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Resilience and stability of *Cymodocea nodosa* seagrass meadows over the last four decades in a Mediterranean lagoon

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ABSTRACT

Understanding what controls the capacity of a coastal lagoon ecosystem to recover following climatic and anthropogenic perturbations and how these perturbations can alter this capacity is critical to efficient environmental management. The goal of this study was to examine the resilience and stability of *Cymodocea nodosa*-dominated seagrass meadows in Urbino lagoon (Corsica, Mediterranean Sea) by characterizing the spatio-temporal dynamics of seagrass meadows over a 40-year period and comparing (anthropogenic and climatic) environmental fluctuations. The spatio-temporal evolution of seagrass meadows was investigated using previous maps (1973, 1979, 1990, 1994, 1996, 1999) and a 2011 map realized by aerial photography–remote sensing combined with GIS technology. Environmental fluctuation was investigated via physical-chemical parameters (rainfall, water temperature, salinity, turbidity, dissolved oxygen) and human-impact changes (aquaculture, artificial channel). The results showed a severe decline (estimated at −49%) in seagrass meadows between 1973 and 1994 followed by a period of strong recovery (estimated to +42%) between 1994 and 2011. Increased turbidity, induced either by rainfall events, dredging or phytoplankton growth, emerged as the most important driver of the spatio-temporal evolution of *Cymodocea nodosa*-dominated meadows in Urbino lagoon over the last four decades. Climate events associated to increased turbidity and reduced salinity and temperature could heavily impact seagrass dynamics. This study shows that Urbino lagoon, a system relatively untouched by human impact, shelters seagrass meadows that exhibit high resilience and stability.

1. Introduction

Seagrass meadows are one of the most productive coastal communities (Duarte and Chiscano, 1999) and play key ecological roles in lagoon, estuarine and marine ecosystems by providing food and shelter for many important organisms, stabilizing sediments, and regulating nutrient cycles (Hemminga and Duarte, 2000; Larkum et al., 2006; Short et al., 2007). Seagrass meadows thus hold important economic value (put at 19 K US$ ha^{-1} $year^{-1}$; Costanza et al., 1997). However, they are rapidly declining across the globe, with rates increasing from median of 0.9% yr^{-1} before 1940 to 7% after 1990 (Orth et al., 2006a; Waycott et al., 2009). Anthropogenic pressures (e.g., industrial, agricultural and aquacultural disturbances) that induce water nutrient enrichment and chemical contamination have damaging effects on seagrass meadows and are now considered the main factors of seagrass decline (Orth et al., 2006a; Burkholder et al., 2007; Waycott et al., 2009). Moreover, climate change is expected to further accelerate seagrass regression in the coming years (Waycott et al., 2009).

Since the mid-20th century, there is a consensus view that lagoons and estuaries count among the most disturbed coastal ecosystems worldwide (De Jonge et al., 2002), which means that seagrass meadows in these coastal areas may be particularly vulnerable. In order to better understand the capacity of an ecosystem to efficiently recover after exposure to perturbations, there is a need for spatial data gathered on long time-scales (Fukami and Wardle, 2005). Measuring rates of increase or decrease in lagoon seagrass surface area, such as via spatio-temporal investigations, could provide useful information on the global evolution of lagoon ecosystems in response to environmental factors (Charpentier et al.,

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2005; Bernard et al., 2007; Plus et al., 2010). Folke et al. (2010) defined the dynamics and development of complex social–ecological systems via three aspects: resilience, adaptability and transformability. Changes in system dynamics are called regime shifts (Scheffer et al., 2001), and such shifts may be reversible, irreversible, or effectively irreversible (i.e., not reversible on time-scales of interest to society). Understanding what controls the capacity of an ecosystem to recover following disturbances and how human activities can alter this capacity is critical to efficient ecosystem management (Folke et al., 2004; Hugues et al., 2005; Nyström et al., 2012). In many coastal areas, altered ecosystems such as seagrass may take long to revert to their original state due to new ecological feedbacks that reinforce the degraded state (Nyström et al., 2012). This is of grave concern, as the potentially bi-directional influence of feedbacks can lead to undesirable alternative states that are resilient to restorative efforts (Nyström et al., 2012). For example, a model established by van der Heide et al. (2007) found that altered hydrodynamics was a major driver of the observed lack of *Zostera marina* recovery following a protist infection combined with eutrophication: when the seagrass cover fell below a threshold, current and wave velocities increased and sediment stabilization was lost, which increased turbidity, reduced the growth and density of the remaining seagrasses, and prevented seagrass recruits from establishing.

Urbino lagoon (Mediterranean Sea, France, Corsica; Fig. 1) offers an interesting case study to better understand the functioning of lagoon systems under anthropogenic and climatic pressures and test seagrass resistance and resilience. Indeed, over the last few decades, the lagoon has been the focus of strong environmental changes (anthropogenic and climatic disturbances) but also of long time-series data recordings on its seagrass meadow surface area and environmental parameters (data from the early 1970s: De Casabianca et al., 1973; SOMIVAC and CTGREF, 1979; Fernandez et al., 2006). The dominant seagrass species in Urbino lagoon is *Cymodocea nodosa* (Ucria) Ascherson, a subtidal species native to the Mediterranean Sea and extending in the Atlantic northward to Portugal and southward to Senegal, including the Canary Islands (Den Hartog and Kuo, 2006). *Cymodocea nodosa* can form extensive meadows in shallow and sheltered areas such as lagoons (Terrados and Ros, 1992; Ribera et al., 1997).

The objectives of the present study were (1) to characterize the spatio-temporal dynamics of *Cymodocea nodosa*-dominated seagrass meadows over the last 40 years in Urbino lagoon, and (2) to investigate the possible causes of the observed variations through comparisons with environmental fluctuations (anthropogenic and climatic). The resilience capacity of the system was discussed in light of the findings.

2. Material and methods

2.1. Study site

Urbino lagoon is located on the eastern coast of Corsica, France (Mediterranean Sea; 42°03′ N; 9°28′ E; Fig. 1). This lagoon is under the influence of a Mediterranean climate, with strong and unpredictable rainfall fluctuations from one year to the next (Fernandez et al., 2006). In 2007, Urbino lagoon was acquired by the *Conservatoire du Littoral*, a French public agency promoting the conservation of threatened coastal habitats. The lagoon is managed by the regional public agency *Conseil Général de la Haute-Corse*, and in 2009 it was included in the RAMSAR list of wetlands of international importance. With a surface area of 7.6 km^2 and a sub-circular shape, the lagoon has an average depth of 5 m (maximum depth: ≈ -10 m). Its watershed area is small (31 km^2), resulting in a characteristically highly homogeneous water mass (euryhaline lagoon; Pasqualini et al., 2006). Over the course of the year, water salinity and temperature vary between 26 and 44 PSU and 6 and 31 °C, respectively (see Pasqualini et al., 2006; Fernandez et al., 2006). Urbino lagoon is exposed to moderate anthropogenic pressure, mainly agriculture- and aquaculture-induced pressures. Agriculture (orchards, vineyards) takes place near the catchment area, while aquaculture occurred from 1990 to 2002 and represented 150–250 and 40 t yr^{-1} of fish (*Dicentrarchus labrax* and *Sparus aurata*) and shellfish production, respectively. Urbino lagoon is linked to the sea by an artificial channel, in the north-eastern part (Fig. 1). This artificial channel was made in the early 1970s and given regular heavy maintenance during the fish-farming period (1990–2002), but the maintenance effort has tailed off since (pers. com. J.L. Guaitella).

2.2. Seagrass mapping

There are earlier maps of the main seagrass meadows and bottom types in Urbino lagoon. The two oldest maps were produced by De Casabianca et al. (1973) and SOMIVAC and CTGREF (1979) at a 1:20,000 scale, based mainly *in situ* observations. We scanned and georeferenced each map using ArcGis 9.3 (ESRI®) with Lambert 93 coordinates. Only areas of seagrass meadows were indicated on the maps. For the present study, the seagrass areas of the De Casabianca et al. (1973) and SOMIVAC and CTGREF (1979) maps were redrawn in vector format tracing polygons on the

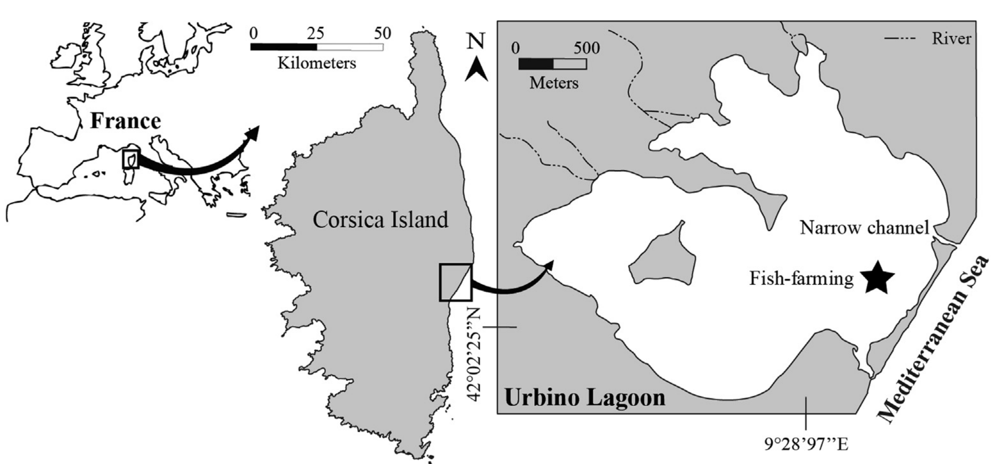

Fig. 1. Location of Urbino lagoon (Corsica, France).