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Effects of long-term grazing on sediment deposition and salt-marsh accretion rates

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ABSTRACT

Many studies have attempted to predict whether coastal marshes will be able to keep up with future acceleration of sea-level rise by estimating marsh accretion rates. However, there are few studies focussing on the long-term effects of herbivores on vegetation structure and subsequent effects on marsh accretion. Deposition of fine-grained, mineral sediment during tidal inundations, together with organic matter accumulation from the local vegetation, positively affects accretion rates of marsh surfaces. Tall vegetation can enhance sediment deposition by reducing current flow and wave action. Herbivores shorten vegetation height and this could potentially reduce sediment deposition. This study estimated the effects of herbivores on 1) vegetation height, 2) sediment deposition and 3) resulting marsh accretion after long-term (at least 16 years) herbivore exclusion of both small (*i.e.* hare and goose) and large grazers (*i.e.* cattle) for marshes of different ages. Our results firstly showed that both small and large herbivores can have a major impact on vegetation height. Secondly, grazing processes did not affect sediment deposition. Finally, trampling by large grazers affected marsh accretion rates by compacting the soil. In many European marshes, grazing is used as a tool in nature management as well as for agricultural purposes. Thus, we propose that soil compaction by large grazers should be taken in account when estimating the ability of coastal systems to cope with an accelerating sea-level rise.

1. Introduction

Global climate change threatens many different ecosystems and human habitats worldwide (Warren et al., 2010). One of the most striking and evident threats concerns the effect of accelerating rates of sea-level rise (Woodworth et al., 2011), which could cause flooding of many coastal habitats in the near future (FitzGerald et al., 2008). Coastal habitats, such as tidal marshes, provide many important ecosystem services including coastal protection of inland areas against tidal and storm-surge flooding (Costanza et al., 2008; Gedan et al., 2010; Temmerman et al., 2012b) and staging sites for migrating waterfowl (Madsen et al., 1999). Tidal marshes accumulate fine-grained, mineral sediment thereby enhancing marsh accretion rates, which in turn may enable marshes to keep pace with accelerating sea-level rise (Cahoon and Reed, 1995; Kirwan and Temmerman, 2009; Stralberg et al., 2011). However, previous studies assessing the ability of marshes to keep up with accelerating sea-level rise found contradicting results. Some marshes have been predicted to become submerged (Bakker et al., 1993; van Wijnen and Bakker, 2001; Kirwan and Temmerman, 2009; Kirwan et al., 2010; Stralberg et al., 2011), whereas other marshes have been predicted to be able to keep pace with the accelerating sea-level rise (Bakker et al., 1993; Neuhaus et al., 1999; Morris et al., 2002; Temmerman et al., 2004). So far, the main focus has been on abiotic controls of marsh accretion rates and the effects of local vegetation on sediment deposition, whereas indirect effects by grazers on the sedimentation process have received much less attention (with exceptions of Andresen et al. (1990), Neuhaus et al. (1999) and Suchrow et al. (2012)).

Important processes affecting accretion rates of tidal marshes identified so far include: tidal-driven deposition of mineral suspended sediment on the marsh surface (especially silt and clay); organic matter accumulation (from local vegetation); erosion, and auto-compaction of the soil sediment (Cahoon et al., 2006). Both deposition of mineral sediment and organic matter accumulation can enhance marsh accretion (Day et al., 2011; Suchrow et al., 2012) and are influenced by marsh vegetation. Firstly, above-ground vegetation can positively affect sediment deposition (Mudd et al.,

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2010; Day et al., 2011). As inundating water flows over the marsh surface, the vegetation offers resistance and reduces velocity of the tidal current (Christiansen et al., 2000; Neumeier and Amos, 2006a, 2006b; Temmerman et al., 2012a), thereby enhancing the settling of suspended sediment from the water column onto the marsh surface (Mudd et al., 2010). Tall, stiff vegetation can decrease current velocities more efficiently, which can result in a more positive effect on sediment deposition (Peralta et al., 2008). Secondly, belowground roots form an important part of the organic matter accumulating in the soil (Nyman et al., 2006; Neubauer, 2008). With respect to processes that reduce accretion rates, erosion is generally not significant in most marshes because the aboveground vegetation canopy diminishes flow velocities and belowground roots consolidate sediment, thus increasing their resistance to disturbance (*e.g.* Howes et al., 2010). However, auto-compaction of the deposited sediment can be a significant process that reduces marsh accretion rates. Thick layers of fine-grained sediments on older marshes can auto-compact due to age, weight and drought (Cahoon et al., 1995, 2011; Allen, 2000; Bartholdy et al., 2010).

As mentioned previously, presence of vegetation on the marsh can enhance sediment accretion rates and this will positively affect the ability of marshes to keep pace with the accelerating rate of sea-level rise. When grazers are present in a system, they generally change vegetation structure, most notably reducing vegetation height (Bakker, 1989; Andresen et al., 1990; Bos et al., 2002). There are many different grazers present on marshes ranging from small (*e.g.* hare and different goose species) (Madsen et al., 1999; van der Wal et al., 2000b) to large species (*e.g.* cattle and sheep). Livestock are used for nature management practices as well as for agricultural purposes (Bakker, 1989; Kiehl et al., 1996). By grazing, herbivores can create short dense 'grazing lawns' consisting of short highly palatable vegetation (Bos et al., 2002, 2004). This could negatively impact sediment deposition as the grazers remove the tall vegetation needed to reduce current velocities so that suspended sediment can settle on the marsh surface. Additionally, grazing has been shown to alter the grain size of particles found at the local scale (Yang et al., 2008).

This study quantified the effects of grazers on 1) vegetation height, 2) sediment deposition and 3) resulting marsh accretion rates. To achieve this, we compared plots that had been grazed over the long term with those that had been excluded from grazing by either small herbivores (*i.e.* hares and geese; 16 years of exclusion using wire mesh exclosures) or large herbivores (*i.e.* cattle; 22 years). Ultimately, we tested two hypotheses: 1) grazing by both small and large herbivores will shorten vegetation height, thereby reducing rates of sediment deposition, and 2) large herbivores will compact the soil by trampling, thereby reducing marsh accretion rates.

2. Materials and methods

2.1. Definition of terms

For sediment characteristics, we use similar terms as those defined in a review by Nolte et al. (2013), who in turn adapted most of their terminology from Cahoon et al. (1995) and Van Wijnen and Bakker (2001). The terms commonly used in this paper are sediment deposition, total deposited sediment, fine-grained sediment layer thickness, (auto-) compaction, bulk density and marsh accretion rate. Marsh formation starts when pioneer vegetation establishes on a coarse-grained sandy plain (hereafter referred to as the base elevation) and fine-grained sediment is slowly deposited on the marsh surface (hereafter referred to as sediment deposition (g cm^{-2})). Total deposited sediment (g cm^{-2}) is used to refer to all the sediment accumulated on the marsh surface since marsh formation. The thickness of the layer containing sediment deposited since marsh formation is referred to as the fine-grained sediment layer thickness (cm). Increasing age and thickness of the layer will generally result in auto-compaction. Under the influence of its own weight, the bulk density (g cm^{-3}) will increase and the fine-grained sediment layer will decrease in thickness. Ultimately, a combination of total deposited sediment, compaction of the sediment and root material added from the local vegetation will determine the marsh accretion rate (increase in surface elevation in mm yr^{-1}). It is this accretion rate which determines whether a marsh can keep up with accelerating rates of sea-level rise.

2.2. Study site

This study was carried out on the back-barrier marsh of the island of Schiermonnikoog located in the Dutch Wadden Sea (Fig. 1, 53 30′N, 6 10′E). Tidal amplitude is approximately 2.3 m and extreme high tides (*i.e.* tides reaching higher than 1.3 m above MHT) occur approximately 5 times each year. This back-barrier marsh was formed when large dune formation prevented the bare sand flat behind them from being frequently inundated by tidal water from the North Sea and daily inundations only continued from the gentler waters from the south side of the island.

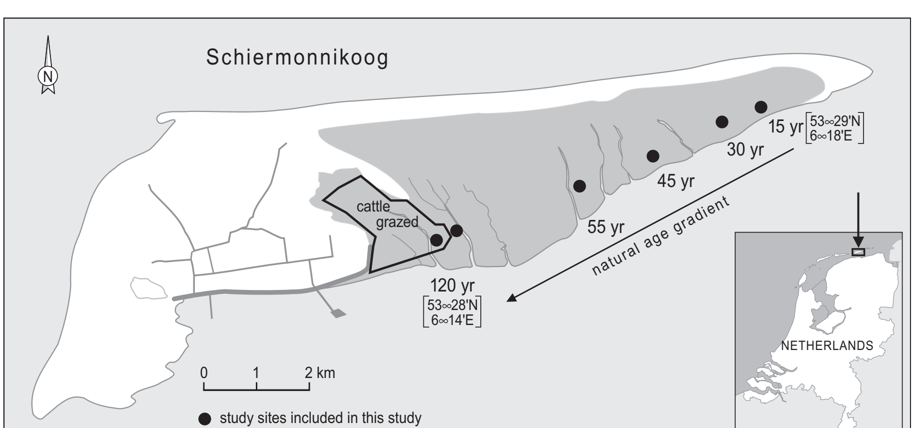

Fig. 1. A map is shown of the eastern part of the back-barrier marsh of Schiermonnikoog (grey area), including the natural successional gradient. Each study site is indicated with a black dot, representing an exclosure and approximate age of the site is shown. The most western marshes are grazed by cattle (indicated with the black line) and the eastern marshes are only grazed by hares and geese.