Natural and Social Sciences of Patagonia

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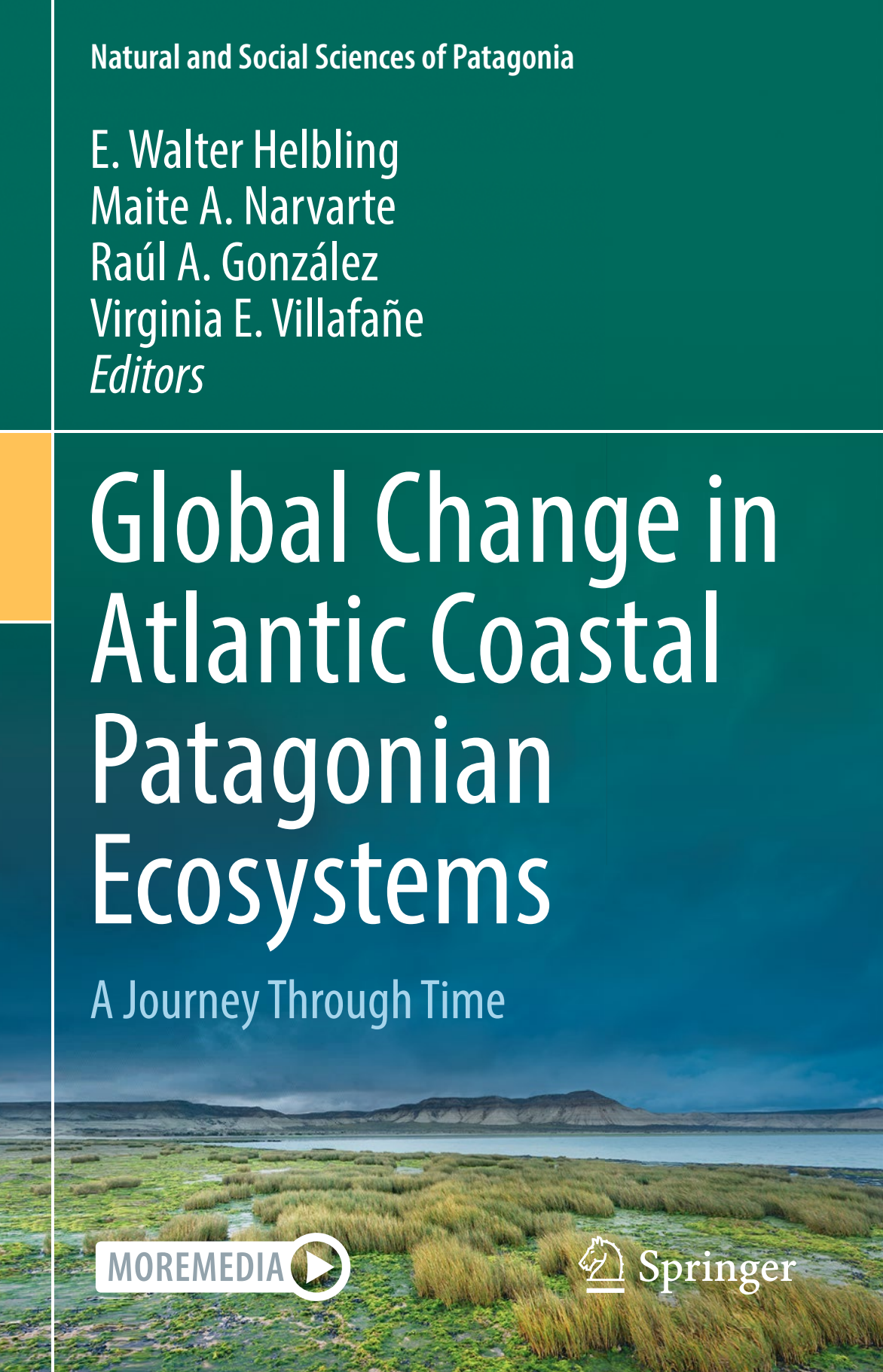
Global Change in Atlantic Coastal Patagonian Ecosystems

A Journey Through Time



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Natural and Social Sciences of Patagonia

Despite being an underpopulated region, Patagonia has attracted the attention of scientists since the very beginning of its settlement. From classical explorers such as Darwin or D'Orbigny, to modern science including nuclear and satellite developments, several disciplines have focused their efforts on unraveling Patagonia's natural and social history. Today, scientific and technological research is shifting from being shaped by northern agendas, towards more locally oriented objectives, such as the management of natural resources, the modernization of energy production and distribution, and the coexistence of rural and cosmopolitan social lifestyles. At the intersection of all these topics, new conflicts concerning the economy, human development, population, and the proper and long-standing planification and management of the landscape and its natural resources have emerged. These conflicts, of course, have also caught the attention of many interdisciplinary research groups.

This series is aimed at describing and discussing various aspects of this complex reality, but also at bridging the gaps between the scientific community and governments, policymakers, and society in general. The respective volumes will analyze and synthesize our knowledge of Patagonian biodiversity at different scales, from alleles, genes and species, to ecosystems and the biosphere, including its multilevel interactions. As humans cannot be viewed as being separate from biodiversity, the series' volumes will also share anthropological, archaeological, sociological and historical views of humanity, and highlight the wide range of benefits that ecosystems provide to humanity including provisioning, regulating and cultural services.

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Foreword: What Is This Book About?

This book is about the past, present, and future of the environment and environmental changes in the southwestern Atlantic Argentinean Patagonian coast; a beautiful and always windy region. The book is truly a journey through time, describing the environmental and biotic changes and, at the end, including humans as a main component challenging the environmental sustainability. The content will be appealing to scientists interested in environmental change, but it should also be of interest to managers, policy makers, and planners. The chapters focus on different components of the ecosystem and different time scales, and include the most recent research in climate and oceanographic science, ecology, urbanization, management, and conservation in coastal Patagonia. Finally, the authors also provide insights and strategies to develop a human-environment coexistence in a changing "near future" scenario. As the reader will see, the Argentinean Patagonian coast is also a land of science, conservation, and new urban developments.

The Argentine Patagonian coast extends for around 2000 km (it depends on how small or large is the unit of measure used) from the South of the Argentina Pampas (about 40°S) to the southern tip of South America (58°S). It is a relatively sparsely inhabited coastline (about one million inhabitants) with a few relatively larger cities with no more than a few hundred thousand people each (see chapter by Capandeguy and Sprechmann). Most of the coastal Patagonia is characterized by the presence of sharp perpendicular cliffs, which may be up to 70 m high, indicating an erosive coastal environment (see chapter by Isla and Isla). Overall, as seen in the chapter by Pessacg et al., Patagonia is a dry and windy region. Including its coasts and offshore marine shelves, it is dominated by the famous Westerlies, winds that flow from subtropical high-pressure belts to subpolar/circumpolar low-pressure belts. These winds are present year around, with a maximum intensity between 45° and 55° S. But, interestingly, during the warm seasons, wind patterns in the coastal areas are strongly influenced by the "sea breeze." This is the result of differential air heating over coastal land and the adjacent waters, and thus occurs mostly during the afternoon in the spring and summer months when the heating difference is higher. Coastal Patagonian "sea breeze" is still a poorly studied phenomenon, but is well known and highly predictable by the local population. This is good for windsurf and

kiteboarding, but it also has the potential of being useful for benthic intertidal or shallow subtidal species. Indeed, the high predictability of this phenomenon generates a strong potential for selection, and thus intertidal and shallow subtidal sedentary benthic species may use the current generated by this wind (surface flows onshore during the day, while bottom water flows offshore) to export or import their planktonic larvae. The well-known phototaxis of many of these larvae appears to have arisen to take advantage of this transport mechanism.

Thereby, the coast generates a typical boundary ecosystem, with biota specifically adapted and a mixture of species from the two adjacent environments linked by energy, material, and organism flows across this boundary. The coastal Patagonian marine biota is not homogeneous (see chapters by López-Gappa, and Horta et al.). To the north of 43°S–44°S, there is the warm-temperate waters of the Argentine Biogeographic province (that can extend up to southern Brazil), and to the south, there is the cold-temperate waters of the Magellanic Biogeographic province (that can extend up to southern Chile in the Pacific). In the adjacent land, the central and coastal Patagonian climate is semi-desert (see chapter by Pessacg et al.) with low rainfall levels mainly concentrated in winter. Thermal amplitude is important, but compared to the same latitudes of the northern hemisphere, the thermal variations in Patagonia are much lower, which is largely the product of the oceanic environment. The coastal Patagonian vegetation, adapted to arid and windy environments, is dominated by the shrub steppe of the Monte Biogeographic province in the North (approximately up to 43°S) and the grass steppe of the Patagonia province in the South. Thus, the interface is not homogeneous given the combination of different terrestrial and marine biogeographic provinces. Moreover, while the coastal land is desertic, the coastal waters are immersed in one of the large world "oceanic oases," the Patagonian shelf. This region belongs to one of the large marine ecosystems (LMEs), which are regional units described for the conservation and management of living marine resources. In this case, this LME incorporates the coastal environments, continental shelf, slope, and ocean basins, covering 6,581,500 km^2 of marine platform. Why this area is one of the highly productive shelves of the World is described and discussed in the chapter by Saraceno et al. But essentially, besides being fueled by the cold, nutrient-rich waters coming from the Antarctic Circumpolar Current either through the Malvinas Current (offshore along the Patagonian slope) or through the Patagonian Current on the shelf directly affecting the coast, a series of upwellings ("marine frontal systems") enhance the productivity of this area. The authors also describe in detail the different types of coastal features (e.g., gulfs, shelves) that regionally affect the oceanography and the productivity of this region.

This marine high productivity leads to large local biodiversity (see chapters by López-Gappa, Galván et al., Crespo, Horta et al. and Quintana et al.) The area is also of importance for distant migratory birds, fish, turtles, and marine mammals, including some of the most charismatic species that breed and feed in this region (e.g., black-browed albatrosses, Magellanic penguins, southern elephant seal, and southern right whale). The Patagonian sea, as expected, supports several high-volume fisheries, primarily for Argentine hake, Argentine red shrimp, and Argentine

shortfin squid. Obviously, there are conflicts between fishing and wildlife, which is discussed further in the chapters by Crespo, Narvarte et al., and Sala.

The coastal geography is characterized by tall sharp cliffs that generate beautiful scenic sites. They are made up of layers of sedimentary rock and are sometimes loaded with fossils, mainly invertebrates such as bivalves. These cliffs tell a story of large environmental changes. Indeed, as described in the chapter by Griffin et al., the presence of fossils in these mainly Cenozoic rocks as indicators of changes has been known for many years, although the scientific interest started with the first scientific explorers, such as d'Orbigny (1834–1847)[1] and Darwin (1846).[2] Now, this evidence tells us that since the initial opening of the Atlantic Ocean in the Early Cretaceous, this region has been affected by a number of marine transgressions. Undoubtedly, the separation from the Antarctic generating the Antarctic Circumpolar Current became a turning point in the provincialization of the weather in Patagonia. The fossil record also reflects large climatic oscillations and large changes in the sea water level, with important retractions and intrusions of the sea on the current Patagonian land. However, a trend towards desertification has been a constant process, although in the Late Pleistocene-Early Holocene transition when humans arrived in Patagonia, the climate was drier and colder than at present.

Closer in time, during the quaternary, dynamic processes affected the Patagonian coasts, leading to the characteristics of the beaches that we have today, which are described in the chapter by Isla and Isla. The combination between sea level change with alterations in the fluvial discharge intensity due to climatic variations models the coastline. Indeed, the estuaries and deltas have changed notoriously during the Holocene. Just due to changes in the watershed, some rivers increased their discharges where others reduced their flow depending on the dynamics of the glaciation, leading to estuaries of different shape and size that we have today.

Nowadays, there is no doubt that the Earth is enduring climate change, with a strong warming of the planet, accelerated at an unusually high rate due to anthropic effects. Although the phenomenon is directional (increase in global temperature), the effects vary widely between regions. Most likely, due to the oceanic characteristics, the effects of climate change are less important on the Patagonian coast when compared with the northern hemisphere. A well-known feature of global warming scenarios is that there is stronger warming on the land when compared with the sea. In the northern hemisphere, a region with a high land-sea ratio, the annual average temperature is higher than the southern hemisphere, and the northern hemisphere has been warming faster than the southern hemisphere since the early 1980s. Here, in the chapter by Pessacg et al., the authors describe the current climate characteristics and assess expected climate changes in Patagonia with a special emphasis on coastal areas. They show that mean temperature has been increasing in the continental Patagonia, at least during the last 70 years, but this warming trend is not

[1] d'Orbigny A (1834–1847) Voyage dans l' Amerique meridionale.

[2] Darwin CR (1846). Geological observations on South America. Being the third part of the geology of the voyage of the Beagle, under the command of Capt. Fitzroy, R.N. during the years 1832 to 1836. 337 pag. London: Smith Elder and Co.

occurring in the coastal areas where there is even evidence of cooling. Precipitations show a large interannual variability; although it seems to be a decreasing trend, extreme events are predicted. Overall, projections indicate that temperature and precipitation will increase. On the coastal waters, the chapter by Saraceno et al. explored the possibility of having detectable changes in oceanographic variables. Overall, they found that water temperature in the Argentine shelf shows some increase in surface in the northern part of the Patagonian coast, while the southern end of this area is cooling. There is also some increase in primary production in certain areas. Additionally, an increase in sea level occurs as expected for the southwestern Atlantic (approximately 1.6 mm $year^{-1}$), with some areas where the increase is higher (part of the San Matías gulf). Indeed, the coastal Patagonian sharp cliffs are evidence of an actual erosive environment (see chapter by Isla and Isla), with an estimated cliff retreat that varies between 0.3 and 1.4 m $year^{-1}$. In the chapter by Saraceno et al., the authors analyze possible effects on circulation based on models and discuss the potential oceanographic effects of increased freshwater input in the southern part of the Patagonian region due to the melting of the glaciers. Overall, changes are not important but are already occurring.

However, although the effects may still not be too apparent, we know that the inertia in the climate system may lead to effects in the future. Even if there is a complete stop to carbon dioxide emissions, the temperatures, and thus sea level, will continue increasing for several centuries. As described before, although still not very important in magnitude, the Patagonian coast is already enduring changes. Moreover, the coastal human population and urbanization has increased, generating an increase in industries, agriculture activities and therefore having some effects. These changes are expected to affect primary production, which in a highly productive region may result in important environmental changes. In the chapter by Villafañe et al., the authors extensively describe the complexity of understanding the final effects of different environmental drivers on the plankton dynamics. In particular, they do an exhaustive analysis of regional studies addressing the relationship between environmental change drivers and plankton abundance and diversity, discussing the methodological aspects and their limitations for these studies. Most of the studies performed have evaluated the individual responses to solar ultraviolet radiation (UVR), and a few evaluated the spatial distribution of zooplankton in relation to anthropogenic influence. They note that there is a gap in studies on pollutants such as heavy metals and microplastics, specifically experimental ones. There is no doubt that the studies done so far have contributed significantly to our understanding of the effects. However, the authors suggest that there is a need to integrate different trophic levels in order to best understand plankton responses and improve predictions of the impact of global change in this region.

There is no doubt that the interaction between species adds an extra complexity to understand the effect of drivers of climate change on the biotic system. As discussed in the chapter by Valiñas et al., the effects of environmental changes on the species are complex and not straightforward given that changes in the environmental conditions can modify the outcome of species interactions leading to different community structures. Hence, making predictions on the direct effects of global

change on individual species or groups of species may not be the best approach. To support their assertion, the authors of this chapter review the information about how some global changes related to environmental changes (e.g., increase in nutrient inputs, changes in UVR) affect biological interactions of species inhabiting coastal Patagonia. In particular, they review two well-known common regional environments, the coastal vegetated areas (salt marshes and macroalgal beds) and the nearshore waters. The evidence shows that the biological outcome of environmental changes is hard to predict if it is not investigated in the context of community structuring processes.

Even though community dynamics are well known and the species interactions well understood, the arrival of a new species may completely change the species relationships and thus community structure. This is exactly what happens with species invasions, which is, without a doubt, an anthropogenic effect that causes global change and has become one of the most serious threats to the World's coastal ecosystems. The Patagonian coast is not an exception. While Valiñas et al. show examples on how invasive species alter native communities through biological interactions, the chapters by López-Gappa and Horta et al., describe and analyze the invasion of non-indigenous benthic invertebrates and algae into intertidal and shallow subtidal habitats. There are a few introduced species, but the green or shore crab, the intertidal reef forming Japanese oyster, and the shallow subtidal brown wakame kelp are potentially the most important. The Japanese oyster was introduced to a bay in the northern limit of the Patagonian coast (San Blas bay) for aquaculture purposes in 1982, and fortunately, today their presence is mainly restricted there. The wakame kelp (see chapter by Horta et al.,) was first detected on the Patagonian coast in 1992 but now occupies more than 1000 km and continues to spread. Overall, their community effects are still poorly known, but all the species have the potential to spread along the whole Patagonian coast and generate important ecosystem impacts.

However, to actually understand the ecosystem effects of environmental change requires to know a reference baseline condition, which usually needs long-term information. Indeed, it will be desirable to have long-term ecological studies to get an integrated understanding of how the components of the ecosystems interact over time in a changing environment. Unfortunately, long term datasets are uncommon for many species, communities, or ecosystems, but count of population numbers and some life history characteristics are available in this region for some fish assemblages (see chapter by Galván et al.), which is available in greater detail for marine birds (see chapter by Quintana et al.) and marine mammals (see chapter by Crespo), allowing exploration of certain effects of a changing environment.

If the sea waters of coastal Patagonia are warming (see some examples in the chapter by Saraceno et al.), it is expected to have a southward range shift of warm-temperate species (those originated in the Argentine Biogeographic province), including fishes. In the chapter by Galván et al., the authors, by analyzing data of the coastal Patagonian fish assemblages since the 1970s, show evidence that this is starting to happen. They identify an increase in the number of fish species due to the arrival of warm water species in the northern and central Patagonia coasts.

Essentially, they see a pattern of tropicalization of temperate waters such as described in other parts of the World. Interestingly, several species, including elasmobranchs, have become less common, probably due to the direct or indirect effect of fishing. How these new arrivals affect the ecosystem functioning still remains to be investigated.

The Patagonian coasts are inhabited by several important bird species, including the three penguins, a petrel, five cormorants, three terns, and two skuas (see chapter by Quintana et al.). Many of these species have very large, colorful, and noisy colonies that constitute important touristic attractions, mainly during the breeding seasons. However, natural and human-induced environmental changes are their main threats. Climate variability largely influences their population dynamics, and thus they are good indicators of marine environmental changes. On the Patagonian coast, there is some long term (mainly population numbers) information on the Magellanic penguin, petrels, and the imperial cormorant. According to these data, one of the largest Magellanic penguin breeding colonies is declining, but new colonies are emerging elsewhere. On the contrary, petrels are increasing in their two breeding colonies. However, as described in the chapter by Quintana et al., just population numbers – the most common information – may not be sufficient to understand the actual or potential effects of climate change. To address this issue, they describe their results from a relatively long-term integrated dataset (i.e., 16-year period) for the imperial cormorant. Their information includes population numbers, breeding parameters, and foraging patterns (by sex and age), which allow them to describe inter-annual variation. At the same time, they examine how both sexes exploited the depth-dependent "energy landscape" of the area around the colony. Finally, in their chapter, Quintana et al. discuss the value of long-term tracking, breeding, and population data for ecological studies, as well as the implications for conservation and management strategies.

Although the effects of climate change on marine mammals in this region are not evident, they have endured large changes due to human activities. Fortunately, there are several species with long-term information. In his chapter, Crespo reviews the existing data of distribution, population numbers, and trend of the most conspicuous species of marine mammals in this region, which includes the South American sea lion, South American fur seal, southern right whale, and the dusky and Commerson's dolphins. Several of them are recovering after being on the verge of extinction due to interactions with humans, mainly during the early European colonization. None of them has reached a stable population size. However, although it is unknown what will be the equilibrium size for these populations, the author emphasizes that in an expected changing environment, there is a need to seriously consider managing the ecosystem under a new paradigm, which includes fisheries. The Patagonian sea is highly productive, supporting large fisheries based primarily on Argentine hake, Argentine red shrimp, and Argentine shortfin squid (see chapter by Narvarte et al.). All of them are also connected directly or indirectly through the food web with all marine mammals (and also oceanic birds). Given that it is expected that these fisheries will continue operating, it will be necessary to manage the fisheries in order to coexist with a healthy population of top predators. However, given that some of

these species are highly migratory, just an agreement restricted to the Argentine sea may not be enough. It should also include international management strategies.

As described before (see also chapter by Narvarte et al.), large-scale fisheries are important in Patagonian waters, which have significantly increased since last century, producing more than three quarters of the Argentine landings and exports. But, the relationship between environmental change and Patagonian fisheries is still poorly understood, perhaps because there is still no strong evidence of the effects of environmental changes. However, there is some strong evidence of humans inducing changes in fish and shellfish populations. In this book, Narvarte et al. tell us the history of the Argentine fisheries, and describe the few cases of strong effects on the fish population. As they describe, problems in Argentina's fisheries have been more related to overfishing than to environmental problems. Overfishing is one of the main anthropic stressors, but the effects of climate change constitute another stressor that, even if it is not acting now, is expected to be important in the future. Given that, in their chapter, Narvarte et al. develop an ad-hoc framework to examine the vulnerability of stocks of the Patagonian fisheries, taking into account the most evident physicochemical (temperature and acidification) and anthropic (overexploitation and market forces) stressors. Using this technique, they identify fisheries that are more vulnerable to different stressors, including the ones related to environmental changes. Moreover, the authors discuss alternatives to reduce vulnerabilities and discuss the management options under an ecosystem management approach. The take-out message is that well-managed fisheries are better prepared to confront environmental changes.

Going back to the coastline, there is no doubt that humans have long been attracted to the coastline, most likely due to the relatively easy access to resources. There is even evidence that early humans left Africa along the Red Sea coastline and colonized the Americas before the ice-free corridor opened up. Nowadays, about 40% of the human population live on the coastline. Human settlements on the Patagonian follow the same pattern. In their chapter, and as Gómez Otero and Svoboda report, the northern part of the Patagonian coast has been occupied since at least the Middle Holocene until the Natives-European contact period. These hunter-gatherers exploited marine resources such as mollusks, fish, birds, and pinnipeds. The large coastal shell middens, or "conchales", generated at least 5,300 years BP, indicate the heavy use of intertidal and or shallow subtidal as a food source. The relative importance of food items in the diet of humans varies over time; while mussels were more common at the beginning, Southern sea lions became more common by the end of this period. This change in the diet was probably due to changes in human behavior, which may have been influenced by climate change, changing their relationship with the coastal environment. Interestingly, the decrease in the representation of marine fauna in their diet is hypothesized to be linked to the introduction of horses, which have other needs and provide a lower hunting cost tool to capture terrestrial prey such as guanacos and rheas.

Today, the Patagonian human population is primarily associated with the coasts (see chapter by Capandeguy and Sprechmann), and urbanization is generating increasing pressure on coastal ecosystems. To provide ideas of how to confront this

problem under a changing environmental scenario, the chapter by Capandeguy and Sprechmann gives a description of the recent history of urbanization in the region, analyzing the urban planning, and the coastal uses by tourism. Reviewing the literature, the authors analyze the different territorial perspectives based on different conceptual backgrounds (i.e., a land-sea strip with humans concentrated within a large territory, a mosaic of phenomenological landscape, and a captive environment within viscous hyperobjects), which were used to understand the coastal Patagonian urbanization. The principal historical features and main activities of cities and towns are described, detailing their major challenges and their social and environmental vulnerabilities. The strong relationship between urbanization and tourism, a major activity of several urban areas of the Patagonian coast since the mid-twentieth century, is also analyzed. They discuss urbanism and its adaptation in times of climate change. Perhaps, as the virus pandemic is teaching us, the Anthropocene, or the time where nature was dominated by humans, is coming to an end and we should review our relationship with nature. Thus, the paradigm discussed in the chapter by Capandeguy and Sprechmann, of achieving a "multi-species architecture and urbanism," came at the right moment. Interestingly, this paradigm involves considering marine conservation as part of urban planning.

Besides local urbanization, human activity in general is a major threat to biodiversity. The human population is growing and is continuously moving up the "carrying capacity," which threatens biodiversity because their higher use of resources directly (e.g., exploitation) or indirectly (e.g., displacing other species) affects biodiversity. Coastal Patagonia, an area with high biodiversity, is not an exception to this pattern. Although their human population size is rather low, their effects could be important. As Sala describes in his chapter, this is also a region with a variety of management actions aimed at regional or global conservation of species, habitats, and ecosystems. All fisheries are managed (see also chapter by Narvarte et al.), and there are several large-scale protected areas under different jurisdictional management. However, conservation science is a dynamic field of science, and Sala takes us through the development of the idea of conservation science up to the present, showing the many approaches to reach the goal of maintaining biodiversity. The author then provides us with the history of conservation science of coastal environments in Patagonia, noting the key role of stakeholder involvement, mainly through NGOs, in pushing many of these actions. However, such a wide range of management and conservation actions was not always developed under the same paradigm, which resulted in conflicts. Furthermore, in many cases, the view of the natural and social worlds as separate persists. Given that, he makes a strong point toward adopting the vision of a "social-ecological system" (SES), thus integrating the social and ecological dimensions in conservation science in general, and on the Patagonian coast in particular. This will undoubtedly be difficult due to the need to incorporate a multidisciplinary approach, but the results should be more robust and adaptive in a changing scenario. It is interesting to note that even coming from very different areas of science, the idea of adopting a "SES" view of development has similarities with the idea of developing with a "multi-species urbanism" approach proposed in

the chapter by Capandeguy and Sprechmann. This convergence may be important when we think about the future.

In closing, this book takes us on a journey through time, mainly along the Patagonian coast, but also through the southwest Atlantic. On this trip we see the geological history, its environmental changes, its biodiversity, its first and current settlers, and its present and future problems derived from environmental changes. In the end, the authors propose a variety of ideas of how to converge to a vision of development based on sustainability, where, in a changing environment and even using their ecosystem services, we will be able to coexist in harmony with the different components of the ecosystem. That is why this book will not only be interesting for scientists but also for planners, managers, and decision makers.

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Introduction: When and How Our Journey Started

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Since its formation, our planet underwent significant alterations, from large displacement of land masses that resulted in the current continents and seas to an increasing oxygenation that changed the Earth's atmosphere. In addition, an intense volcanism activity released huge amounts of greenhouse gases (GHGs), mainly water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere. The natural increase in GHGs triggered a key phenomenon, the "greenhouse effect", that allowed an increase of surface temperature making it possible the life on Earth (Tyndall 1863). For instance, the mean temperature of 15 °C at present would have been minus 18 °C without this effect (Mesarovic 2019). Paleoclimate investigations on ice cores allowed to infer the natural variations of one of the GHGs (i.e., CO_2) over geological timescales (~800,000 years; Fig. 1A, B), evidencing changes up/down over time as large as ca. 100 ppmv within time lapses of 10–30

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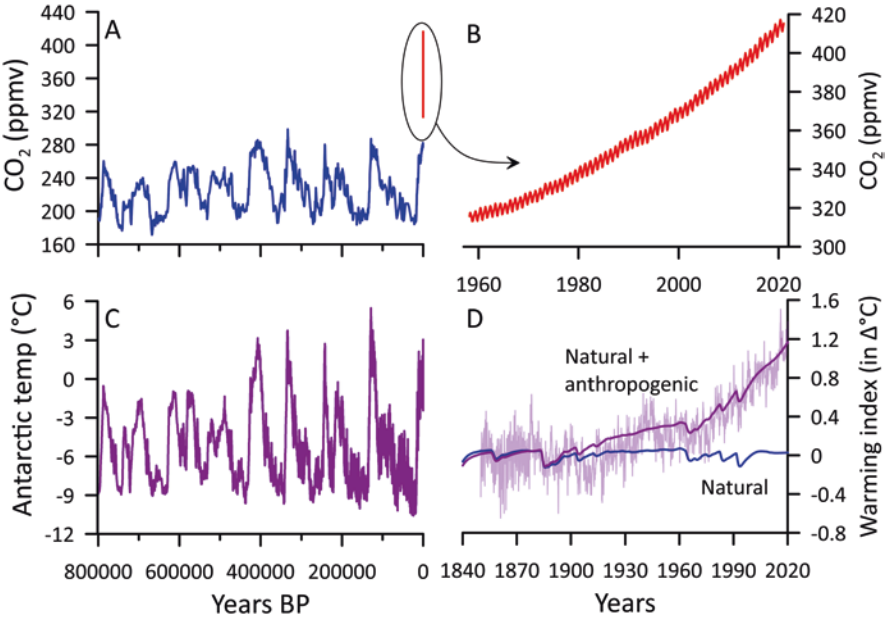

Fig. 1 Estimation of variations in carbon dioxide (CO_2) concentrations (**A**; Lüthi et al. 2008) and temperature (**C**; Jouzel et al. 2007) measured in Antarctic ice cores over the last 800,000 years before present. (**B**) Mean atmospheric CO_2 concentrations measured in the Mauna Loa Baseline Observatory since the 1950s (https://www.esrl.noaa.gov/gmd/ccgg/trends/). (**D**) The mean global warming index for the 1840–2020 period (https://www.globalwarmingindex.org/AWI/info_page.html; Haustein et al. 2017). The blue line represents the natural contribution (solar radiation and volcanic activity), the purple line shows the combined contribution (natural and human-induced) to the temperature change, and the evolution of the warming index over time

thousand years. These variations in CO_2 concentrations were accompanied with changes in temperature (Fig. 1C, D); hence, the Earth alternated between cold (e.g., the Little Ice Age, nineteenth century) and warm (e.g., Medieval Warm Period, 800–1300 AD) periods, such as demonstrated through paleoclimate investigations (Neukom et al. 2019). Fine measurements carried out by Keeling et al. (1976) on air samples taken at the Mauna Loa Observatory in Hawaii since the late 1950s showed that not only the increase of CO_2 in the atmosphere reached concentrations far above those due to natural variations (Fig. 1A, B) – as high as 420 ppmv in 2020 – but also that they increased at much higher rate, than previously observed, of about 100 ppmv in ca. 70 years. This higher rate of increase in CO_2 concentration over the last decades have been coupled with a concomitant increase of the global temperature of 1.2 °C in 120 years (Fig. 1D).

Some decades ago, researchers posed the possibility whether this "natural dynamism" observed in air samples and ice cores over short- and long-term timescales, respectively, could be influenced by humankind. This proposal lies in two important facts: (1) a huge increase in the human population occurred since the eighteenth