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Long-term fluctuations in *Cystoseira* populations along the west Istrian Coast (Croatia) related to eutrophication patterns in the northern Adriatic Sea

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A B S T R A C T

An exploration of historical data suggested that eutrophication patterns might drive long-term fluctuations in *Cystoseira* populations along the west Istrian Coast (northern Adriatic Sea, Croatia). The regimes of northern Italian rivers, which flow approximately 100 km west of the study area, mainly modulate the eutrophication levels of the northern Adriatic Sea. A regression of *Cystoseira* populations from the 1970s through the 1990s corresponded to increased levels of eutrophication in the study area. During the late 1990s, the density of sea urchins, which are efficacious macroalgal predators, decreased, likely due to an intense formation of pelagic mucilage aggregates that resulted in mass mortality episodes of macrozoobenthic species. During the 2000–2013 period, an oligotrophication of the northern Adriatic formed the basis for the recovery of *Cystoseira* taxa, whose abundances from 2009 to 2013 were similar to those characterising the most flourishing Mediterranean *Cystoseira* assemblages.

1. Introduction

The canopy-forming macroalgae that compose marine forests are clearly declining at local, regional and global scales at an alarming rate (Airoldi and Beck, 2007; Steneck et al., 2002; Connell et al., 2008; Kang et al., 2008). *Cystoseira* species (Phaeophyceae, Fucales) are large, canopy-forming brown macroalgae, and they are able to form dense belts or forests on the rocky substrate of the Mediterranean Sea that extend from the upper level of the sublittoral to the upper circalittoral zone (Giaccone and Bruni, 1973). Their distribution is usually strictly dependent on depth and the intensity of the wave action (Sauvageau, 1912; Feldmann, 1937; Ercegović, 1952; Molinier, 1960; Verlaque, 1987; Ballesteros, 1988, 1990; Giaccone et al., 1994; Cormaci, 1995), and as habitat engineers (sensu Jones et al., 1994), *Cystoseira* species shelter numerous organisms and thus play an important role in sustaining the biodiversity of Mediterranean coastal ecosystems (Molinier, 1960; Ballesteros et al., 1998, 2009; Pitacco et al., 2014). However, *Cystoseira* species are particularly sensitive to anthropogenic pressures, so all Mediterranean species, except *Cystoseira compressa* (Esper) Gerloff and Nizamuddin subsp. *compressa* (Thibaut et al., 2015), are listed as protected species in Annex II on the List of Endangered or Threatened Species (UNEP-PAM-RAC/SPA, 2012); *C. compressa* subsp. *compressa* is not included because it can withstand intermediate levels of pollution (Soltan et al., 2001; Mangialajo et al., 2008; Pinedo et al., 2013; Thibaut et al., 2014). Although *Cystoseira* species are listed as threatened in international conventions, they are not effectively protected (Thibaut et al., 2015). Furthermore, *Cystoseira* species have been successfully used as ecological indicators of pristine environments (Orfanidis et al., 2003; Ballesteros et al., 2007; Asnaghi et al., 2009; Bermejo et al., 2013; Nikolić et al., 2013) for the implementation of the Water Framework Directive (EC, 2000).

In addition to anthropogenic pressures, global warming (Harley et al., 2012; Mineur et al., 2015), overgrazing by herbivores (Hereu, 2006; Guidetti, 2006; Vergés et al., 2009; Gianguzza et al., 2011; Bianchi et al., 2014; Vergés et al., 2014) and physical sea conditions, such as extreme storms (Navarro et al., 2011) and prolonged low tides (Rodrìguez-Prieto, 1992), negatively affect *Cystoseira* populations. Anthropogenic impacts can act at local or larger spatial scales. Sewage discharge and urban pollution degrade *Cystoseira* populations at a restricted spatial scale (Munda, 1980a, 1982; Soltan et al., 2001; Perkol-Finkel and Airoldi, 2010; Sales et al., 2011; Thibaut et al., 2014; Pinedo et al., 2015), and further examples of local impacts include increased grazing by herbivores due to overfishing of sea urchin predators (Sala et al., 1998; Guidetti and Sala, 2007) and the deleterious effects of harvesting date mussels (Guidetti et al., 2003). However, larger-scale phenomena, due to anthropogenic influences on patterns of pelagic eutrophication, might also affect *Cystoseira* demography. The extinction of some *Cystoseira* species along the coasts of the Tremiti Archipelago

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(central Adriatic Sea, Italy) was related to a reduction in water transparency, and as the archipelago was not subjected to local pollution (Cormaci and Furnari, 1999), the observed increase in turbidity could be due to fluctuations in offshore eutrophication.

The northern Adriatic is the northernmost biogeographic sector of the Mediterranean Sea (Bianchi and Morri, 2000). It is a shallow (maximum depth of approximately 50 m) and semi-enclosed basin characterised by seawater temperatures below 11 °C in February (Bianchi, 2007). The runoff regimes of northern Italian rivers, which discharge their waters approximately 100 km from the west Istrian Coast, play a pivotal role in short-term and long-term variations in the eutrophication levels of the northern Adriatic Sea (Degobbis et al., 2000; Djakovac et al., 2012, 2015). On its west and north sides, the northern Adriatic biogeographic sector encompasses the predominantly sandy Italian Coast from Ancona to Trieste, and the west coast of the Istrian Peninsula delimits its eastern border. Along this coast, the sea bottom is mainly rocky up to a depth of approximately 12 m, so it is particularly suitable for the formation of large *Cystoseira* forests. Comprehensive historical data on the distribution of *Cystoseira* species along the west Istrian Coast date back to 1950 (Ercegović, 1952), and subsequent studies have provided additional information on their distribution patterns (Munda, 1979, 1980a, 1980b, 1982; Hanel, 2002).

Of the approximately 40 Mediterranean *Cystoseira* taxa (Ribera et al., 1992; Gómez Garreta et al., 2001; Draisma et al., 2010; Cormaci et al., 2012; Guiry and Guiry, 2015), only eight dwell along the west Istrian Coast (Ercegović, 1952). These eight taxa can be considered eurythermic because they can be found across the whole Mediterranean Sea and are capable of withstanding the cold winter seawater temperatures characteristic for the northern Adriatic Sea (Ercegović, 1952). The eight taxa are:

(1) *Cystoseira amentacea* var. *stricta* Montagne; described as *Cystoseira spicata* spec. nov. in Ercegović (1952) and referred to as *C. amentacea* in the following text;
(2) *Cystoseira barbata* (Stackhouse) C. Agardh f. *barbata* (Thibaut et al., 2015); described as *C. barbata* J. Agardh in Ercegović (1952) and referred to as *C. barbata* in the following text;
(3) *C. compressa* (Esper) Gerloff & Nizamuddin subsp. *compressa* (Thibaut et al., 2015); described as *Cystoseira abrotanifolia* C. Agardh in Ercegović (1952) and referred to as *C. c. compressa* in the following text;
(4) *C. compressa* subsp. *pustulata* (Ercegović) Verlaque comb. nov. (Thibaut et al., 2015); described as *C. abrotanifolia* subs. *pustulata* subs. nov. Ercegović in Ercegović (1952) and referred to as *C. c. pustulata* in the following text;
(5) *Cystoseira corniculata* (Turner) Zanardini; described as *C. corniculata* Hauck in Ercegović (1952);
(6) *Cystoseira crinita* Duby; described as *C. crinita* Bory in Ercegović (1952);
(7) *Cystoseira foeniculacea* f. *schiffneri* (Hamel) Gómez Garreta, Barceló, Ribera & Rull Lluch; described as *Cystoseira discors* C. Agardh in Ercegović (1952) and referred to as *C. foeniculacea* in the following text;
(8) *Cystoseira spinosa* var. *spinosa* Sauvageau; described as *Cystoseira adriatica* Sauvageau in Ercegović (1952) and referred to as *C. spinosa* in the following text.

Among these eight taxa, only *C. amentacea* is able to dwell in the upper level of the sublittoral zone, where it forms dense belts, but along the eastern coast of the Adriatic Sea, sparse thalli of *C. amentacea* can be found up to a depth of 2–3 m. The alga exclusively colonises habitats that are exposed to wave action with very low sedimentation rates but is rare in areas subject to extreme wave action; such habitats are usually devoid of *Cystoseira* species (Ercegović, 1952). *C. crinita* forms belts from immediately below the upper level of the sublittoral zone to 3 m in depth in habitats that are sheltered and intermediately exposed to wave action; the species is less sensitive to sedimentation than *C. amentacea*. The remaining six taxa are found in the eastern Adriatic Sea from immediately below the upper level of the sublittoral zone to approximately 40 m in depth, except *C. foeniculacea*, which was sampled up to 110 m in depth (Ercegović, 1952). Of these six taxa, only *C. barbata*, *C. crinita*, and *C. c. compressa* form dense forests at shallow depths (from 0.5 to 3 m), and all six are adapted to dwell in habitats with intermediate levels of sedimentation. At shallow depths, they are present in habitats that are intermediately exposed to wave action, with two exceptions. First, *C. barbata* is widespread but exclusively found in very sheltered habitats, and second, *C. c. compressa* can colonise very exposed as well as very sheltered habitats. In habitats that are highly exposed to wave action, the thalli of *C. c. compressa* have a flattened form, which Ercegović (1952) termed "rosetta". In habitats that are very sheltered from wave action, *C. c. compressa* thalli are very vertically developed, attaining a total thallus height of more than 0.5 m, which, in the eastern Adriatic Sea, can only be compared to the height of *C. barbata* thalli (Ercegović, 1952).

The aim of this study is to investigate whether long-term variations in *Cystoseira* populations along the west Istrian Coast have developed in relation to the changes in eutrophication levels occurring in the pelagic region of the northern Adriatic Sea. First, to estimate the status of *Cystoseira* populations along the west Istrian Coast, we compared recently assessed abundance values with those reported for other, less impacted Mediterranean regions. Second, we evaluated if the regression-recovery phases of *Cystoseira* populations reflect long-term variations in eutrophication levels. Finally, we examined whether historical variations in the abundance of sea urchins, which are generally recognised as major macroalgal grazers (Sala et al., 1998), are related to the pelagic mucilage phenomenon. Mucilage aggregates formed episodically in the water column of the northern Adriatic Sea during the 19th and 20th centuries (Degobbis et al., 1995, 2000), provoking mass mortality events of macrozoobenthic organisms (Stachowitsch et al., 1990; Müller et al., 1998).

2. Materials and methods

2.1. Study area and historical data

The west Istrian Coast (Fig. 1) extends from Cape Savudrija in the north to Cape Kamenjak in the south. The length of the coastline totals 439 km, and the islands contribute an additional 89 km, according to a 1:5000-scale map (source: Institute for Physical Planning — Region of Istria). Floristic data on *Cystoseira* taxa for the study area dating back to the 19th century were collected from Kuckuck's field diaries (revised by Munda, 2000) and the herbarium collection of the Center for Marine Research in Rovinj (results reported in the Supplementary material). However, more comprehensive data for the study area were found in Ercegović (1952) and Munda (1980a, 1980b, 1982, 2000), and historical data on sea urchin distributions are from Munda (1982); Hanel (2002) and Guidetti and Dulčić (2007). Information on the occurrence of the mucilage phenomenon in the water column of the northern Adriatic Sea came from the Database of the Center for Marine Research in Rovinj (Croatia).

2.2. Eutrophication levels

The eutrophication levels in the study area were characterised as the concentrations of chlorophyll *a*, orthophosphate and nitrate, which were measured at an oceanographic station (Station RV001, 45° 4′ 48″ N; 13° 36′ 36″ E) located several nautical miles from the city of Rovinj (Fig. 1). Station RV001 is part of a system of 7 stations that encompasses the entire northern Adriatic from the Rovinj region to Italian waters in the proximity of the Po River delta, and long-term studies demonstrate that data from Station RV001 reflect the eutrophication fluctuations of the entire basin (Degobbis et al., 2000; Djakovac et al., 2012). The concentration of chlorophyll *a* was measured fluorometrically after extraction with