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REPORT

Patagonian Fjord Ecosystems in Southern Chile as a Highly Vulnerable Region: Problems and Needs

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Abstract Southern Chile encompasses one of the most extensive fjord regions of the world, the Patagonia, currently exposed to natural and anthropogenic perturbations. These fjord ecosystems provide important services to humans, which have not been adequately measured and valued. As a consequence, ecosystem services are commonly ignored in public policy design and in the evaluation of development projects. Here we tackle questions that are highly relevant for the nation's development, namely (1) understanding fjord functioning, and (2) developing management strategies based on ecosystem services, in order to secure simultaneous and adequate use of these ecosystems which area influenced by ecological (e.g., biogeochemical) and productive (e.g., aquaculture, fisheries) processes. We also seek to strengthen the analysis of fjord ecosystem value from the economical (including coastal zoning), socio-cultural, institutional, and governmental points of view. In addition, the investigation of current and future effects of climate change on this large region offers a unique opportunity to understand the social and economic consequences of a global phenomenon at local to regional scales. Biogeochemical and socio-economic models will be used to simulate future scenarios under a gamut of management options.

Keywords Patagonian fjords · Ecosystem services · Oceanography

Fjords, estuaries and other coastal "semi enclosed" ecosystems are some of the most biogeochemically active areas of the biosphere. They exchange (or transport) large amounts of matter and energy and connect terrestrial systems with the open ocean across continental slopes. Changes in fresh water and matter exchange between the terrestrial and coastal ocean systems, which are driven by climate change and/or direct human activities, affect nutrient and carbon cycling and, thus, the health of entire coastal fjords ecosystems. Ongoing and further research to understand these processes is the key to the sustainable management of Chilean fjords and estuarine systems. A major pollution problem in aquatic habitats is the overfertilization of waters by excessive nutrient inputs (particularly nitrogen and phosphorus) from agriculture, aquaculture and soil erosion. Nutrients (N and P) are essential for microalgae growth; however, changes and fluctuations in concentrations can result in numerous undesirable effects, such as increased harmful algal blooms (HABs), which can eventually result in fish kills, major shifts in the food web structure, and biogeochemical changes in both the water column and sediments. These changes eventually could lead to the loss of valuable ecosystem goods and services. Southern Chile contains one of the major fjord regions of the world. This region is within the Valdivian Rainforest Eco-Region and the transition zone of the West Wind Drift Current, which is classified amongst those with the highest global conservation priority worldwide due to its threats and high degree of endemism (Dinerstein et al. 1998). Furthermore, it can provide a basis for comparative studies on fjord ecosystems from the Northern Hemisphere (USA, Norway, Sweden) and Southern Hemisphere (New Zealand) with contrasting levels of human disturbances.

Oceanographically, this region could be considered a transitional marine system, influenced by oceanic deep waters of high salinity/nutrients and surface freshwater of low salinity/nutrients. The estuarine waters are relatively poor in nutrients, with the oceanic Subantarctic Waters (SAAW) being the main source of nutrients, as documented for the southern Chile shelf margin (Silva and Neshyba 1979). In Chilean fjords, the horizontal buoyancy input resulting from freshwater runoff has an important effect on the primary production (PP) of algae that are isolated from their principal source of nutrients (i.e., the nutrients trapped below the pycnocline), thus, leading to the eventual shutdown of production after short bloom periods (Valle-Levinson et al. 2007; Iriarte et al. 2007). The highly seasonal variability in PP (1–3 g C m^{-2} day^{-1}; 4) has been associated with efficient export production to the sediments (0.2–0.6 g C m^{-2} day^{-1}; 5), suggesting that the Chilean fjord region is a major "CO_2 sink" during the highly productive season. It is, therefore, relevant to understand the processes/factors that modulate the efficiency of the biological pump in Chilean fjord systems (González et al. 2009). In addition, the factors affecting freshwater dynamics would impact nutrient load and water circulation on a local scale; they would also affect ocean productivity and climate from the regional to the global scale. For aquatic systems in southern Chile, such as rivers, estuaries, and fjords, several proxies have been used such as sediment cores to track past climatic variability (El Niño; 6), environmental conditions (aquaculture impacts; 7), and river streamflow reconstructions by information contained in tree rings (Lara et al. 2005).

PROBLEMS AND NEEDS: MAJOR IMPACTS IN CHILEAN FJORD ECOSYSTEMS

Drastic and sustained reductions in precipitation and river discharges, which are driven by both local and remote processes, may produce strong fluctuations and a reduction in the streamflow from the rivers and glaciers that reach the fjord and channel regions of southern Chile (Lara et al. 2005). Our preliminary analysis showed that negative anomalies of streamflows values of Puelo River at Reloncavi fjord (41°S) are associated with positive anomalies (El Niño events) sea surface temperatures in the equatorial Pacific Ocean (140°W). This suggests that a reduction in freshwater streamflow could reduce the surface nutrient loading (particularly of silica) into the fjords and, thus, decrease the overall productivity, pattern that has been observed within the Puyuhuapi fjord (47°S) in the last 100 years (Sepulveda et al. 2005; Rebolledo et al. 2005).

Changes in nutrient loading from natural or anthropogenic sources are associated with changes in ambient nutrient ratios (N:P and Si:N), which in turn have been used to explain shifts in the composition of phytoplankton assemblages. For example, possible consequences of silicic acid limitation on PP are a shift towards high flagellate to diatom ratios (Ptacnik et al. 2008) and a decrease in both PP and the vertical flux of particulate organic carbon. This change in the phytoplankton assemblage has the potential to reduce the strength of the biological pump and the magnitude of the CO_2 sink in the fjord region, and consequently produce a negative feedback on global climate change. On the other hand, changes in nutrient ratios (N:P and Si:N) can lead to blooms that reduce water quality and cause temporal hypoxia, due to post-bloom decomposition of biomass, and toxic blooms, due to potentially toxic species. Both types of blooms can have serious consequences on human population (health and employee turnover and performance) and business (tourism, artisan fishing, and shellfish and salmon aquaculture) in the fjords of southern Chile. In addition, aquaculture activities, like routine fertilizer and feed additions in coastal salmon farms (mainly ammonium input), could also modulate the seasonal phytoplankton blooms and stimulate the growth of HAB in southern Chile (Arzul et al. 1999; Iriarte et al. 2005). At present, the salmon farming industry faces its major challenge after the ISA virus outbreaks occurred during 2007–2008 in the northern Patagonian region (41–43°S), which has been used extensively for salmon-cage farming during the last two decades. The precise estimation of the carrying capacity of the fjord systems (for aquaculture activities) and the possible impacts of changes in the carrying capacity on ecosystems services is a major scientific challenge in this pristine region. Ecosystem services are critical to the functioning of coastal systems and contribute significantly to human well-being, representing a considerable portion of the total economic value of the coastal environment. Coastal systems cover only 6.3% of the world's surface, but are responsible for 43% of the estimated value of the world's ecosystem services (Costanza et al. 1997). It follows that the loss of coastal and open ocean ecosystems, which is occurring throughout the world, represents a major loss to the world's and to individual coastal nations' natural capital (Craig 2007). In particular, fjords provide services (e.g., water availability

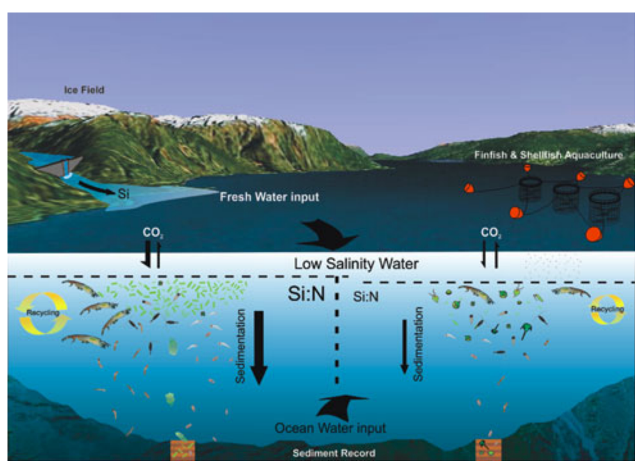

Fig. 1 Schematic model of fjord ecosystem services and energy and materials flows considering direct and indirect drivers in Patagonian fjords

and regulation, nutrient cycle, food production, biodiversity refugee) that we have started to asses based on modelling and management tools supported by field and experimental research in southern Chile.

Since freshwater discharge plays a critical role in the scientific understanding of regional change processes (e.g., biogeochemical cycles and land use change patterns) in the Patagonian fjord ecosystem (Fig. 1), we postulate the following questions to guide our research: (1) Does the reduction in streamflow alter the effectiveness of the biological pump and the export flux in southern Chile? (2) Will the short-term (seasonal) and long-term (decadal) decrease in the freshwater streamflow pattern drastically reduce the local productivity and the effectiveness of the fjord region as a CO_2 sink? (3) How do changes in the fjord ecosystem functions and processes that are driven by natural and anthropogenic factors affect key ecosystem services and, consequently, the well-being of different social groups that benefit from fjord ecosystems?

The investigation of current and future effects of climate change (i.e., CO_2 cycle) on Chilean fjords offers a unique opportunity to understand the environmental, social, and economic consequences of a phenomenon of global importance. At present, few studies have estimated the benefits of Chilean fjords and they have concentrated on direct benefits such as recreational opportunities (Arismendi and Nahuelhual 2007). On the contrary, we are not aware of any ongoing or published study that evaluates the indirect economic benefits from fjord ecosystems. We expect to identify main relationships between regulatory and habitat functions and services based on the following assumptions: **Case i**: Changes in nutrient ratios and loads affect the PP of fjords; in turn changes on PP affect *fisheries production*, which directly influences people's well-being, specifically through reduced fish catch. **Case ii**: Changes in nutrient ratios and loads promote toxic blooms that affect *people's health*; in this case the indirect benefit of maintaining well-functioning nutrient cycles can be seen as the avoided damage on human health. **Case iii**: Changes in nutrient ratios and loads promote algal blooms (non-toxic) which may reduce water quality causing hypoxia; in turn, altered water quality conditions can affect *shellfish and salmon aquaculture*.

Finally, we propose three strategic objectives for a long-term scientific programme in Patagonian fjords:

(1) To understand the processes and mechanisms that control the fate of PP in southern Chile fjord ecosystems and how these processes are affected by climate change variability and human activities.
(2) To propose fjord management strategies based on ecological and economic findings, whilst taking into account the Chilean institutional setting (property rights and current regulations) and integrating relevant stakeholders.
(3) To develop an integrated modelling approach for ecosystem service assessment in the Chilean fjords. This model will incorporate ecosystem dynamics, management tools, impacts of human activities and climate change, mitigating procedures and regulations, using an ecosystem approach.

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