Ecological Modelling 272 (2014) 116–128

Contents lists available at ScienceDirect

Ecological Modelling

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

Review

Eelgrass re-establishment in shallow estuaries is affected by drifting macroalgae – Evaluated by agent-based modeling

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ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form 4 September 2013
Accepted 8 September 2013
Available online 26 October 2013

Keywords:
ABM
Macroalgae bedload transport
Seagrass
Light
Ballistics
Sediment stability

ABSTRACT

It has been suggested that bedload transport of macroalgae in shallow lagoons and estuaries may negatively impact eelgrass through increased turbidity and physical stress. Increased turbidity and reduced benthic light availability for eelgrass occur when bedload transport of macroalgae erode surface sediment. Furthermore, drifting macroalgae ballistically damage eelgrass beds and increase seedling mortality. The frequency and impact of drifting macroalgae in Odense Fjord was evaluated with an agent-based model. The aims of this model were to understand and predict the mobility of opportunistic (*Chaetomorpha linum*) and non-ephemeral (*Fucus vesiculosus*) macroalgae and to describe and quantify the intensity and spatial distribution of bottom substrate physically affected by drifting macroalgae. The longest simulated movement by macroalgae was found to be 270 and 170 km for brown and green algae respectively; while the macroalgae losses (export) out of the fjord were up to 11% of the total biomass; the simulated area impacted by macroalgae drift varied between 16% and 96.5% of the total fjord area; finally the degree on physically impacted area varied from 0.01 to 28.5 m of algae track m^{-2}. The simulated pattern of drift distribution and hot spots for both brown and green algae fitted the geographical locations in which the algae community was observed on the field. Such high values for sea bed disturbances will have a major impact on the light availability due to sediment resuspension in bare bottoms and on rooted vegetation due to ballistic impacts in areas affected by algae drift.

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http://dx.doi.org/10.1016/j.ecolmodel.2013.09.008

1. Introduction

Seagrass are among the most stable, diverse and productive ecosystem in temperate coastal waters. In the last decades a significant reduction of seagrass ecosystem coverage has been observed, primarily due to heavy nutrient loading (Cardoso et al., 2004; Orth et al., 2006; Burkholder et al., 2007; Van Katwijk et al., 2011). Nitrogen and phosphorus enrichment leads to increased epiphytic coverage and phytoplankton blooms. Altogether the reduced benthic light availability affects the survival of rooted vegetation (Borum, 1985; Ralph et al., 2006). Furthermore, high concentrations of dissolved inorganic nutrients, both in the water column and sediment, stimulate the growth of opportunistic benthic macroalgae, such as *Ulva* sp., *Chaetomorpha* sp. Compared to eelgrass, ephemeral macroalgae have high loss rates and a very fast turn over (Geertz-Hansen et al., 1993; Salomonsen et al., 1997; Bergamasco et al., 2003). A fast turn over, meaning faster life cycles and easily degradable organic matter creates instability in the system promoting frequent periods of anoxia during decomposition.

Danish estuaries hold a history of euthrophication from the early 70s (Flindt et al., 1999; Andersen et al., 2004). In order to reduce the external nutrient loading a number of initiatives, such as restrictions on the agricultural land use has been implemented since the 1980s. These restrictions have been partly efficient, where especially nutrient loading from residential areas have been reduced due to construction of treatment plants. Nutrient run off from agricultural areas have also been reduced but are still considered too high (Petersen et al., 2009). Nowadays net production of phytoplankton and opportunistic macroalgae has been reduced, and the light availability in some coastal waters has improved and the anoxic periods previously observed are less frequent. Despite this improved water quality, the seagrass communities have not yet recovered (Nature Agency Odense, 2007). The lack of successful seagrass reestablishment can be partially explained by nutrient loadings not yet sufficiently reduced, the insufficient size of the remaining seagrass population for recolonization, a non-reversible shift in the benthic vegetation, or a combination of all these factors. The reasons behind the lack of seagrass recolonization are not yet fully understood and need further research. In some estuaries, as in Odense Fjord (Funen, Denmark), the nutrient reduction has resulted in a system change. Opportunistic macroalgae such as *Chaetomorpha linum* or *Ulva* sp. are still common in the inner fjord; however the outer fjord has shifted from an opportunistic macroalgae system to a system dominated by *Fucus vesiculosus* and *Fucus serratus* instead of the desired seagrass recovery (Valdemarsen et al., 2010, personal observations). *Chaetomorpha* grows always unattached and becomes buoyant at very low current velocities (Flindt et al., 2007). *Fucus* grows on the other hand, attached to the substrata and is typically abundant on rocky shores, where it is considered to be desirable vegetation due to their slower turnover and the associated high biodiversity. In Danish estuaries, where the sediments primarily consist of a mixture of fine sand and mud, suitable hard substrates are rare and species such as *Fucus* sp. grow attached to small stones and shells. This attachment to small objects gives macroalgae a highly mobile potential. *F. vesiculosus* will initially stay immobile at the bottom, until their growth of biomass and development of air vesicles compensate for the weight of their attachment (anchor). When the relative density of the combined anchor and macroalgae assemblage decreases the anchored macroalgae will start moving as bed load transport, eroding the sediment surface (drifting). As the macroalgae biomass increases and the overall density decreases, the threshold velocity to initialize drifting movement will decrease as well. Finally, *F. vesiculosus* will end up floating in the water column.

The majority of drifting macroalgae, both opportunistic and non opportunistic species, moves as bedload (near the bed) and creates ballistic disturbances on the sediment affecting subsequently any organism living at the sediment surface. When macroalgae are drifting along the sediment they create substantial resuspension and reduce the benthic light availability (Canal-Vergés, 2011) which affects eelgrass reestablishment. For instance Valdemarsen et al. (2010) found a relation between the ballistic impacts generated by drifting macroalgae and the mortality of eelgrass seedlings in Odense Fjord.

A number of models include description of both attached and/or unattached macroalgae growth dynamics (Flindt and Kamp-Nielsen, 1997; Trancoso et al., 2005; Brush and Nixon, 2010). However, the focus has mainly been on the macroalgae production and how macroalgae affect the nutrient turnover and mass balance of the system. This approached fits to the category of eularian models with fixed calculation points (grid calculations), where the focus is on the temporal changes in the modeled areas (in each grids). Just a reduced number of models have focused on macroalgae mobility, their dispersion, and the implication of macroalgae drift on the state of the ecosystem (Salomonsen et al., 1999; Flindt et al., 2004; Yñiguez et al., 2008; Canal-Vergés, 2011). In the present paper, we present a lagrangian, agent based model (ABM), where macroalgae are introduced as mobile "particles", that dependent on the local environmental conditions to realize less or more growth. In this case the focus will be on the moving "particle" (langragian component) and not on the background conditions (grids in which our particles are moving and to which they react). Therefore the present model is essentially an ABM model combined with an eulerian hydrodynamical model and an eulerian eutrophication model (grids). The aim of this model development is to study the transport of attached and unattached macroalgae and the physical disturbance that this transport creates on the sediment surfaces and the eelgrass reestablishment process in the Odense Fjord estuary.

2. Methods

2.1. Site description

Odense Fjord is located on the island of Funen, Denmark, and has an extension of 62 km^2 (Fig. 1). It is a shallow estuary with an