Ecological Modelling 333 (2016) 11–42

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Modelling stressors on the eelgrass recovery process in two Danish estuaries

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ARTICLE INFO

Article history:
Received 10 November 2015
Received in revised form 4 April 2016
Accepted 7 April 2016
Available online 30 April 2016

Keywords:
3D MIKE
Arenicola marina
Ecological modelling
Eelgrass restoration

ABSTRACT

Eelgrass (*Zostera marina* L.) depth limit is used as an environmental indicator in Danish coastal waters in the Water Framework Directive (WFD) to evaluate coastal waters and their ecological condition. Even after decades of reduced nutrient loadings the reestablishment of eelgrass has not yet succeeded. The mechanisms hindering/delaying eelgrass recovery were recently identified: 1) lack of sediment anchoring capacity, 2) resuspension created by drifting ephemeral macroalgae, 3) seedling uprooting created by current and wave forces, 4) ballistic stress from attached macroalgae and 5) burial of seeds and seedlings by lugworms. These processes were quantified and introduced to an ecological MIKE 3D model. The developed model was calibrated and validated on two Danish estuaries, Odense Fjord and Roskilde Fjord. Analyses of the simulations were performed on area distribution maps. The parameterized stressors impact has been investigated over a three-year period.

The results indicate accumulated effects from multiple stressors weakening the capability of eelgrass to recolonize. Combining all stressors in the model decreased the total area covered by eelgrass 83.72% in Odense Fjord and 80.30% in Roskilde Fjord compared to simulation without stressors. Eelgrass peak biomass declined in both fjords from 33.4 to 4.55 ton C km^{-2} in Odense Fjord and from 24.42 to 5.58 ton C km^{-2} in Roskilde Fjord. Combining lugworm burial of seeds and seedlings with resuspension from macroalgae and wave forcing had the second strongest negative impact on eelgrass growth, area reduction of 78.31% and 73.14% in Odense and Roskilde Fjord was seen. Ballistic stress from attached macroalgae also reduced growth drastically. Light conditions, sediment organic content along with shear stress at the sediment surface impact the ability of eelgrass to cope with above mentioned stressors. The spatial resolution of the model setup made it possible to generate maps where eelgrass is exposed to lowest stress, revealing areas for potential eelgrass recovery. The developed eelgrass model is now used as a national tool to predict areas where eelgrass restoration effort may be initiated.

1. Introduction

Eelgrass (*Zostera marina*) is the most common seagrass in the Northern Temperate hemisphere (Krause-Jensen et al., 2011). Eelgrass beds provide ecosystem services as: improving water quality by their growth related nutrients uptake and trapping of suspended matter (Hemminga and Duarte, 2000), act as nursery ground for juvenile stages of different species that vary by region and climate (Orth et al., 2006; Terrados and Duarte, 2000), act as carbon sinks (Duffy, 2006) and increases biodiversity (Hemminga and Duarte, 2000). Dense seagrass beds control their own environment with respect to physical, chemical and biological conditions by changing water flow, nutrient cycle and food web structure (Orth et al., 2006).

Community decline along the European and North American coastlines has been seen over the last century, mainly due to wasting disease in the 30s and later anthropogenic eutrophication (Hauxwell et al., 2003; Petersen, 1934; Rasmussen, 1973; Valdemarsen et al., 2010). About 90% of the plant cover in Odense Fjord has been lost since 1983 (Valdemarsen et al., 2010). In recent years there has been attention to the ecological condition of the coastal environments in Europe. The nutrient loading of the Danish coastal waters has been significantly reduced during the last decades to improve the water quality, but recolonization of *Z. marina* beds is still lacking. The eelgrass depth limit was introduced

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http://dx.doi.org/10.1016/j.ecolmodel.2016.04.008

as a biological key element in the management of the EU Water Framework Directive (WFD). At the national level coastal managers and scientist have discussed if the eelgrass depth limit is sufficient environmental information for processing the ecological state into the classes of "bad", "poor", "moderate", "good" or "high" ecological condition. In most Danish estuaries eelgrass fails to recover even shallow areas, where benthic light intensity actually is supporting reestablishment. This lacking recovery is caused by a suite of stressors that together are hindering the expansion process.

Several empirical models (Dennison et al., 1993; Duarte et al., 2007; Greve and Krause-Jensen, 2005; Krause-Jensen et al., 2000; Nielsen et al., 2002) have described the relationship between eelgrass and depth limit. These models are all static correlation models predicting the eelgrass depth limits depending on the light climate in the water column, dynamic ecological modelling where different primary producers like eelgrass and macroalgae have competed for space depending on their Monod kinetics ability for light and nutrient saturation (Coffaro and Bocci, 1997; Flindt and Kamp-Nielsen, 1997) while (Short et al., 2007) also include stressors such as water levels and wave energy. One-dimensional hydrodynamic model has been used by (Carr et al., 2010) to investigate feedback mechanisms between eelgrass bed stability, turbidity, sediment and light environment. A coupled vegetation growth model with hydrodynamic model has been used to investigate seagrass bed resilience to climate change (Carr et al., 2012). Pastres et al. (2004) examined the eelgrass growth model robustness in eutrophied environments. Kenworthy et al. (2014) looked at eelgrass light requirements in different environmental conditions.

In a strategic research project (REELGRASS) many mechanisms and processes hindering/delaying the recovery of eelgrass were found (Canal-Vergés et al., 2014, 2010; Valdemarsen et al., 2010, 2011). The anchoring capacity of the sediment is a major problem (Lillebø et al., 2011) along with the mobility of opportunistic macroalgae who create ballistic impact on eelgrass seedlings and also stimulates resuspension events (Canal-Vergés et al., 2014, 2010; Valdemarsen et al., 2010). Macroalgae starts drifting at low current velocities (2–3 $\mathrm{cm\,s^{-1}}$) where they increases resuspension during the mobility (Canal-Vergés et al., 2010; Flindt et al., 2007) reducing light availability for benthic vegetation (Hauxwell et al., 2003). In Danish waters the lugworm (*Arenicola marina*) has invaded former sandy eelgrass areas, with normal densities of 3–80 $\mathrm{ind.\,m^{-2}}$ (Valdemarsen et al., 2011). *A. marina* inhibits the reestablishment of eelgrass due to the worms feeding behaviour is reworking the sediment and herby burying both seeds and seedlings (Valdemarsen et al., 2011). Another stressor for eelgrass is resuspension induced by currents and waves. Sediment stability (shear stress) differs between sediment types and is especially low in muddy sediments. Share stress is highly influenced by benthic diatom biomass (Frederiksen, 2007). Frequent sediment resuspension lowers benthic light conditions and eelgrass anchoring capacity. This leads to eelgrass bed decline and seedling uprooting, therefore reducing eelgrass recovery potential (Carstensen et al., 2006; Orth et al., 2006).

All the above stressors have been introduced into the dynamic ecological MIKE 3D model. Hence, the impact of each of the stressors can be analyzed on a system level for both Odense and Roskilde Fjord. 3D MIKE models were used to evaluate the stressors influence on eelgrass growth and spatial distribution. The dynamical models used are good instruments to analyze complex systems, reveal system properties, discover knowledge caps and test scientific hypothesis (Jørgensen and Fath, 2011). The aim of this study was to investigate the magnitude of the stressors on eelgrass in two Danish fjords with different physical properties and area specific nutrient loadings by using the same setup in 3D MIKE dynamical models. The different model scenarios were made to help investigate potential areas for eelgrass recovery.

2. Material and methods

2.1. Site description

Two Danish fjords were selected for the model study simulating stress on the reestablishment of eelgrass (*Z. marina*). Odense Fjord is located on Funen and Roskilde Fjord on Zealand (Fig. 1). The area of Odense Fjord and Roskilde Fjord is 62 $\mathrm{km^2}$ and 122 $\mathrm{km^2}$, respectively (Flindt et al., 1997a).

Odense Fjord has an average depth of 2.2 m and tidal amplitude of 0.3 m with an average resident time is 17 days (Table 1). The shallow inner fjord has a mean depth of 0.8 m. Odense Fjord has a runoff area of 1095 $\mathrm{km^2}$. The inner part receives most of the external nutrient loading from Odense River (2000 $\mathrm{ton\,N\,y^{-1}}$ and 50 $\mathrm{ton\,P\,y^{-1}}$) (Riisgård et al., 2008). The outer fjord has a more variable bathymetry with an average depth of 2.7 m and a higher current and wave activity (Fig. 1). The inner part of the fjord is too eutrophied to fulfil the EU WFD. High concentration of dissolved inorganic nutrients (DIN, DIP) supports excessive growth of opportunistic macroalgae (*Ulva lactuca, Chaetomorpha linum*) and high turbidity, due to both phytoplankton growth and resuspension. In the outer part nutrient availability is lower and here the benthic system is dominated by perennial macroalgae (*Fucus vesiculosus, Fucus serratus*). Eelgrass covers about 2% of the system and grows down to depth of 2.9 m.

Roskilde Fjord (Fig. 2B) has an average depth 3 m and tidal amplitude of 0.2 m. The salinity ranges from 8‰ in the Southern part to about 20‰ in the Northern part at the outer boundary. Stratification of the water column occurs, but it is generally well-mixed. The total runoff area is 1127 $\mathrm{km^2}$. The yearly external nutrient loading from 20 tributaries and a suite of point sources is about 1000 $\mathrm{ton\,N\,y^{-1}}$ and 50 $\mathrm{ton\,P\,y^{-1}}$. The resident time in the Southern part is about 1 year, while it in the Northern part is about 3–4 weeks (Flindt et al., 1997b). Eelgrass is covering about 8% of the system mainly located along the shallow coastline. In the deeper broads (4–5 m) the sediment has low anchoring capacity caused by the high organic content (10–20% LOI). Excessive growth of opportunistic macroalgae is supported by the internal nutrient loading supporting high biomasses in the growth season.

2.2. Model set up

The model was setup with a 3 dimensional hydrodynamic model, a wave model and an ecological model, using a commercial software system by DHI (www.mikepoweredbydhi.com). MIKE 3FM was used for the hydrodynamic model, MIKE SW for the wave model, and ECOLab software was used for the ecological model. The same ecological model with eelgrass was used to model both estuaries. The hydrodynamic model includes three-dimensional flows, tidal elevations, water densities, salinity and temperature (DHI, 2012d; Rasmussen et al., 2009a). Water movement is driven by wind (Fig. 3), changes in water level at the model boundary, density gradients and riverine inflow from land. Wave and current generated shear stress at the bottom was calculated by the ECOLab model using a root-mean-square method to combine shear stress from waves and current (Soulsby and Clarke, 2005). The number of days with shear stress above 0.08 $\mathrm{N\,m^{-2}}$ is presented in Fig. 2. In the horizontal plane the bathymetric set up for Odense and Roskilde Fjords included 2388 and 7630 elements respectively with flexible grid size. In the vertical plane Odense Fjord has 3 sigma layers from 0 to 3 m and fixed 1 m layers from 3 m to bottom. Roskilde Fjord has 2 sigma layers from 0 to 2 m and fixed 0.5 m layers from 2 to 5.5 m and fixed 3 m layers from 5.5 to bottom. The hydrodynamic and the wave modes was run first and the ecological model was