ecosystem services, forecasting, lakes, eutrophication, rivers, temperature

1. What are wetlands? Ecological importance

Wetlands encompass a large and heterogeneous spectrum of aquatic habitats. Despite their limited extension when compared with marine and terrestrial biomes they are widely recognized as biodiversity hotspots (IPCC, 2002) and among the most populated worldwide. As estimated in the *Global Review of Wetland Resources and Priorities for Wetland Inventory* (Finlayson and Davidson, 1999), wetlands cover more than 1,280 million ha, representing less than 3% of the total biome area of the Biosphere. However, because of the overall high specific richness, endemism levels and productivity many wetlands have a world conservation status (i.e. Ramsar sites).

Table 1. Summary of average value of annual wetland services. Open cells indicate services that do not occur or are known to be negligible. Values for tropical forest are shown for comparison (Costanza et al. 1997).

Ecosystem	Estuaries	Seagrasses/ algae	Coral reefs	Saltmarsh/ mangroves	Swamps/ floodplains	Lake/ rivers	Tropical forests
Area (ha x 10 ⁶)	180	200	62	165	165	200	1.900
Services (\$ ha ⁻¹ y ⁻¹)							
<i>Climate regulation</i>							223
<i>Disturbance regulation</i>	567		2.750	1.839	7.240		5
<i>Water regulation</i>	-	-	-		30	5.445	6
<i>Water supply</i>	-	-	-		7.600	2.117	8
<i>Erosion control</i>	-	-	-				245
<i>Nutrient cycling</i>	21.100	19.002					922
<i>Waste treatment</i>			58	6.696	1.659	665	87
<i>Habitat/ refugia</i>	131		7	169	439		
<i>Food production</i>	521		220	466	47	41	32
<i>Raw materials</i>	25	2	27	162	49		315
<i>Genetic resources</i>							41
<i>Recreation</i>	381		3.008	658	491	230	112
<i>Cultural</i>	29		1		1.761		2
Total value (\$ ha ⁻¹ y ⁻¹)	22.832	19.004	6.075	9.990	19.580	8.498	2.007
Total global value (\$ y ⁻¹ x 10 ⁹)	4.110	3.801	375	1.648	3.231	1.700	3.813

According to the *Ramsar Convention on Wetlands*, wetlands include all inland aquatic habitats (permanent or temporary, whether fresh, brackish, or saline, and including lakes, streams, rivers and inland seas), coastal systems shallower than 6 m depth at low tide (lagoons, estuaries, marshes, mangroves, seagrass beds, mud flats and coral reefs), and human-made systems such as reservoirs (6,000–7,000 km³ according to recent estimates) and rice paddies. Wetlands are highly dependent on water levels, and so changes in climatic conditions that affect water availability will highly influence its structure and function.

Due to the exceptional diversity and productivity, wetlands provide a wide range ecosystem goods such as food (e.g. fisheries in coastal waters contribute \$34 billion to gross world product annually) or drinking water supply (c. a. 1.5–3 billion people depends on groundwater supply, often recharged through wetlands) and services to human population and welfare (e. g. water purification, climate regulation, flood regulation, coastal protection, recreational opportunities and tourism) (Table 1). Costanza *et al.* (1997) estimated the total global value of goods and services provided by coastal areas and wetland ecosystems to be 15.5 trillion USD y⁻¹ being 46% of the total value of services that global ecosystems are estimated to provide.

2. Climate change and impact on wetlands: a conceptual approach

The degradation and loss of wetlands is a worldwide phenomenon and seems to progress faster than in other ecosystems. For example between 1970 and 2000, populations of freshwater species included in the *Living Planet Index* declined on average by 50%, compared with 30% for marine and other terrestrial species (Millennium Ecosystem Assessment, 2005). Over the past century, non-climatic direct anthropogenic impacts have been more noteworthy than impacts directly attributed to climate change (Scavia *et al.*, 2002). The major non-climatic impacts include drainage of wetlands, water withdrawal, deforestation and land reclamation, habitat fragmentation, discharge of sewage, eutrophication and pollution, overharvesting and overexploitation, and the introduction of invasive alien species (IAS).

Climate change is expected to intensify the loss and degradation of many wetlands not only because of the complex relationships and feedbacks between climate and wetlands (thought the hydrological cycle, specifically the nature and variability of the wet and dry seasons, and the number and severity of extreme events) but also because of the likely synergistic effects of the non-climatic and climatic drivers (i.e. the so called global change), especially in coastal and low lying-areas (Fig., 1). It is widely acknowledged that global change will increase the likelihood of potentially abrupt changes in wetlands, which can be large in magnitude and difficult, expensive, or impossible to reverse (Millennium Ecosystem Assessment, 2005).

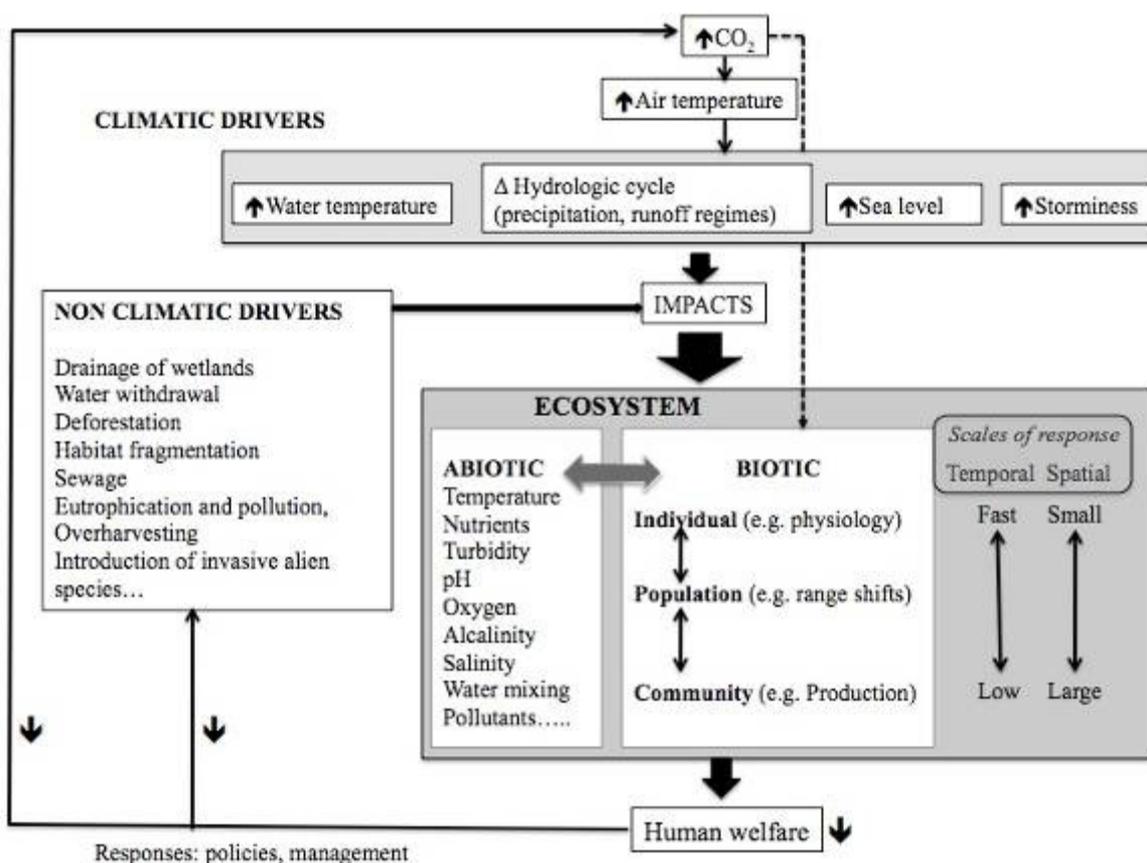


Figure 1. Conceptual approach of the impact of climate drivers and non-climatic drivers on wetland ecosystems, and the human responses. Dashed arrow indicates direct effects of lesser known importance.

An ecosystem can be defined as a dynamic complex of biotic communities (i.e. plants, animals and microorganisms), and the non-living environment, interacting as a functional unit. Climate change is expected to affect both the non-living and the biotic components (from individual organisms, populations, to communities) of the ecosystems, and in turn, their whole structure and functioning. The major consequences of the climate change will depend on the temporal and spatial scales at which effects are assessed. Transitional scales pertain to landscape-level shifts in location, morphometry, and persistence of wetlands and their biota over decades to centuries. Perturbational scales pertain to events with return times of years to decades that affect whole wetlands, such as floods, droughts or biota recruitment events (Carpenter *et al.*, 1992). Physiological scales relate mostly to fast (seconds to months) acclimatizing responses operating at small spatial scales (from single leaf or organ to the cellular and sub-cellular levels).

Wetlands are generally considered as resilient (i.e. the ability to maintain particular ecosystem services as conditions change) despite large inter-annual variation in hydrologic and temperature conditions, but rapid climate change may over-impose new environmental regimes that will exceed the resilience thresholds of wetlands. The resilience of many wetlands and their ability to adapt naturally is likely to be exceeded by 2100 by an unprecedented combination of change in climate, associated disturbances (e. g. flooding, drought), and other global change drivers cited above. The overall impact of climate change in inland wetland ecosystems will largely depend on the rate

and magnitude of change in two critical climate drivers: temperature and water availability from precipitation and runoff; in addition sea level and storm surges will also be important drivers in coastal and low-lying wetlands (Poff *et al.*, 2002).

Many biological processes are tightly controlled by temperature. Therefore, a change in the thermal regime (e.g., extreme temperatures, their extent, and seasonal rates of change) can directly regulate physiological traits such as physiological rates (e.g. growth) and behavioural performance (e.g. phenology), and influence habitat preference. Organisms are adapted to a specific range of temperatures, thus increased temperatures could exceed thermal optima for some coldwater species, mainly in summer. Because species have varying tolerance ranges for temperature, changes in temperature can produce shifts in species composition that, in turn, can affect the overall metabolism and productivity of wetlands (IPCC, 2002). Global warming is also expected to shift the potential geographic ranges of species (populations) to northward, or upward (in highlands) regions. Similarly, the southernmost (or lower-elevation) part of the present geographic range of many species will become unsuitable.

The feasibility of species to migrate into the new expanded ranges will depend on both the habitat availability and the capability to move along dispersal corridors. However, both circumstances will largely depend on wetland type and on the habitat fragmentation. In fact, the degree of fragmentation of the landscape in which wetlands occur is unparalleled historically (Dale, 1997). Wetlands are increasingly isolated and disconnected, making adjustment to rapid climate change through animal and plant dispersal very difficult. Thus, climate change clearly represents an additional, significant threat to wetlands, one that will interact in complex ways with existing human-caused stresses (Poff *et al.*, 2002).

The water volume in a wetland directly influences ecosystem functioning by determining the extent of suitable habitat for species and many aspects of water quality. Regional precipitation and runoff regimes determine the seasonal dynamics of the water volume of a certain wetland. By the middle of the XXI century, annual average runoff and water availability are projected to increase by 10-40% at high latitudes and in some wet tropical areas, and decrease by 10-30% over some dry regions at mid-latitudes and in the dry tropics, with an increase in heavy precipitation events (IPCC, 2007). Such seasonality strongly influences the species composition that thrives in a wetland. Therefore, a change in climate that alters the existing hydrologic regime has the potential to greatly modify habitat suitability for many species and cause significant ecological changes (even if the thermal regimes would remain unchanged).

Changes in the hydrological cycle (i.e. in the freshwater flow) as well as a rise in sea level and increases in storm surges driven by global warming will result in the enhanced erosion of shores and coastal habitats, salinization of groundwater and estuaries, altered tidal ranges in rivers and embayments, changes in sediment inputs and nutrient loadings, and increased coastal flooding and, consequently in a decrease of freshwater availability for humans and ecosystems in coastal areas. Wetlands, such as mangroves, saltmarshes and floodplains, can play a critical role in the physical buffering of climate change impacts (Scavia *et al.*, 2002)

3. Potential impacts of climate change in wetlands

Since the first Intergovernmental Panel on Climate Change report (IPCC, 1990), numerous reports and journal articles have addressed the observed and potential impacts of climatic change on species and their habitats. Although these studies documented changes that are clearly related to climate trends, they also revealed many challenges in predicting the outcome on species and ecosystems (Burkett *et al.*, 2005).

The ability to forecast the effects of climate change on ecosystems depends largely on the uncertainties about (1) future emissions and concentration of greenhouse gases, (2) constructing scenarios of climate change (3) sensitiveness of the climate change to perturbations (4) influence of non-climatic drivers. In addition, there is an established, but incomplete evidence of critical ecosystem thresholds and the increasing likelihood of triggering non-linear responses (i.e., the output is not directly proportional to the input) once thresholds have been exceeded, resulting in abrupt changes and novel states (poorly understood) (Burkett *et al.*, 2005). Moreover, projecting the impacts of climate change on ecosystems is further complicated by a patchy knowledge of the interlinked temporal and spatial scales of ecosystem responses and the multiple (climatic *versus* non-climatic) drivers involved (IPCC, 2007).

Accordingly, predictions about the extent and direction of climate change on species and ecosystems are associated with varying degrees of confidence. There is some confidence in predictions of global warming effects on organisms (physiology, abundances, distributions), dissolved oxygen concentrations, and sea level. There is also some confidence in predictions of the effects of sea-level rise on shallow continental margins, including flooding of wetlands, shoreline erosion, and enhanced storm surges. However there is less confidence regarding the effect of increased temperature on biotic interactions. Since the timing of response in different taxonomic groups is not always synchronous, there may be decoupling of species with their food sources, disruption of symbiotic relationships, and change in inter-specific competition (Poff *et al.*, 2002). Due to the combination of species-specific responses and interactions that can occur theoretically at any point in a food web, ecological communities existing today could easily be disaggregated (Burkett *et al.*, 2005). Finally, there is greater uncertainty to predict the effects of climate change on precipitation, wind patterns, and the frequency and intensity of storms, all these variables having a key influence on wetlands response to climate change (IPCC, 2007).

More specific and detailed information on both observed and potential impacts of climate change in lakes, running waters (streams and rivers) and coastal wetlands is addressed in the next section.

3.1. Lakes

The size spectrum of the freshwater lakes ranges from Lake Baikal (the deepest- 1620 m maximum depth- and the largest - 23.000 km³-) to a myriad of small-shallow lakes (less than 10 m depth) scattered in glaciated landscapes (Wetzel, 2001). Lake typology is based on the vertical temperature profiles and their seasonality. During spring and summer, as mid-latitude lakes (of sufficient depth) warm develop thermal stratification with a warm, lighter top layer (the epilimnion), and a cool, denser bottom layer (the

hypolimnion), with an in-between interface characterized by a steep temperature gradient (the thermocline). Climate interacts with lake morphometrics and wind (which affects the depth of the epilimnion) to determine the strength and extent of thermal stratification. Due to wind-driven water mixing and photosynthetic activity the oxygen levels of the epilimnion are high, whereas the hypolimnion may undergo oxygen depletion due to decomposition of dead organic material settling from the productive epilimnion, influencing habitat suitability for many species as will be addressed below.

Lakes will be affected by climate change through warmer temperatures, longer ice-free seasons and modifications in the hydrologic cycle. The response to climate change will largely depend on lake morphometrics (surface area and depth), exposure to wind and location (altitude, latitude and elevation). Such factors will determine the occurrence, strength and duration of thermal stratification, and, therefore, the seasonal extent of cool and warm water habitats available for species. Since the 1960s, epilimnion of many lakes around the world has warmed by 0.2 to 2°C and the hypolimnion (which reflect long-term trends) has increased by 0.2 to 0.7°C (IPPC, 2001). In warmer years, epilimnion temperature is higher, evaporation increases, summer stratification occurs earlier in the season, and thermocline becomes shallower. In several lakes in Europe and North America, the stratified period has advanced by up to 20 days and lengthened by 2 to 3 weeks, with increased thermal stability. The extent of ice cap for northern hemisphere lakes during the past 150 years is one of the strongest evidences of climate change. On average, from 1846 to 1995 the freeze data was 8.7 days later and the ice breakup 9.8 days earlier (Magnuson *et al.*, 2000).

The water supply to lakes may be differently affected by climate change depending on whether the water originates from glacier, snowmelt, rain, or aquifers. Water levels will probably increase in high latitude lakes, where climate models forecast increased precipitation, whereas water levels at mid- and low latitudes are projected to decline. Small lakes, endorheic (closed) lakes and temporary water bodies are most vulnerable to climate change because of their sensitivity to variations in the balance of inflows and evaporation. In cases where both precipitation and evaporation increase, lake levels might vary little but water turn over rate would likely be accelerated (Allan *et al.*, 2005).

Fauna and flora constitute an important component of the freshwater biota. In general, the dominant species of fauna are cold-blooded organisms which metabolism increases with temperature until an upper (species-specific) tolerance threshold is reached. Using a metanalysis approach it has been pointed out an increase in 3-30% of the macroinvertebrate production for every 1°C increase (Benke, 1993). Primary production is also expected to increase with warming. Additionally, increases in the amount of dissolved CO₂ (and for some species, HCO₃⁻), would result into higher rates of photosynthesis. Thus, acknowledging that there may be complex and unpredictable changes in species composition (Stefan *et al.*, 2001), an overall increase in system productivity would likely be a common response to climate warming if other factors do not limit the potential for enhanced productivity. However, if warming and eutrophication occurs together, the respiration of the whole community can easily counterbalance the primary production and the whole system becomes heterotrophic (i.e. a potential source of carbon).

Global warming will modify the extent of habitat availability for cool- and warm-water species, resulting in geographical range modifications (expansions or contractions).

Thus, in northern latitudes, the southernmost limit of the geographical distribution of same species will shift northward. Although some projections have been carried out for fish species (Sweeney *et al.*, 1992) they are only useful as a preliminary approach, since it is assumed that water warms about as much as air (valid for shallow, well-mixed lakes), there are dispersal corridors, and that other system processes (e. g. biotic interactions) remain unchanged. Thermal stratification adds further complexity to the effects of climate change. In large deep lakes, a summer warming of 3.5°C would increase suitable thermal habitat for warm-water fishes of the epilimnion. Cool-water fishes of the hypolimnion are also expected to thrive, since slight warming will raise metabolic activity yet remaining well within thermal tolerances, and oxygen concentrations will be high enough to support such aerobic metabolism (Magnuson *et al.*, 1997). Contrastingly, in smaller and shallower lakes the bulk lake volume is likely to warm significantly; therefore fish requiring cool hypolimnetic water (especially large, predatory fish) may suffer a reduction in the habitat.

Excessive nutrient inputs (eutrophication) used to trigger blooms of invasive aquatic weeds or nuisance algae (HABs, harmful algal blooms) including cyanobacteria (blue green algae). It promotes a reduction in water transparency and quality, the hypolimnion may become anoxic from excessive decomposition of organic matter that settles out from epilimnion, and some cyanobacteria species release toxins affecting dangerously to the water quality. A growing number of lakes are undergoing cultural eutrophication, and warming is expected to increase lake productivity (IPPC, 2001). However, because climate-driven processes have interacting, seasonal, and often opposing effects, the relationship between eutrophication and climate change is complex. A longer period of summer stratification will increase the likelihood of summer anoxia in the hypolimnion, whereas shorter ice duration will reduce the chance of winter anoxia (Stefan *et al.*, 2001). Increased nutrient loads, including dissolved organic carbon (DOC), will be delivered to lakes by their catchments under wetter climates, and less under dryer climates resulting in longer water residence times and increasing the importance of internal recycling (Schindler *et al.*, 1996). Light penetration (including the enhanced UV-B radiation due to the reduction in stratospheric ozone) will also augment if fewer DOC is exported from catchments into lakes resulting in increased primary production at greater depths. These complex and offsetting interactions make it extremely difficult to predict how lake ecosystems will respond to alternative climate scenarios (IPPC, 2001).

3.2. Running waters (streams and rivers)

Analyses of impacts of climate change on lakes have usually highlighted responses to temperature, whereas those on running waters have also been focused on changes in the flow regime (Poff *et al.*, 2002).

Because most of the running waters are relatively shallow, turbulent and well mixed, their response to variations in air temperature is relatively rapid (time lag of weeks or less) in comparison to lakes. Hence, it is expected that climate warming will raise the seasonal water temperature of the majority of rivers, especially in small and shallow ones (and, particularly, those most polewards). If temperature increases within the thermal tolerance range for a given riverine species, it is expected a physiological acclimation to the new conditions. On the contrary, if temperature augments above the thermal tolerance, species will face local extinction unless they migrate to a new

thermally suitable habitat. Such migration will depend both the dispersal mode (e.g. aerial, aquatic) of the species and the availability of suitable migration corridors, largely affected by human activities (Sweeney *et al.*, 1992). Many species may simply move upstream, because headwaters are generally cooler than downstream. However, warmer headwaters could result in the loss of species that already are confined to cool headwaters. So, although upstream migration may be feasible for some species, generalized reduction in biodiversity in many watersheds can be expected, as cool-adapted headwater species lose critical habitat. Moreover, warming of higher latitude running waters is more likely to open them to invasion, since biological traits of some alien species are accelerated by global warming (Shuter and Post, 1990).

The most obvious and immediate effects of climate change in stream and rivers involve changes in hydrologic patterns. River flow is characterized by the magnitude, duration, frequency, timing and rate of change of flow, and it is subjected to temporal (intra-annual, inter-annual and multi-annual) and regional variations associated to climate, vegetation and geomorphology (Carpenter *et al.*, 1992). The seasonal pattern of precipitation in a catchment area is translated into surface runoff that feeds into streams and rivers. Most of the streams in mountains or northern basins have snowmelt runoff regimes characterized by seasonal predictable flow periods (i.e. high flows in late spring followed by a predictable period of late summer, autumn, and winter base flow). One major consequence of global warming in snowmelt-dominated regions will be a shift from spring peak flows to late winter peaks (resulting in lowered summer flows) or even a shift from winter snow to rain and snow, or primarily rain, depending upon latitude, but resulting generally in more variable flow periods (Frederick and Gleick, 1999). Increasing aridity may render flows of many more streams unpredictable.

Some climate change models predict possible increases in the intensity of rainfall on fewer rain days resulting in enhanced flooding events (IPCC, 2007). High magnitude floods cause channel widening, which is exacerbated by sparse riparian vegetation typical of drought periods. An increase in floods would probably result in more silt, pollutants and organic matter entering streams and rivers with the corresponding degradation in water quality that could lead to a loss of sensitive stream species. Periods of increased precipitation allow reinstallation of riparian vegetation with attendant channel narrowing and flood flow control. Arid and semiarid regions experience, in comparison to wet regions, augmented runoff response to precipitation change, higher streamflow variability and more acute flash floods that could result in intermittent habitats. These facts lead several authors to suggest that these systems might provide early warnings of climate change (Carpenter *et al.*, 1992).

Future projections indicate that arid and semiarid regions will become even drier (IPCC, 2007). Decreased flows result in reduced connectivity of the river with its floodplain and riparian zone, emerging isolated pools where mobile organisms are concentrated and biotic interactions surely strengthen. These interactions or physiological stresses may differentially affect species or size classes of organisms (Carpenter *et al.*, 1992). Many riverine communities are partially dependent on riparian floodplains, either for nursery habitat for fish or for seasonal export of nutrients from floodplain wetlands to the river (see below). If these floodplains become disconnected from the main rivers because of reduced stream flows, aquatic productivity and diversity may decline. In arid regions, long periods of low flows are common, but rewetting is critical to maintaining ecosystem structure and functioning (Stanley *et al.*, 1997). In wetter regions, periods of

no flow are less common. Accordingly, increasing the duration of no-flow periods in these streams would represent a large deviation from usual conditions affecting their structure and dynamics.

At the level of ecosystem, the whole river metabolism will be affected by climate change. As aforementioned for lakes, temperature directly affects rate of photosynthesis and respiration in running waters, but respiration (R) tends to increase faster than primary production (P) as temperature rises, and the P/R ratio falls, assuming no limitation of organic substrates. Other factors being equal, a drop in P/R renders streams more of a sink than a source for organic matter and will decrease export downstream (Wetzel, 2001). In addition to production and respiration, river ecosystem metabolism depends on import, export, and intrasystem storage pools of organic matter. Litter from the riparian zone is quickly colonized by microorganisms, and subsequently consumed by a wide variety of invertebrates within the channel from headwater to mouth (according to River Continuum Concept, RCC) (Vannote *et al.*, 1980). Climate change is likely to affect the detritus decomposition rate and functioning of the microbial-shredder (leaf consumers) food web linkage in complex ways. Warming may result in altered carbon to nitrogen ratios of leaves, reducing palatability and affecting leaf/litter processing rates by feeders (e.g. microorganisms-shredders), and floods may export significant amounts of detritus downstream before it can be processed (Allan *et al.*, 2005), altering longitudinal patterns described by the RCC (Vannote *et al.*, 1980).

3.3. Coastal wetlands

Coastal wetlands are among the most productive ecosystems on earth. The high productivity is largely supported by nutrients delivered by freshwater runoff and the tidal mixing. It has been estimated that estuaries support about 5 % of global fish production yet only represent only 0.5 % of the world's marine environment (Millennium Ecosystem Assessment, 2005). Coastal wetlands are also among the most altered and threatened natural systems due to multiple human pressures. Many coastal wetlands will change as a consequence of projected sea level rise, increased storm and tidal surges, changes in storm intensity and frequency, and subsequent changes in river flow regimes and sediment transport (Poff *et al.*, 2002).

Coastal vegetated wetlands (e.g. marshes) are sensitive to climate change and long-term sea-level change as their location tracks sea level rise. Between 2000 and 2080 global losses of 33% and 44%, with significant regional variations, have been estimated for sea level rises of 36 and 72 cm respectively (McFadden *et al.*, 2007a). However, sea-level rise does not necessarily imply vegetation losses when soil accretes vertically at a rate at least equal to water level rise. Given that over the next 100 years the sea level is estimated to increase at a rate up to 2 to 9 mm y⁻¹, sediment accretion will have to proceed at a much higher rate than that observed over the last century (average values, 1.3 to 2.1 mm y⁻¹). Accretion depends on inorganic and organic matter inputs to the soil. Belowground plant tissues (roots) mostly provide the organic matter, whereas inorganic matter is mainly supplied as sediment inputs from either the sea or freshwater (the most important). In areas where riverine sediment supply is low or the backshore environment contains a fixed infrastructure (e. g. a dam), vertical accretion rates do not counterbalance the sea-level rise and water logging of wetland soils will lead to death of emergent vegetation, a rapid loss of elevation due to decomposition of the below-ground tissues, and ultimately submergence and erosion of the substrate causing a

substantial loss of coastal wetlands (Kesel, 1989). Such loss will produce negative cascade effects in the ecosystem. For example, coastal fisheries will be negatively affected, since wetlands are suitable habitats (nursery, feeding, living) for many fish and shellfish species.

In addition sea-level rise will lead to increasing salinity in coastal wetlands (reinforced if river discharge decreases), thereby tending to displace existing coastal plant and animal communities inland if migration is not blocked (e.g. habitat fragmentation) and if the rate of change does not exceed the capacity of communities to adapt or migrate. Climate change impacts on one or more cornerstone species, however, can result in abrupt community changes. Saltwater intrusion into freshwater aquifers is also potentially a major problem.

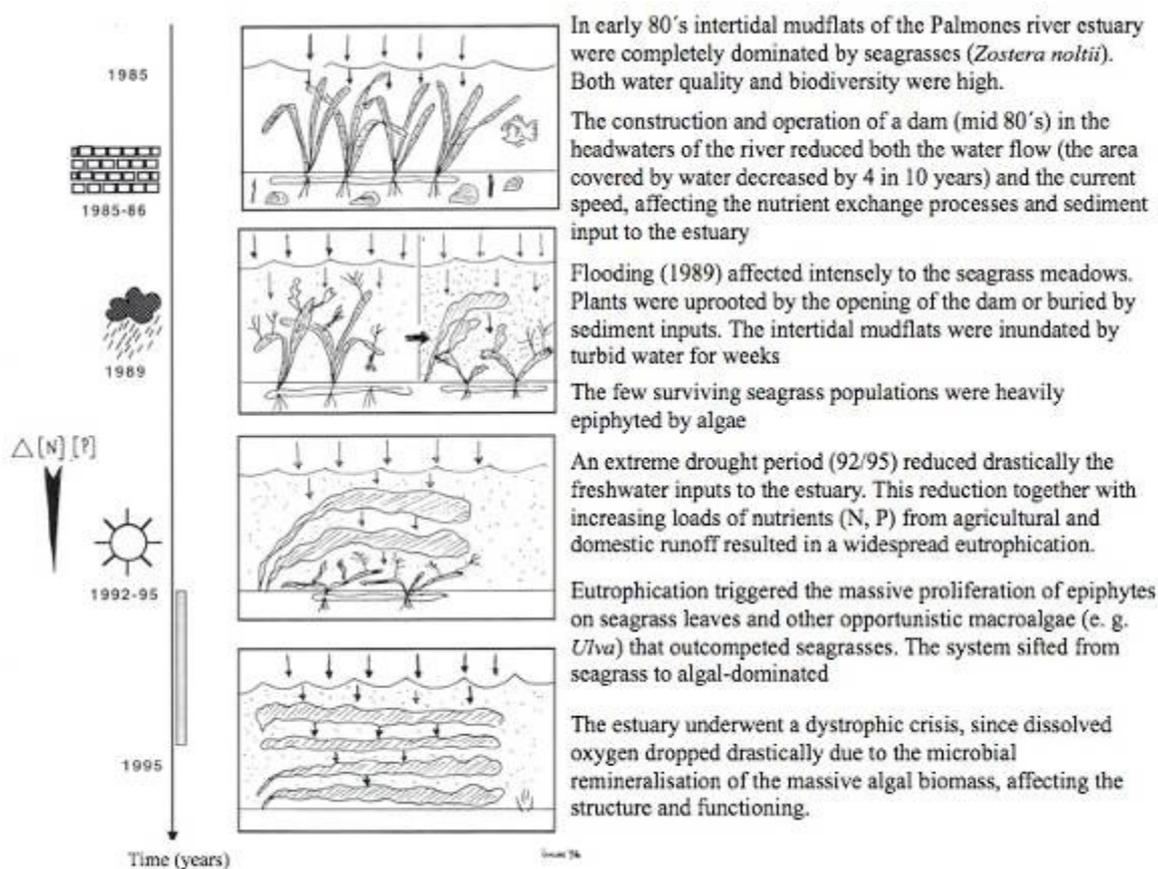


Figure 2. Schematic sequence of events occurred at Palmones river estuary (Southern Spain) due to human disturbances (dam construction, eutrophication) and extreme climatic episodes (flooding, drought) that resulted in a shift of species.

Some of the greatest potential impacts of climate change on coastal wetlands, particularly in estuaries will be driven by changes in freshwater runoff (Scavia *et al.*, 2002). Changes in freshwater inflow to coastal wetlands will alter the availability of sediment needed to accrete soils as sea levels rise. Increased freshwater discharges can have both pros and cons. The advantages of vertical soil accretion have already been addressed. An extra benefit could be an increase in fisheries since the nutrients delivered into estuaries stimulate primary production, increasing the energy available for herbivores on which fish forage. However, the most common situation is the proliferation of nuisance algae with increasing nutrient loads and altered physical

mixing (vertical stratification). Increased freshwater inflows decrease water residence time and increase vertical stratification, and vice versa. The effects of altered residence times can have significant effects on both phytoplankton and free-floating or benthic opportunistic macroalgae populations thriving under nutrient-enriched conditions (Valiela *et al.*, 1997). Consequently, in estuaries with very short water residence times bloom will be dominated by opportunistic macroalgae populations whereas in estuaries with longer water residence times, blooms will be dominated by phytoplankton species, some being toxic (Harmful Algal Blooms, HABs). The decrease in light availability for benthic aquatic vegetation beneath (e. g. seagrasses), and the depletion in oxygen levels due to the microbial respiration of senescent algal biomass will result in a dystrophic crisis affecting the whole functioning of the ecosystem, such as massive dead of fish and shellfish. One documented example of seagrass shift by macroalgal proliferation driven by changes in the hydrological cycle and eutrophication is the Palmones river estuary (Carreira *et al.*, 1995; Fig., 2). The increase in temperature (and CO₂) due to climate change is expected to reinforce such dystrophic crisis episodes. On one hand, the respiration of the community will increase proportionally more than the photosynthesis; on the other hand the warmer the water the lower the levels of dissolved oxygen. Another expected effect of warming is shifts in geographical species ranges. The frequency, duration, intensity of storms are also expected to change with global climate change. Storms events accompanied by heavy rainfall intensity and flooding will increase the freshwater delivery and the aforementioned increased inputs of sediments, nutrients, pollutants, etc. in estuaries and other coastal habitats.

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