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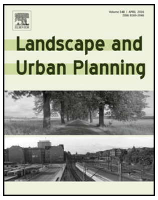

Primary succession on re-created coastal wetland leads to successful restoration of coastal halophyte vegetation

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HIGHLIGHTS

- Fast primary succession on re-created mudflats in a previously degraded saltmarsh.
- Deterministic successional pathway revealed.
- Three target habitat types developed after 6 years along a microelevation gradient.
- Replicable example for landscape planning of artificial coasts under threat from sea level rise.

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ABSTRACT

Understanding the causes of patterns in plant distribution is especially important when we want to create new terrain for vegetation development for conservation purposes. In Škocjan Inlet Nature Reserve it was carefully planned for new mudflats and islets to be created along a microaltitudinal gradient, aiming to achieve the spontaneous development of at least three target habitat types (mudflats not covered by seawater at low tide, Mediterranean glasswort swards and Mediterranean saltmarsh scrubs, including the transitional forms between them) through the primary succession pathways. Thus, this study was actually projected as a field experiment, on the one hand, and as a practical conservation measure, to recover a degraded area, on another. Vegetation cover on the newly constructed mudflats changed by 92% over 6 years of succession. In general, un-vegetated mudflats decreased from 71% to 26%. In contrast to this, Mediterranean glasswort swards increased from 6.5% to 28.2%, whereas saltmarsh scrub had the longest positive trend, constantly gaining area from 2008 (0.6%) to 2012 (28.9%). Detailed mapping showed rather deterministic successional pathways, which make restoration plans for halophyte communities more predictable. The study shows that this "ecological experiment" might have concrete implications for the restoration or re-creation of halophyte plant communities along sedimentary seacoasts—in general, all priority habitats in the European Union. The approach of creating artificial terrain within coastal protected areas is especially important in the light of the climate change-driven rise in sea level, often in conjunction with the "coastal squeeze" phenomenon.

1. Introduction

Centuries of over-exploitation, habitat modification and pollution have led to estuarine and coastal zone degradation, biodiversity loss and a decline in ecological resilience (Lotze et al., 2006). Coastal habitats, especially on the densely populated European coasts, are already severely endangered by the rapid, anthropogenically driven landscape changes of recent decades (Ivajnšič & Kaligarič, 2014). Thus, the restoration or creation of habitats that have been lost, destroyed or substantially altered has become a tool for many environmental agencies, parks, regions, states or NGOs. Specifically, the creation and restoration of wetlands constitute developing areas in science and technology (Mitsch & Wilson, 1996); the most important restoration factor in such cases is the water regime, which facilitates wetland vegetation and organism recolonization, as well as restoration of wetland functions (Onaindia, Albizu, & Amezaga, 2001).

In general, successful restoration of plant communities depends on the availability of target species and suitable abiotic conditions

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(Bakker, Poschlod, & Strykstra, 1996). Such conditions in wetlands mainly depend on restoring the hydrological conditions, and in coastal wetlands also on the tide regime and salinity. However, the availability and dispersal of target species may represent a bottleneck for successful vegetation re-assembly and, despite the potential for long-distance dispersal by tidal waters, there is a tendency towards local dispersal in coastal settings (Garbutt & Wolters, 2008;Wolters, Garbutt, & Bakker, 2005a). The establishment of a target plant community at a restoration site depends on the presence of seeds—or on a seed bank at the site or on seed dispersal to the site (Dausse, Bonis, Bouzille, & Lefeuvre, 2008; Wolters & Bakker, 2002). The presence of target plant communities near the restoration site has been shown to highly facilitate the restoration process in various types of ecosystems, including salt marshes (Bakker, 1985; Bischoff, 2002; Brown, 1998; Dausse et al., 2008; Donath, Hölzl, & Otte, 2003; Wolters et al., 2005a, 2005b). If seeds disperse to the target sites, germination, recruitment, establishment and survival of the species develop through environmental filters, here mostly identified as waterlogging and salinity. Estrelles et al. (2015) pointed out that local climate and soil features are the key factors in germination strategies for salt-affected plant communities.

Salt marsh vegetation spatial distribution is neither random nor spatially uncorrelated but is, on the contrary, organized in characteristic patches, following the zonation of plant communities (Silvestri, Defina, & Marani, 2005). Silvestri et al. (2005) has studied zonation in salt marsh environments and has evaluated a range of environmental factors affecting the distribution of halophytes. In most studies, spatial zonation is clearly dependent on microelevation above the relative sea level of the marsh, which reflects a certain humidity (inundation) and salinity gradient.

It is currently possible to simulate many kinds of physical design or hydro-geomorphology, but the biological components usually take a much longer time frame to respond, mostly beyond reasonable monitoring expectations. However, the halophyte vegetation of shallow seacoasts comprises relatively simple plant communities, based on the presence/dominance of only a few highly specialized species, filtered by strong environmental filters (Ivajnšič & Kaligarič, 2014). This simplifies the monitoring of such communities in the post-restoration period. During the winter of 2007/08, the Škocjan Inlet Nature Reserve near Koper in Slovenia was improved, by restoring and remedying the habitat loss and degradation that had occurred in the 20th century. In the coastal lagoon, artificial mudflats were constructed and reinforced at different microelevations. This was done according to a previously elaborated construction plan, which assured dredging of all needed materials from the site and anticipated the development of the three most important target Natura 2000 habitat types (bare mudflats and sandflats—N2000 code 1140; Mediterranean glasswort swards—N2000 code 1310; and Mediterranean saltmarsh scrubs—N2000 code 1420) (Kaligarič, 1998a). The new habitats were constructed from dredged sediments at different microelevations, in the form of tabular mudflats in a variety of shapes, mostly as small islets. It was proposed by Yozzo et al. (2004) that sediment management might be a key feature in successful restoration, since the use of dredged material may become increasingly important as a tool in creating marshes and upland wildlife refugia. However, nutrient analysis of the dredged material is essential to provide information for establishing good growing conditions, apart from the appropriately set micro-altitude. Andreucci et al. (1999) gave an example how complex is the development of halophyte vegetation due to variations in water level, salinity and soil structure in the Italian Northern Adriatic coast.

It was hypothesized that, after some initial years of primary succession, the different target types of halophyte communities (all Natura 2000 habitats) would develop at different microelevation intervals. A deterministic succession pathway was anticipated during the colonization phase, and established plant communities along the microelevation gradient were expected after five years of reconstructed mudflats and islets. In this study, we aimed to document the spatiotemporal patterns of primary succession, based on six temporal windows from 2008 (the first vegetation season after construction of the mudflats) until 2013, and to illustrate the development of plant communities/habitats on constructed mudflats in 2007/08. Furthermore, we sought to answer the following questions: (1) is there one successional trajectory or more than one? Does the process follow a deterministic (rather than stochastic) pathway? (2) What is the role of microelevation, if we presume that, after six years of succession, the plant communities/habitats are more or less established? (3) How did the area change in terms of habitat diversity between 2008 and 2013?

2. Methods

2.1. History of the site

Since ancient times, the wider area of Škocjan inlet has been shaped by natural forces, but also by human factors (Fig. 1). Although the number of rulers that have governed Škocjan inlet over the last millennium is impressive, the area has remained not much altered by man since 1900 (Šalaja et al., 2007). Human intervention became intensive after the building of the port of Koper in the late fifties and the shrinking of the area by backfill in the eighties (Fig. 1). Thus, at the beginning of the third millennium, destructive activities had left Škocjan inlet in very poor condition. However, in 1998 Škocjan inlet was designated by the government of Slovenia as a nature reserve. Extensive restoration of the reserve, led by the Ministry of the Environment and Spatial Planning, managed by the DOPPS BirdLife Slovenia and co-financed through a LIFE project, was completed in 2008. The restoration included regulation and enhancement of freshwater, seawater and brackish habitats. In the frame of the restoration activities, artificial mudflats in the form of islets or small peninsulas were constructed and reinforced with wooden palisades at different microelevations, as foreseen in a study carried out by one of the co-authors of this study (Kaligarič, 1998a, 1998b).

2.2. Delineation of the core study area

Initially, a core study area within Škocjan Inlet Nature Reserve (Fig. 2) was determined as a means of following the succession process on newly created mudflats. Digital ortho-photo (DOF50 = 0.5 m horizontal resolution) and near infrared ortophoto (DOF100IR = 1 m horizontal resolution) imagery for 2006 and geodetic ground elevation measurements performed in 2006 (before restoration procedures), based on the high resolution GNSS (Global Navigation Satellite System) instrument, (Zmax Thales Navigation, geodetic accuracy of 1 cm) and the Slovenian Geoid Model (GURS, 2010) were used to objectively determine the border between areas before and after restoration. The near infrared image (DOF100IR) was pan sharpened to 0.5 m spatial resolution using ArcGIS 9.3 (ESRI, 2010). Three visible bands of the DOF50 image, the pan sharpened near infrared band of the DOF100IR (wavelength 675–850 nm) and the Normalized Difference Vegetation Index (NDVI), as a derivative extracted from both images (NDVI = (IR − R)/(IR + R); Gallo & Owen, 1999; Tucker, 1979), were used for image classification (supervised classification technique, maximum likelihood parametric rule). By then intersecting the classified main land in 2006 and the 2008 habitat map, the core study area was determined.