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Recovery of black-necked swans, macrophytes and water quality in a Ramsar wetland of southern Chile: Assessing resilience following sudden anthropogenic disturbances

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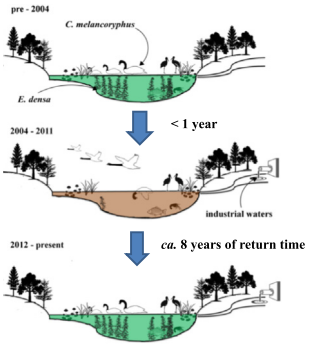
HIGHLIGHTS

- In 2004, the Rio Cruces wetland, a Chilean Ramsar site was affected by an anthropogenic disturbance.
- Swan numbers and weights decreased drastically across the wetland.
- Swan decrease correlated with abundance of their main food source: the macrophyte *Egeria densa*
- Swan hepatic abnormalities were associated with increased iron content in *E. densa*.
- The swan population and *E. densa* cover returned to normal conditions in 8 years.

GRAPHICAL ABSTRACT



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ABSTRACT

In 2004 migration and mortality for unknown reasons of the herbivorous Black necked swan (*Cygnus melancorhyphus* (Molina, 1782)) occurred within the Río Cruces wetland (southern Chile), a Ramsar Site and nature sanctuary. Before 2004, this wetland hosted the largest breeding population of this water bird in the Neotropic Realm. The concurrent decrease in the spatial occurrence of the aquatic plant *Egeria densa* Planch. 1849 - the main food source of swans - was proposed as a cause for swan migration and mortality. Additionally, post-mortem analyses carried out on swans during 2004 showed diminished body weight, high iron loads and histopathological abnormalities in their livers, suggesting iron storage disease. Various hypotheses were postulated to describe those changes; the most plausible related to variations in water quality after a pulp mill located upstream the wetland started to operate in February 2004. Those changes cascaded throughout the stands of *E. densa* whose remnants had high iron contents in their tissues. Here we present results of a long-term monitoring program of the wetland components, which show that swan population abundance, body weights and histological liver conditions recovered to pre-disturbance levels in 2012. The recovery of *E. densa* and iron content in plants throughout the wetland, also returned to pre-disturbance levels in the same 8-year time period. These results show the temporal scale over which resilience and natural restoring processes occur in wetland ecosystems of temperate regions such as southern Chile.

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1. Introduction

Wetlands are areas of marsh, fen, peat land, swamps, wooded wetlands, whether natural or artificial, permanent or temporary, with water that is static or flowing, which may be fresh, brackish or salty, including coastal areas of marine water to a depth which at low tide it does not exceed six meters (www.ramsar.org). Wetlands provide valued ecosystem services to society, including water purification, carbon storage, trapping of nutrients and pollutants, sediment and flood control, biodiversity maintenance, fisheries and tourism, among others (e.g., Zedler and Kercher, 2005). In spite of their importance, wetlands are frequently degraded by human-induced activities such as land conversion to agriculture, water extraction and overloads of polluted waters (e.g., Zedler and Kercher, 2005).

Due the broad degradation of wetland ecosystems, many efforts have been attempted for their restoration, with different level of success, highlighting the importance of integrating resilience in restoration planning, The latter is now envisioned as a dynamic and adaptive process, in which natural variability has paramount importance in reducing risk of population decline and loss of ecosystem services; for instance, when confronting uncertain climate impacts (e.g., Timpane-Padgham et al., 2017). Therefore, identifying the spatial and temporal scales of natural variability in ecosystems will improve decision -taking processes in restoration objectives operating at different biodiversity levels (i.e. individuals, population, and communities; e.g. Naeem and Li, 1997). Resilience describes the capacity of an ecosystem to absorb disturbances, as it reorganizes and retains their dynamical structure through mechanisms such as resistance to and recovery from perturbations (e.g. Walker et al., 2004). Thus, understanding recovery timescales of wetland ecosystem components after a natural or anthropogenic disturbance, provide a unique opportunity to estimate resilience in a broad perspective (Ives, 1995; Neubert and Caswell, 1997).

To date, nearly 14 million hectares in 1600 sites around the world have been designated as wetlands of international importance; thirteen of these sites are in Chile (spanning nearly 362.000 ha) (http://www.ramsar.org). Until 2004, the Río Cruces wetland, a Ramsar Site and a nature sanctuary adjacent to the city of Valdivia (40°S), was the main breeding site of the charismatic herbivorous Black-necked swan, *Cygnus melancorhyphus* (Molina, 1782) (swans hereafter) in the Neotropic Realm (Schlatter, 1998; Schlatter et al., 2002). This swan is an herbivorous water bird (Corti and Schlatter, 2002) and the only native species of the genus *Cygnus* in this biogeographic region (Araya and Millie, 1986; Navas, 1977). Its geographic distribution spans southern Brasil, Paraguay, Uruguay, Argentina and much of Chile (Casares, 1933; Schlatter et al., 1991a, 1991b). Data collected from 1986 to 2004 showed that the breeding season of this swan extended from June to September, with a mean clutch size (all seasons included) close to 3.1 eggs (Silva et al., 2012). The swan population at the Río Cruces wetland consisted of ~12,000–14,000 swans in 1994–1996, likely well above carrying capacity. Between 2000 and 2004, the population declined to around 5000–6000 birds (data from Corporación Nacional Forestal (CONAF), Chile; www.conaf.cl). At that time, these water birds were primarily supported by *Egeria densa* Planch. 1849 (Corti and Schlatter, 2002), an aquatic macrophyte which used to be the dominant submerged plant in the wetland (Steubing et al., 1980).

However, the swan population of the Río Cruces wetland decreased primarily due to emigration starting in mid-2004, with only a couple of hundred individuals observed during 2005–2006 (Lagos et al., 2008). This emigration event resulted in higher abundances in wetlands away from Río Cruces. For example, Ramírez et al. (2006) reported increases in swan abundance after 2004 at the Lago Lanalhue and the urban lagoons in the city of Concepción (200 and 320 km north of the Río Cruces wetland, respectively). This emigration event was clearly not related to major environmental process that operates at interannual timescales such as ENSO events (Schlatter et al., 2002). In addition to population decreases due to emigration, absence of nest and chicks and mortality of swans due to previously-unknown causes were observed (Jaramillo et al., 2007; www.conaf.cl). For example, nearly 100 dead swans were found during 2004–2005 in the wetland. Concurrently, a reduction in the spatial occurrence of *E. densa* was also observed and water turbidity changed notoriously due to a higher load of suspended solids, a fact inferred to be caused by the demise of the natural anchor of sediments by the formerly abundant *E. densa* (Lagos et al., 2008). The macrophyte *E. densa* plays a crucial role in determining the degree of food availability for herbivorous water birds (Corti and Schlatter, 2002), the functional group that presented stronger impacts across the wetland as compared with carnivorous birds (Lagos et al., 2008).

During the spring of 2004, the former National Environmental Commission of Chile (CONAMA) commissioned a study to the Universidad Austral de Chile (UACh hereafter), to primarily assess the causes of swan emigration and mortality. Post-mortem analyses showed emaciation, high concentrations of iron and histopathological abnormalities in their livers. In addition, necrotic patches and higher loads of heavy metals (mainly iron) in remaining *E. densa* plants collected within the wetland as compared with healthy plants collected outside this area, were also observed (UACh, 2005). The most plausible hypothesis, stated that these situations were associated with significant changes in water quality within the wetland, concomitant with the onset in early 2004 of a new wood pulp mill located 25 km upstream from the wetland (Escaida et al., 2014). Those changes would have originated in a sudden short-lived spillage of residual waters from the pulp mill that resulted in high concentrations of some chemicals in the wetland waters, a fact subsequently detected by monitoring programs (UACh, 2014). The abrupt decrease of *E. densa* was concomitant with those changes in water quality resulting in the emaciation of swans. In addition, histopathological abnormalities in the livers of dead swans were associated with high iron contents in remaining *E. densa* plants (Jaramillo et al., 2017; submitted). Those results strongly suggest that the wetland was subjected to the cascading impacts of a disturbance event (Pinochet et al., 2004; UACh, 2005; Woelfl et al., 2006; Jaramillo et al., 2007; Lagos et al., 2008; Escaida et al., 2014). A legal procedure was initiated during 2005 by the State Defense Council of Chile and in July 2013, the Civil Court of Valdivia ruled that the wood pulp mill was responsible for the environmental changes described above, supporting conclusions of an earlier study (UACh, 2005). Consequently, the Civil Court of Valdivia ordered a series of measures to mitigate the damage to the wetland, including evaluation and monitoring programs. The results showed that after 2006, concentrations of chemicals in wetland waters are below thresholds specified by Chilean environmental regulations (UACh, 2014, 2015, 2017).

Since 2004, we have monitored the Río Cruces wetland quantifying swan population abundances and spatial occurrence of *E. densa*. In this study, we assess the resilience of these two ecosystem components, as well as the current environmental state of the Río Cruces wetland and its tributary rivers (the wetland hereafter). We evaluated the temporal variability of the main ecosystem components altered in 2004: i) swan population abundances, ii) body weights, histopathological conditions and iron concentrations of hepatic tissues of swans, iii) spatio-temporal variability of *E. densa* and iv) water quality within and outside the wetland.

2. Material and methods

2.1. Study area

The Río Cruces wetland (Fig. 1) includes a nature sanctuary under Chilean law and the first Neotropical Wetland of International Importance by the Ramsar Convention, both established in 1981. The sanctuary (4877 ha) and shallow water zones of the tributary rivers of Río Cruces (i.e. the wetland), originated during May 1960 as a result of land subsidence caused by the 1960 earthquake, the largest seismic