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The combined impact of land use change and aquaculture on sediment and water quality in oligotrophic Lake Rupanco (North Patagonia, Chile, 40.8°S)

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A B S T R A C T

Water and sediment quality in North Patagonia's large, oligotrophic lakes are expected to suffer as native forest continues to be fragmented and degraded by its conversion to cropping and pasture land uses. These changes in land use are expected to increase diffuse nutrient loads to the region's lakes. In addition, these lakes are home to the world's second largest salmon aquaculture industry which provides additional point sources of nutrients within the lakes. We studied the combined influences of land use change and salmon farming on the nutrient concentrations in a North Patagonian lake (Lake Rupanco, 233 km^2 water surface, 163 m average depth) in four sub-watersheds ranging in disturbance from near-pristine forest to 53% converted to cropping and pasture. Nitrogen exports from the tributary sub-watersheds increased from 33 kg TN/km^2/y to 621 kg TN/km^2/y as the proportion of crop and pasture land increased. The combined nutrient load from land use change and salmon farming has led to significant differences in the nitrogen concentrations of the lake's water column and sediments in the near-shore zones across the lake. Total nitrogen concentrations in the sediments varied from 37 ± 18 mg/kg in near-pristine sub-watersheds without salmon farming to 6400 ± 698 mg/kg where the sub-watershed was dominated by crop and pasture lands combined with the presence of salmon farming. These results demonstrate the importance of considering the impacts of both salmon farming and land use on water and sediment quality for future environmental planning, management and decision making.

1. Introduction

Conversion of pristine landscapes, especially native forests, to agricultural and pastoral land uses is known to increase diffuse pollutant loads of sediment, nitrogen and phosphorus to receiving waters due to increased soil erosion and wash off of applied fertilizers and pesticides (Carpenter et al., 1998; Harris, 2001). Increasing sediment loads can reduce water transparency and can cause profound changes in aquatic ecology such as transitions from clear macrophyte-dominated systems (both marine and freshwater) to more turbid phytoplankton dominated systems. Increased nutrient loads mainly nitrogen and phosphorus, from diffuse sources in watersheds plus intensive activities in the water column such as salmon farming in net cages, can cause environmental imbalances (Boyer et al., 2006; Guo et al., 2009) by accelerating eutrophication of the freshwater and coastal marine receiving waters (Smith, 2003). This may lead to harmful algal blooms, loss of biodiversity, and the generation or establishment of hypoxic and/or anoxic conditions in the water column and sediments (Rabalais et al., 2009).

Land use change is a primary anthropogenic perturbation (Foley et al., 2005) and more scientific effort is required to elucidate better

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how this change affects hydrologic processes and nutrient loads (e.g., Ierodiaconou et al., 2005). The composition and spatial arrangement of land uses have been greatly modified by deforestation for the expansion of cropping and pasture activities across the world (Zak et al., 2008). These changes have increased both diffuse and point contributions of nutrients from watersheds (Stoate et al., 2009).

Much of our knowledge regarding land use change and its influence on aquatic systems comes from research conducted in the Northern Hemisphere (e.g., De la Crétaz and Barten, 2007). In contrast, the far-southern reaches of the Southern Hemisphere, such as Chilean Patagonia (39°S–55°S), have been used mainly to analyze these processes under conditions of low anthropogenic perturbation or directly in pristine conditions (Hedin et al., 1995). The forest ecosystems of southern Chile make up a third of the world's temperate forests and provide essential ecological functions such as soil protection, nutrient recycling, and hydrologic control (e.g., Oyarzún et al., 2010).

Perakis and Hedin (2002) report that watersheds of this region which are dominated by broad-leaved evergreen rainforests have significantly lower exports of nitrogen, principally in its inorganic forms, than those in the temperate forest ecosystems of the North Hemisphere, which experience greater anthropogenic perturbation. Although an important area of Chilean Patagonia can be considered pristine, the northern portion of this territory (hereafter North Patagonia; 39°S–44°S) has a long history of land use change and is currently characterized by a heterogenous mosaic of native forests, shrubland, crop and pasture lands, and plantations of exotic trees (Echeverría et al., 2012). Given this transformation of the landscape it is not surprising that research done on rivers within this region has begun to show increasing nutrient concentrations and exports, mainly of inorganic nitrogen (e.g., Pizarro et al., 2010).

In addition, farming of salmon in floating cages has experienced a significant growth in recent decades (Bostock et al., 2010). The increase in salmon farming has been linked to water quality impacts (water column and sediments) in the areas below and around the floating net cages, largely through contributions of nitrogen and phosphorus from the unconsumed food, feces, and urine of the farmed fish (Kutti et al., 2007; Guo et al., 2009). In Chile, during the early nineteen-nineties, salmon farming generated incomes of US $160 million per year (140,000 tonnes). By 2011, salmon production exceeded US $2.9 billion (650,000 tonnes) and had become one of the main economic activities of the country. One reason for the strong growth of this industry has been its ability to implement its production cycle in oligotrophic lakes with low levels of disturbance in their drainage basins. In particular, the use of lakes for the smoltification process (the transition between freshwater to seawater) has been one of the more practical features of the Chilean salmon industry. This pattern of production has led to the establishment of more than 50 salmon farms (floating cages from 100 to 400 m^2; 7–10 m depth) in 16 lakes with different morphological characteristics (León-Muñoz et al., 2007).

In the Chilean North Patagonian watersheds, the combined impact of land use change and salmon farming threatens the water quality of the oligotrophic lakes in the region. These lakes have, until relatively recently, experienced low nutrient exports from watersheds with high forest cover (Steinhart et al., 2002). Despite its importance for environmental decision-making, planning, and management, little scientific information is available on the combined impacts of land use change and salmon farming on freshwater lakes. Here, we evaluated the effects of land use change and salmon farming on nitrogen and phosphorus loads in a North Patagonian lake, Lake Rupanco. The lake's sub-catchments exhibit a gradient of land use disturbance and we examined the relationship between diffuse pollutant loads and the level of watershed disturbance. We also investigated the impact of salmon farming operations on the lake's water column and sediment chemistry. We expect to find that the water quality of the near-shore zone is strongly influenced by the native forest conversion to crop and pasture land and the presence or absence of salmon farming (floating net cages) in the nearby area. Finally, we offer recommendations regarding water quality targets and the future management of Lake Rupanco and its watershed.

2. Materials and methods

2.1. Study area

The present research was carried out in Lake Rupanco (40.8°S–72.5°W; 118 m a.s.l.; Fig. 1). The system is of glacial origin (11,000 years ago) and experiences a rainy temperate climate with annual precipitation that varies with altitude from 1600 to 4800 mm (50% of this occurs between May and July) (Oyarzún and Huber, 2003). According to the limnological studies performed in this system (233 km^2 water surface, 163 m average depth), Rupanco is an oligotrophic (Secchi disc = ~15 m), temperate, monomitic lake, with a water column that is mixed in winter (~10 °C) and stratified in summer (~19.7 °C, epilimnion 15–20 m) (Campos et al., 1992). The lake's hydraulic residence time has been estimated to be approximately 12 years based on the streamflow of its only outflow (Rahue River Q = ~100 m^3/s). According to the Chilean National Service of Geology and Mining (SERNAGEOMIN, 1982) the watershed area (778 km^2) is 3.3 times the size of the body of water (233 km^2) and comprised of soils derived from volcanic ash in the upper zones and glacial and fluvio-glacial sediments in the flatter sections. By the end of the seventies the Rupanco watershed was dominated by large fragments of native forest (~65%), but in the lower zones and toward the mouth of the watershed, patches of shrubland and crop and pasture lands increased substantially (~20%) (Fig. 1) (Echeverría et al., 2012). Additionally, the Lake Rupanco is one of the most important freshwater systems for Chilean salmon farming accounting for 20% of salmon production in Chilean lakes. There are seven salmon farms covering 161 ha of lake surface with nearly 2500 tonnes produced annually (León-Muñoz et al., 2007).

2.2. Sampling design

We selected four tributary sub-watersheds (sites A, B, C and D) within Lake Rupanco with different degrees of forest conversion and with presence and absence of salmon farming near the shore zones (Fig. 1). These study sites were selected so as to include: watersheds with different proportions of crop and pasture lands (5% to over 50%); sectors from the head to the mouth of the lake; and near-shore zones without salmon farming nearby (site A) and with salmon farming in floating net cages (sites B, C, and D, Fig. 1).

2.2.1. Tributary sub-watersheds

In each of the four tributary sub-watersheds, we generated a thematic map with the following land use types: barren soil and snow covers, native forest (for old-growth forest, secondary forest, and krumholz), shrubland, and crop and pasture lands. This was conducted through a supervised classification of Landsat ETM + images (years 1998, 2001, 2006; 30 m resolution) using ENVI 4.2 image processing system (Exelis Visual Information Solutions, Boulder, Colorado). Spatial patterns of land uses were analyzed with FRAGSTATS 3.3 (McGarigal and Marks, 1995) using the following landscape metrics: total area (CA); percentage of landscape (PLAND); largest patch index (LPI), understood to be the percentage of the watershed covered by the largest patch of each