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The effect of water management on extensive aquaculture food webs in the reconstructed wetlands of the Doñana Natural Park, Southern Spain

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ABSTRACT

Extensive aquaculture in coastal and estuarine wetlands can support both increased food production and wider ecosystem services when underpinned by effective management to promote productivity and hence food webs that support both commercial species and biodiversity. Changing hydrology, specifically water movement, within wetlands significantly impacts the physico-chemical properties of the water body and hence can be employed to manipulate productivity and alter patterns of recruitment of commercial species and may also transfer non-native species from the supplying water bodies. The reconstructed wetlands of Veta la Palma in the Doñana Natural Park are subjected to either a 1% or 5% d^{-1} water exchange with water drawn from the adjacent Guadalquivir estuary. This site provides an excellent opportunity for examining the effect of water management on the food webs that support both the birdlife and aquaculture activities for which this habitat is managed. Stable isotopes were used to examine food webs in three replicate lagoons under each water management scheme. In lagoons receiving higher water exchange, phytoplankton productivity appeared to be more important than benthic production in supporting food webs. Increased water exchange also changed the shape of the food webs, facilitated the colonisation of at least one non-native species and increased the importance of non-native species in the diets of large commercially harvested fish (>60% of seabass diet). Lagoons with high water flows also had between three and four times greater shrimp biomass than those of low flow lagoons. Non-native fauna were opportunistic omnivores, eating marginally more non-natives in lagoons with greater water exchange. Overall non-native cordgrass *Spartina densiflora* contributed only slightly more to food webs compared with the native reed *Phragmites australis*, despite the lagoon edge occupancy ratio of 9:1, respectively. Non-natives also appear to enhance food provision for large predators and wetland birds, by increasing biomass, without competing for resources with native species, supporting the dual management objectives of aquaculture and waterbird conservation.

Statement of relevance: Extensive aquaculture productivity appears to be positively correlated with water exchange rates.

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1. Introduction

The strategic guidelines for sustainable development of EU aquaculture from the European Commission (EC, 2013) highlight the constraints on growth of the industry and particularly the need for a reduction in administrative barriers. To address these issues, adoption of an ecosystem approach can help illustrate both the possible environmental impacts and the potential ecosystem services supported by aquaculture developments. This can inform spatial planning for future aquaculture development and is particularly important when aquaculture activities are adjacent to or within designated conservation areas, such as Natura 2000 sites, where identification and quantification of likely significant effects on conservation features are a critical step in the approval process. Extensive aquaculture in coastal and estuarine wetlands has a long history in Asia, but is less well-developed in temperate regions, including Europe, where it offers considerable potential for integration of increased aquaculture production with the provision of wider ecosystem services from wetlands. As more than 90% of all European wetlands are estimated to have been lost (Mitsch and Gosselink, 2000) with some 60% being drained and converted to agriculture (Revenga et al., 2000), our study site, Veta la Palma, is an example of how aquaculture can be a driver for the reconstruction of wetlands. Where once extensive cattle ranching occurred on drained wetlands degraded by siltation and the

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construction of dykes and drainage channels, permanently flooded wetlands have been created. Three thousand hectares of lagoons, each of approximately 70 ha, have been constructed since 1990 for the extensive eco-aquaculture of fish and shrimp. As Veta la Palma is within the Doñana Natural Park boundary, the area is also managed for conservation, with more than a 100 purpose-built islands in the lagoons providing nesting and shelter for the birdlife. The Natural Park is a Ramsar wetland of international importance being a significant transitory area for the six million migratory birds that pass through on the European–West African flyway and a major overwintering site for more than 500,000 waterbirds (UNEP, 2011). It is also the most important European wintering site for ducks (Anatidae) (Rendon et al., 2008).

Hydrology is the major factor in determining the structure and function of any wetland with water flow impacting not only the physicochemical conditions but also the biology including species composition and primary productivity (Mitsch and Gosselink, 2000). Wetland ecosystems are impacted at all trophic levels by altered flow regimes with changes reported in the relative importance of primary producers (Nilsson and Svedmark, 2002; Vis et al., 2007), in invertebrate communities (González-Ortegón and Drake, 2012), and fish composition (Poff and Allan, 1995; Roy et al., 2005; Xenopoulos and Lodge, 2006). In aquaculture increasing water exchange normally improves water quality resulting in better survival and growth of the cultured organism (Pillay, 1990). Understanding how environmental factors impact the food web, and in particular primary productivity, is essential in extensive aquaculture as these constrain total harvest rates.

Changes in hydrology can lead to state shifts in ecosystems and may facilitate the invasion success of non-native species (Bunn and Arthington, 2002). Non-native species research mostly focuses on their negative environmental impact with media coverage being similarly biased (Chew and Laubichler, 2003) and more than 2.9 billion euros are spent annually on the control or eradication of non-native species in the European Union (extracted from Gren et al., 2007; Kettunen et al., 2008). Although it is generally accepted that once a non-native species becomes invasive they can reduce biological diversity, some non-natives are benign and others are economically valuable cash crops. Moreover, recently two reviews have highlighted beneficial interactions between non-native species and some part of the host ecosystem (Rodriguez, 2006; Schlaepfer et al., 2011). Therefore careful assessment of both the positive and negative impacts are needed in order to determine if the cost of control is warranted, taking into account the management objectives of the area.

Stable isotopes have been extensively used in trophic ecology since the early work of DeNiro and Epstein (1978, 1981), who showed that carbon is useful in tracking food sources, and nitrogen in discerning trophic level. Early studies used isotopic similarity to infer consumption of a prey by consumer, more recently isotopic mixing models such as IsoSource (Phillips and Gregg, 2003), SIAR (Parnell et al., 2008) and mixSIAR (Stock and Semmens, 2013) have enabled the calculation of the most likely proportional contribution of multiple food sources to the tissue of a consumer, and hence, dietary composition. The effect of non-native species on food webs has been studied using stable isotope mixing models to examine both the impact of introducing non-native fish species on other species (Cucherousset et al., 2007) and non-native primary producers on both primary consumers (Levin et al., 2006) and higher trophic species (Currin et al., 2003; Shang et al., 2008). Isotopic analysis has advantages over stomach contents analysis in providing dietary information as it offers a more integrated longer term dietary signal reflecting assimilated not merely ingested material (Al-Maslamani et al., 2009). Although the use of generalist diet-tissue discrimination factors can be problematic in isotopic analysis, uncertainty can be reduced by the use of the mixing model mixSIAR that incorporates this variability in discrimination factors.

The current study examines the effect of increasing water exchange rate on the productivity and composition of food webs in extensive aquaculture lagoons. Stable isotopes are used to illustrate the change in diet of consumers with increased water exchange. The impact of water exchange on recruitment and density of non-native fauna is also studied as is their roles in support of both the extensive aquaculture production and the birds feeding in these lagoons.

2. Materials and methods

The study site at Veta La Palma, in Southern Spain, south of Seville, is located within Doñana Natural Park and sandwiched between the Doñana National Park to the west and the Guadalquivir estuary to the east and south (Fig. 1). In the 1990s, from previous agricultural land, approximately 3000 ha of wetlands were reconstructed in the form of forty large (70 ha) shallow (0.5 m) brackish-water lagoons, complete with bird shelter/nesting islands and a deeper (1 m) peripheral canal. The permanently inundated lagoons at Veta la Palma provide a vital refuge for these ducks and other waterbirds during the dry season and until winter rains re-flood the Doñana marshes bird populations in Veta la Palma can reach 300,000 (Kloskowski et al., 2009). These lagoons are particularly important feeding grounds for great cormorants (*Phalacrocorax carbo*), greater flamingos (*Phoenicopterus roseus*), black winged stilts (*Himantopus himantopus*) and pied avocets (*Recurvirostra avosetta*) (Rendon et al., 2008), and feeding by flamingos, coots and ducks has been shown to have a significant influence on the biomass of both macrophytes and invertebrate populations (Rodriguez-Perez and Green, 2006, 2012). In parallel with the habitat and food support to birds, a total of more than 800 t of semi-extensive and extensively produced fish and shrimp are harvested annually (Walton et al., in press). Shrimp and some fish bycatch are harvested continuously and fish mostly at the end of each three year cycle when the water levels are lowered, species include seabass *Dicentrarchus labrax* Linnaeus, mullet *Mugil cephalus* Linnaeus, European ditch shrimp *Palaemon varians* Leach, and the oriental shrimp *Palaemon macrodactylus* Rathbun. There are two operational systems for management of the lagoons for aquaculture; designated high flow and low flow lagoons (Fig. 1). In the low flow extensive lagoons aquaculture production is entirely supported by natural productivity. In the high flow extensive lagoons, water comes from a row of small (0.1–0.9 ha) semi-extensive culture ponds were seabass are maintained at 2–4 kg m^{-2} and nutrition comes from both inflowing natural production and formulated feeds supplied by demand feeders. The high flow lagoons have enhanced exchange rates of 5% d^{-1} whereas the low flow lagoons have lower rates of 1% d^{-1}. Water exchange rates were provided by Veta La Palma management and estimated by the relationship between the rate of inflowing water and total water volume of the lagoon. Flow rates are recorded using the water height passing across a weir and calibrated by the time taken to fill a known volume. In the winter when increased freshwater flow reduces estuarine salinity, sluice gates are shut and the isolated water recirculated around the farm. Once estuarine salinity is >10 ppt, estuarine water is introduced and a mix of 30:70 recirculated:estuarine water is pumped through the lagoons.

Six extensive lagoons (3 high flow and 3 low flow) were sampled 4 times over a year (1–4 May 2011, 25–29 July 2011, 1–4 November 2011, and 20–24 February 2012), with each time period selected to represent the typical conditions of each season. Three replicate samples for isotope analysis were taken with each method, from haphazardly-spaced locations within each lagoon. Benthos was sampled using a cylindrical corer (32 cm^2) and box corer (240 cm^2). 'Nasa' traps (Fyke type, funnel-mouthed bag traps) with 3 mesh sizes: 2 mm, 5 mm and 10 mm, were used to catch nekton, mostly fish and shrimp. Zooplankton tows were performed using mesh sizes of 200 μm and 500 μm. Corixids were collected with a 500 μm D-framed pond net. Biofilm was sampled by scraping the top 1 mm off benthic cores. Submerged parts of plants were brushed and vigorously shaken in distilled water and the resultant suspension vacuum filter through pre-combusted GF/C filters (Whatman) to obtain periphyton samples. Macrophytes were collected by hand from the lagoon verge (*Spartina denisflora* Brognand, *Phragmites australis* (Cav.) Trin. ex Steudel) and in the

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