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Global change effects on biogeochemical processes of Argentinian estuaries: An overview of vulnerabilities and ecohydrological adaptive outlooks

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ABSTRACT

The aims of this work are to provide an overview of the current stresses of estuaries in Argentina and to propose adaptation strategies from an ecohydrological approach. Several Argentinian estuaries are impacted by pollutants, derived mainly from sewage discharge and agricultural or industrial activities. Anthropogenic impacts are expected to rise with increasing human population. Climate-driven warmer temperature and hydrological changes will alter stratification, residence time, oxygen content, salinity, pollutant distribution, organism physiology and ecology, and nutrient dynamics. Good water quality is essential in enhancing estuarine ecological resilience to disturbances brought on by global change. The preservation, restoration, and creation of wetlands will help to protect the coast from erosion, increase sediment accretion rates, and improve water quality by removing excess nutrients and pollutants. The capacity of hydrologic basin ecosystems to absorb human and natural impacts can be improved through holistic management, which should consider social vulnerability in complex human–natural systems.

1. Introduction

Global change, the synergic interaction of anthropogenic impacts with climate-driven changes, is already disturbing estuarine ecosystems. Not only projected higher temperatures but also human population growth, sea-level rise, ocean acidification, changes in wind and current patterns, heat waves, extreme hydrological oscillations (e.g., floods and droughts) and coastal storms will strongly alter the dynamic of nutrients and pollutants and their relation with biota in estuarine and coastal systems. Even if the emissions of CO_2 are mitigated, some of the projected climatic changes are inevitable, and adaptation strategies are crucial for the successful management of estuaries and coastal waters. Although considerable research has been carried out on the possible impacts of climate change, little work has been conducted on adaptation strategies. The adaptive capacity of socioeconomic systems in Latin America is very low, whereas their vulnerability to climate change is high (Mata et al., 2001). Furthermore, while developing countries carry a large part of the global impact of climate change, rising atmospheric greenhouse gas concentrations are mainly caused by industrialised countries (Mertz et al., 2009). Therefore, one of the major issues that policy makers, scientists and stakeholders are now facing is the assessment of complex and uncertain climate-driven responses.

Evaluating the effects of and adapting to climate change on estuarine systems is a methodological challenge. Interdisciplinary approaches are needed for the understanding of functional links between basin structure, morphology, and biogeochemistry of different estuaries and adjacent wetlands (Lara et al., 2002; Lara and Cohen, 2006). The ecohydrology concept offers a variety of tools for basin and coastal management under the combined effects of climate change and anthropogenic pressure (Wolanski et al., 2004; Kopprio et al., 2014). This concept was developed within the International Hydrological Program of the United Nations Educational, Scientific and Cultural Organization (UNESCO) and is focussed on the integrated understanding of biological and hydrological processes at a catchment scale to create a solid basis for a

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cost-effective and holistic management of water resources (Zalewski, 2002). The aims of the program are to advance the integration of social, ecological, and hydrological research and to generate outcomes that enable the development of effective policies and practices. Ecohydrological management can be achieved by reversing the degradation and regulating the processes of water and nutrient circulation and energy flow in aquatic ecosystems, using the aquatic biota as water management tools and enhancing their social–ecological resilience. This multidisciplinary and adaptive strategy requires a clear knowledge of biogeochemical processes and their relations with estuarine hydrology to develop an efficient approach to basin management.

Estuarine systems are highly productive but vulnerable environments and are frequently under stress because of human population growth and socio-economic development. Although the coastline of Argentina extends over more than 4000 km, the number of estuaries is relatively low and their morphology and hydrography are highly variable (Piccolo and Perillo, 1999). However, a significant fraction of the Argentinian population is settled along the coasts of estuaries and will directly suffer because of climate-driven alterations of coastal ecosystems. To assess climate change impacts in the main Argentinian estuaries, this work provides an overview of the vulnerabilities and current stressors and suggests adaptive strategies based on an ecohydrological approach.

2. Vulnerability of Argentinian estuaries: an overview

The north extreme of the Pampa is the location of one of the most important estuarine environments of the continent: the Río de La Plata system (Fig. 1A). A microtidal estuary with a mouth of approximately 200 km width and an annual mean discharge of $\sim$22,000 $m^3 s^{-1}$, this estuary is highly productive and sustains valuable fisheries from Argentina and Uruguay. The Río de La Plata is usually stratified but can sporadically be mixed within a few hours by strong winds and is also affected by the El-Niño-Southern-Oscillation (ENSO) on a long-term scale (Nagy et al., 2008; Acha et al., 2008). The river is strongly impacted by anthropogenic activities. The coastline is deeply modified by urban and industrial settlements and presents eutrophic characteristics with recurrent harmful algal blooms and development of hypoxia in bottom waters (Nagy et al., 2002; Gómez et al., 2009; Giannuzzi et al., 2012). The Río de la Plata estuary is also heavily polluted by aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs) (Colombo et al., 1989, 1990, 2005). In addition, several invasive species have been reported in the estuary, such as the golden mussel *Limnoperna fortunei* (Muniz et al., 2005; Boltovskoy et al., 2006), the veined rapa whelk *Rapana venosa* (Giberto et al., 2006; Lanfranconi et al., 2009), and the reef-builder polychaete *Ficopomatus enigmaticus* (Muniz et al., 2005; Borthagaray et al., 2006). Furthermore, toxic strains of *Vibrio cholera* have been detected in waters and planktonic organisms (Binsztein et al., 2004).

Other microtidal estuaries in the wet Pampa are those of the Samborombón and Salado systems, the Mar Chiquita lagoon, and the Quequén Grande River (Fig. 1B–D). The Pampa region is strongly impacted by agricultural activities and suffers recurrent cycles of flood and drought weakly related with ENSO oscillations (Kopprio et al., 2010). In this region, the warm phase of ENSO (El Niño) is generally associated with wet periods, while the cold phase (La Niña) is associated with dry periods. The most important stresses on the Pampean rivers are the discharge of untreated sewage, nutrients, heavy metals, pathogenic agents, pesticides and herbicides, as well as physical changes produced by dredging and canalization (Gómez and Licursi, 2001). The Samborombón and Salado systems (Fig. 1B) have been classified as hypereutrophic (Gabellone et al., 2005; Schenone et al., 2008) and contain heavy metal pollution (Marcovecchio, 2004; Gagneten et al., 2007) and OCPs above the permissible levels (Monserrat et al., 1994). The wetland area of Samborombón bay ($\sim$2440 km^2) was declared a Ramsar site due to its importance for biodiversity conservation and as a breeding area for several fishes and migratory birds. Mar Chiquita (Fig. 1C) is the only coastal lagoon of Argentina. It receives freshwater streams from the Tandilia system, and its wetlands are also an important Ramsar site. This water body of approximately 46 km^2 presents a high biodiversity and is a nursery area for marine fauna. Large discharges of pesticides, fertilisers, particulates, and dissolved metals originating from the intensive agriculture in the surrounding area are threats to the lagoon ecosystem (Menone et al., 2001; Marcovecchio et al., 2006; Beltrame et al., 2009). The Quequén Grande estuary (Fig. 1D) is a primary, coastal-plain, and partially mixed system in which water circulation is highly reduced, producing strong reductive and even anoxic conditions due to the presence of a step at the head of the harbour (Perillo et al., 2005). This estuary is principally influenced by the untreated sewage discharge of the Necochea and Quequén cities. The barnacle *Balanus glandula* and *F. enigmaticus* (Orensanz et al., 2002) are exotic species that modify benthic hard-substrate and have a significant ecological impact in this area.

South of the Pampa, in a semiarid region, is the location of the mesotidal estuary of Bahía Blanca (Fig. 1E). The system is a shallow funnel-shaped estuary (mean depth of 10 m) formed by a series of NW–SE channels separated by interconnected tidal channels, islands, extensive tidal flats, and low marshes (Perillo et al., 2001). The Bahía Blanca estuary is influenced by the cyclical wet and dry periods of the Pampa region. Nature preserves of various uses are located in the Bahía Blanca estuary, such as: Bahía Blanca, Bahía Falsa and Bahía Verde, which were created to preserve biodiversity, sustain fisheries and protect species at-risk for extinction. Despite this ecological importance, the system is strongly impacted by industrial activities and maritime traffic. The Bahía Blanca estuary is considered highly eutrophic (Freije et al., 2008) and is polluted by untreated sewage discharge (Lara et al., 1985; Biancalana et al., 2012; Dutto et al., 2014), hydrocarbons (Lara et al., 1995; Arias et al., 2010), heavy metals (Marcovecchio and Ferrer, 2005; Simonetti et al., 2012; Fernández-Severini et al., 2013), and organotin compounds (Delucchi et al., 2007). The invading species *B. glandula* and the copepod *Eurytemora americana* have caused changes in species richness and diversity (Hoffmeyer, 2004). Antibiotic-resistant *Escherichia coli* has also been isolated from the Bahía Blanca estuary (Baldini and Cabezalí, 1991).

The major Patagonian estuaries are those of the rivers: Colorado, Negro, Chubut, Deseado, Santa Cruz, and Gallegos (Fig. 1F–K). The Patagonian region is characterised by semiarid conditions and strong winds, and its rivers generally feature oligotrophic conditions (Depetris et al., 2005). Despite the low population density, the main pollution problems are related to sewage effluents, agricultural runoff, oil extraction and transportation, and metal wastes (Gil et al., 1999; Gaiero et al., 2003; Brunet et al., 2005). In Patagonian ports with high marine traffic or in areas where ship hulls are painted, the presence of organotin compounds and imposex incidence in gastropods have been reported (Bigatti et al., 2009). Toxic blooms of dinoflagellates and the consumption of bivalves during red tides have been responsible for toxicity in humans (e.g., Esteves et al., 1992), including some cases of human death along the Patagonian coast. The discharges of the Colorado, Negro, and Chubut rivers are influenced by dams for hydroelectrical energy. The estuary of the Colorado River (Fig. 1F) presents a deltaic form, is mesotidal, and is impacted by several hydrological works for irrigation, which modified its hydrological characteristics, such as salinity gradient and intrusion. PAHs and some heavy metals have been detected in its basin (COIRCO, 2012). The Asian clam *Corbicula fluminea* has been reported in the Colorado River (Cazzaniga, 1997).

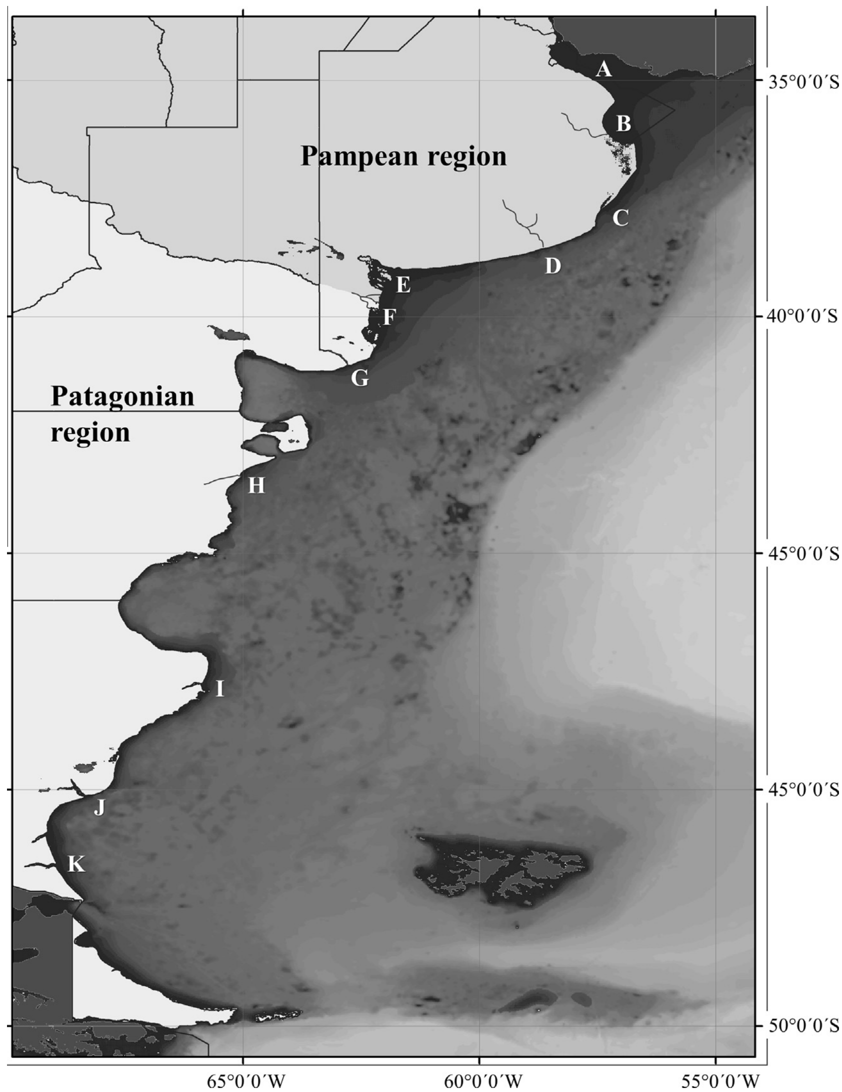

Fig. 1. Main estuaries in the coastline of Argentina. (A) Río de la Plata system, (B) Samborombón bay and Salado river, (C) Mar Chiquita lagoon, (D) Quequén Grande river, (E) Bahía Blanca system, (F) Río Colorado, (G) Río Negro, (H) Río Chubut, (I) Río Deseado, (J) Río Santa Cruz, and (K) Río Gallegos.

This river together with the Negro River is also influenced by exotic cyprinids (Kopprio, pers. obs.).

The Río Negro estuary (Fig. 1G) is characterised by macro-tides, sand banks, and islets with marshes. This environment is vital for juvenile fish and crustaceans and sustains a high biodiversity of marine birds and mammals. Currently, the Río Negro legislature proposes to create a natural protected area in the southern part of the estuary because of the ecological value of its wetlands. The river is extensively farmed along its valleys and is polluted by OCPs, polybrominated diphenyl ethers and PCBs (Isla et al., 2010; Miglioranza et al., 2013; Ondarza et al., 2014). Furthermore, the discharge of the Colorado and Negro rivers is vital for the aquatic communities of the Nature Reserve Bahía San Blas of approximately 300,000 ha, which is a refuge for wildlife with important fisheries. The coasts of this reserve have been deeply modified by the Pacific oyster *Crassostrea gigas*. Faecal coliforms were detected at several times the permissible levels in local points of the Río Negro estuary (Kopprio, unpublished data).

The Chubut estuary (Fig. 1H) is a coastal mesotidal-plain polluted by nutrient inputs from the use of fertilizers and the discharge of effluents (Depetris et al., 2005; Helbling et al., 2010), hydrocarbons from portuary activities (Commendatore and Esteves, 2004), and metals (Gil et al., 1999). The estuaries of the river Deseado, Santa Cruz, and Gallegos (Fig. 1I and J) are macrotidal sea-inlets with extensive coastal plains and a reduced freshwater discharge (Piccolo and Perillo, 1999). The extreme case is the Deseado estuary in which the effect of tidal currents is increased due to the impoverishment of the river, whose valley used to drain the ice cover from the Buenos Aires lake (Isla et al., 2004). The Deseado, Santa Cruz and Gallegos estuaries are also nature reserves for vulnerable marine fauna. According to Ferrari et al. (2005), the main threats to the Gallegos estuary are urbanisation, oil pipes, removal of native vegetation, introduction of exotic species, overgrazing, and uncontrolled recreational activities. The Chubut, Deseado, Santa Cruz, and Gallegos basins are influenced by exotic salmonids introduced for sport fishing (Aigo et al., 2008). The invasive kelp *Undaria pinnatifida*, which appeared in 1992 in Golfo Nuevo, has extended its distribution to reach the Deseado estuary (Martin and Bastida, 2008). In addition, exotic forms of cordgrass *Spartina* spp. modify the coastal zone of the southern Patagonian estuaries (Orensanz et al., 2002). Table 1 summarises the baseline of stresses and pollutants in the estuaries of the Pampean and Patagonian regions.

Table 1
Estuaries of Argentina classified according to their geographical region: characteristics and stresses.

Region	Characteristics	Physical stress	Trophic state	Pollutants	Main invasive species	Bacteria
Pampean	Primary coastal plains, with the exception of a coastal lagoon Microtidal to mesotidal	Dredging, canalization and urban and industrial settlements	Eutrophic to highly eutrophic with HABs and hypoxia cases	Hydrocarbons including PAHs, OCPs and other pesticides, PCBs, heavy metals, herbicides, fertilisers, organotin compounds	*Limnoperna fortunei* *Rapana venosa* *Balanus glandula* *Ficopomatus enigmaticus* *Eurytemora americana*	Toxic strains of *Vibrio cholera* and *Escherichia coli*. Antibiotic resistance species
Patagonian	Primary coastal plains, a delta and three sea-inlets Mesotidal to macrotidal	Dams, works for irrigation and urbanisation	Generally oligotrophic with cases of HABs	Hydrocarbons including PAHs, heavy metals, OCPs, PBDEs, PCBs, fertilisers, organotin compounds	*Corbicula fluminea* *Crassostrea gigas* *Undaria pinnatifida* Exotic cyprinids and salmonids Exotic *Spartina* spp.	Sites of elevated concentration of faecal coliforms, toxic strains unknown

HABs: harmful algal blooms, PAHs: polycyclic aromatic hydrocarbons, OCPs: organochlorine pesticides, PCBs: polychlorinated biphenyls and PBDE: polybrominated diphenyl ethers.

3. Global change effects

Fig. 2 illustrates the projected changes under climate-driven scenarios and expounds the complexity of the interactions. Climate-driven warmer temperatures and hydrological changes are likely to alter the stratification, residence time, oxygen content, salinity, and dynamic of nutrients in estuaries, producing changes similar to eutrophication (Scavia et al., 2002; Najjar et al., 2010; Jarvie et al., 2012). The liberation of more ammonium and phosphorus from the anoxic sediments induced by higher temperatures is likely to impact water quality, increasing turbidity, favouring phytoplankton blooms restructuring communities, and reducing macrophytes and benthonic organisms. According to Guinder et al. (2010), climate change has modified the hydrological features in the inner part of the Bahía Blanca estuary and potentially triggered long-term changes in the phytoplankton community. Furthermore, several changes in the zooplankton assemblage composition and structure have been detected over a 10 years period, probably due to temperature–salinity gradient patterns (Hoffmeyer, 2004). In the marine phytoplankton of Patagonia, feedback mechanisms of increased temperatures causing a shallower mixing depth will expose phytoplankton to higher radiation and will consequently produce a negative effect on bloom and on spring assemblages (Villafañe et al., 2013).

On the other hand, the occurrence of harmful algal blooms is expected overall to increase under future climatic conditions (O'Neil et al., 2012; Paerl and Paul, 2012). Increasing human populations are also expected to increase the nutrient discharge on estuaries. Prolonged blooms and the subsequent microbial decomposition of organic matter consume large amounts of oxygen, which can provoke oxygen minimum zones. Anoxic sediments may also induce liberation of methane and nitrous oxide, promoting more global warming (Moss, 2012). An extension in the distribution of water-borne disease is projected under warmer scenarios. Some bacteria associated with estuaries and plankton (e.g., *V. cholera*) are likely to expand their distribution to higher latitudes (Baker-Austin et al., 2013). Toxic strains of *V. cholera* have been recently detected in the Bahía Blanca estuary (Okuno, unpublished data) and are projected to extend their distribution to Patagonian estuaries. Tropical water-borne diseases are expected to intensify in sub-tropical and temperate regions (Shope, 1991). Dengue is an important emerging disease in Argentina (Carbajo et al., 2001).

Climate-driven hydrological and biogeochemical changes will also alter the dynamic of pollutants and produce physiological and ecological changes on biota. Climate change is predicted to increase the environmental levels and the toxicity of chemical contaminants overall and to mobilise the persistent pollutants (Schiedek et al., 2007; Boxall et al., 2009; Noyes et al., 2009). According to Hooper et al. (2013), climate change can make organisms more sensitive to chemical stressors, while alternatively, exposure to chemicals can make organisms more sensitive to climate-driven stressors. Consequently, the biota of highly polluted systems such as the Bahía Blanca and Rio de la Plata estuaries are likely to be harmed. The Argentinian estuaries are already populated by several exotic species that have modified their coastal structures (e.g., reef building *C. gigas* and *F. enigmaticus*) or have altered habitats (e.g. *U. pinnatifida*) and now interact with the local communities. The extinction or decline of sensitive species and the invasion of more resistant species favoured by warmer temperatures, lower pH and/or better pollutant tolerance can decouple trophic webs and be detrimental to higher trophic levels, thereby endangering fisheries. Evidence shows that fishermen in the Río de la Plata estuary are not prepared to cope with climatic extremes and projected changes for the 2050s (Nagy et al., 2006). The combined effects of higher temperatures and biogeochemical changes are already having a

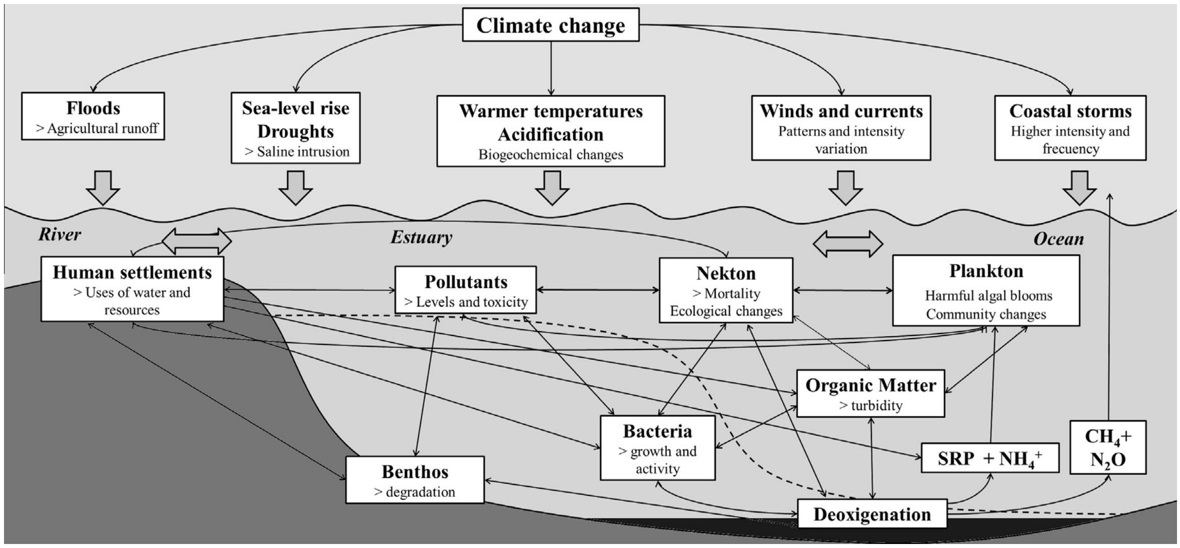

Fig. 2. An overview of possible global change impacts on the biogeochemistry and hydrology of the estuaries.

dramatic effect and will strongly impact organism physiology and behaviour, leading to changes from populations to communities (Harley et al., 2006; Doney et al., 2012; Bijma et al., 2013).

A higher recurrence and severity of natural disasters such as floods, droughts, and coastal storms are projected under scenarios of future greenhouse gas emissions. Multi-model values based on the SRES A1B scenario predict higher precipitation for the Pampa while predicting water deficit for Patagonia (IPCC, 2007). Higher rainfall for the Pampa may increase erosion and generate floods, increasing the transport of sediments, nutrients, and contaminants to the ocean (Rodrigues Capítulo et al., 2010). In the drier Patagonia, an increment in the saline intrusion with a considerable loss of wetlands and an increased concentration of existing pollutants and nutrients is expected. Moreover, an emergence of unprecedented heat waves and the intensification of hot conditions are expected in Argentina, particularly in summer for the south of the Pampa and the north of Patagonia in the latter part of the 21st century (Diffenbaugh and Scherer, 2011). More irrigation in the basins of the Colorado, Negro, and Chubut rivers will reduce the freshwater flow to the sea. However, the combination of globally acting phenomena (e.g., ENSO) and contrasting climate change projections (reviewed by Kopprio et al. (2010)) leave us with an uncertain future, and intensive droughts could occur after flooding.

Although the Pampean estuaries are theoretically benefited by higher precipitation, rising sea-level will induce a higher saline intrusion in this area with a considerable loss of wetlands, marshes, and coast. The Argentinian Patagonia is likely to experience changes below the global mean, up to ~30% in the southern extreme, while the Pampa region will experience changes above the global mean up to ~10% in the northern extreme (Perrette et al., 2013). The northern coastal area of the Pampa is more frequently exposed to higher levels of wave energy and coastal erosion; this trend is consistent with regional climate change and sea-level rise (Dragani and Romero, 2004; Fiore et al., 2009; Codignotto et al., 2012). The Holocene sea-level fluctuations in the Bahía Blanca estuary indicate that relatively short perturbations in global climate could have more important consequences than heretofore recognised (Gómez et al., 2005).

4. Adaptive outlooks and future directions

Good water quality is essential to enhance estuarine ecological resilience to climatic and anthropogenic stresses. However, socio-economic and political constraints in developing countries usually hamper the use of technology to prevent degradation or drive the restoration of estuarine waters (Wolanski et al., 2004). Ecohydrology is an integrative low-cost strategy to manage basins threatened by climate change and pollution and is based on the use of aquatic biota as water management tools. Wetlands are highly productive environments, and their properties are essential for management of estuaries and coasts (Table 2). Many wetlands and coastal vegetation have the capacity to adapt to numerous climate change effects (Lara, 2006; Day et al., 2008; Duarte et al., 2013). These systems offer valuable ecological benefits such as shoreline stabilisation and erosion control, sediment accretion, water retention, aquifer recharge and discharge, and nutrient and pollutant removal.

Table 2
Likely climate changes and wetland adaptive properties.

Climate change impact	Wetland adaptive properties
Sea level rise	Increase sediment and organic matter accretion
Eutrophication-like effects, harmful algal blooms and higher pollutant liberation	Retain nutrient and pollutant in plant biomass
Increased coastal storms	Absorb storm energy, stabilise shoreline, protect from erosion, and provides shelter for fauna
Floods	Decrease water runoff and decrease levels recharging the aquifer
Droughts	Keeps water and increase availability discharging the aquifer
Incremented extinction risks	Protects of vulnerable species, sustain biodiversity
Unexpected weather changes	Stabilises local climate

The ecological importance of wetlands, mostly extended fields of *Spartina* spp. and *Sarcocornia perennis*, has been widely recognised, and almost every Argentinian estuary includes a nature reserve. However, human modification and destruction of wetlands in combination with climate-driven changes threaten their adaptation capacity (Day et al., 2008; Erwin, 2009). In the Bahía Blanca case, 33% of the *S. perennis* marshes have been replaced by human land uses (Pratolongo et al., 2013). Management should also include the establishment of buffer zones between wetlands and human settlements, as well as the creation of new wetlands to restore the lost ecological functions of degraded areas and enhance the resilience of vulnerable coastal sectors. Basic research is needed regarding the capacity of local plant species to absorb nutrients and pollutants under different climatic settings (e.g., saline stress tolerance) for a particular estuary. Exploration of phytotechnologies relying on direct below-ground absorption of nutrients by plant root biomass could provide alternatives to the construction of open wetlands in places where this might involve a proliferation of disease vectors (Lara et al., 2011).

Although wetland vegetation takes up CO_2 and future atmospheric CO_2 levels can promote plant growth, in some cases, wetlands emit greenhouse gases such as methane (e.g., Thiere et al., 2011). The design of new wetlands should take a reduction in the emission of greenhouse gases into account. Moreover, the plant biomass should be harvested for an effective removal of nutrients and pollutants. Dammed rivers such as the Colorado, Río Negro and Chubut usually suffer from sediment starvation and coastal recession. Management programs should be aware of the fact that wetlands can keep pace with sea level rise if they have sufficient input of mineral and organic matter to provide an adequate accretion. Thus, an ecohydrological approach should emphasize the research on wetland plant species that are viable in a potentially endangered system and can provide a higher retention rate of the available yet reduced particle load. Furthermore, careful management of the water discharge of dammed rivers is necessary to be able to mitigate harmful algal blooms, for example, through the previous modelling of the effect of pulsed water discharge on plankton dynamics (Wolanski et al., 2006), as well as on the distribution of invertebrate and fish populations. Reservoirs, flooding plains, and channels can help to mitigate climate-driven hydrological uncertainty.

The Argentinian estuaries range from scarcely studied systems such as those in Patagonia to well-characterised systems such as the Bahía Blanca and Rio de la Plata estuary. Paradoxically, some of the better studied estuaries are those that are more degraded. Basic and applied research is urgently needed to fill the gaps in the understanding of the hydrological, ecological, and biogeochemical processes to develop effective adaptive management strategies for Argentinian estuaries. Ecological studies analysing the response of vulnerable species, their effect on trophic webs, and interactions with exotic species under changing climatic settings are also required. The knowledge of estuarine processes and threats does not necessarily signify better chances of building resilience in estuarine ecosystems, and several socio-economic aspects should also be included.

Particularly in the semiarid Pampa and arid Patagonian regions, the use of irrigation practices involving lower freshwater consumption and a more generally effective control of sewage and industrial discharge are urgently needed. In addressing climate change, human societies must be able to buffer disturbances, to self-organise, and to learn and adapt (Tompkins and Adger, 2004; Adger et al., 2005). Nevertheless, Argentina lacks an adequate legislation and investment policy for the management of water resources, there is a low or ineffective capacity of the public sector for findings solutions to environmental problems, and societal awareness and inclusion in participative management is scarce (Quirós and Drago, 1999). The long-term viability and operability of more than 80% of the marine protected areas in Argentina are threatened by the lack of basic resources, the absence of up-to-date plans, and management measures based on spontaneous decisions in response to immediate needs (Giaccardi and Tagliorette, 2007).

During the floods of the Rio Salado, coordination between the levels of government was practically non-existent, with many levels having shared and overlapping responsibilities in the basin, and there was a lack of experience of the different actors in working together constructively (Herzer, 2003). At the Río de La Plata estuary, the flood of La Plata city in 2013 claimed dozens of lives and generated 3,000 evacuees. Some of the causes of this catastrophe were not only heavy rainfall but also the lack of waterworks, poor environmental awareness, and deforestation. In the Bahía Blanca case, the first report of pollution by raw sewage discharge was mentioned in 1985 (Lara et al., 1985) and is still used as a case study after approximately 30 years (Dutto et al., 2014). Moreover, in the proposal for dredging a navigation channel in the inner estuary of Bahía Blanca, the social costs derived from the loss of the nursery function of the estuary and the loss of jobs associated with fishing activities of about $5 and 6.5 million were not included in the initial study of environmental impact (Zilio et al., 2013). Many anthropogenic modifications in the Quequén Grande estuary have resulted in significative economic expenses to the harbour and city authorities due to the lack of adequate prior studies (Perillo et al., 2005).

Education and training, participatory processes, dialogue to implement effective measures to take advantage of the generation of knowledge and information, forecasting, and early warning systems have been proposed for climate change adaptation of fisheries of the Río de La Plata estuary (Nagy et al., 2006). The same could be applied to increase the resilience of each estuary in combination with adequate legislation, coordination between levels of government, adequate environmental studies, bioremediation actions, basic and applied interdisciplinary research, and long-term investment and management. Long-term policies are fundamental for the successful adaptation of natural resources to climate change in developing countries, however, such policies are seldom governmental priorities and/or are extremely difficult to implement.

5. Conclusions

Most estuaries in Argentina are impacted by untreated sewage-discharge, agricultural runoff, metals, organic pollutants, and exotic species. Global change is likely to produce changes similar to eutrophication and to generally increase the toxicity and availability of pollutants. Eutrophication-like processes are expected under climate change scenarios and are likely to deeply impact the already eutrophic estuaries in the Pampa region. Moreover, the common microtidal regime of systems increases the residence time of nutrients and pollutants. The preservation of good water quality in estuaries is essential for climate change adaptation, and wetlands and coastal vegetation have several adaptive properties. Ecohydrological management should consider the preservation and creation of wetlands. Several socio-economic aspects such as long-term investment and management policies, education programs and an adequate legislation are also essential for an effective adaptation plan in developing countries. The building of social–ecological resilience represents a powerful tool for adaptation to climate change.

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