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Density and habitat dependent effects of crab burrows on sediment erodibility☆

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ABSTRACT

Despite biological interactions being highlighted as a key process in determining particle fluxes, relatively few studies have attempted to establish the links between burrow building bioturbators and sediment stability. The mud crab *Austrohelice crassa*, is a key burrowing species in New Zealand estuaries that has shown context-specific interactions with its environment. Here we use annular flumes to test if sediment stability and erodibility were altered as a function of *A. crassa* burrow density in two contrasting sediment types: a cohesive sandy-mud and a non-cohesive sand. Three burrow density treatments ($n = 3$) reflecting the natural density range in each sediment type (sand; 0–100 m^{-2}, sandy-mud; 0–400 m^{-2}), were collected from the field and subjected to sequential increases in water flow velocity. Flow profiles were measured and bed shear stresses were calculated for each treatment. Increasing burrow density reduced the mass of sediment eroded at 0.35 $m\ s^{-1}$(ME-35, $g\ m^{-2}$) in cohesive sandy-mud, while in non-cohesive sand a unimodal pattern was observed, whereby erosion rates were greatest at the lowest burrow density (19 m^{-2}). In the cohesive sediment, the linear decrease in erodibility with increasing burrow density was likely affected by the sluicing of fine particulates (silt–clay) from burrows when the tide was out creating both a smoothing and consolidating effect on the sediment surface. A reduction in flow velocity due to the increased presence of surficial pellets and greater trapping of bedload transported material was attributed to the reduction in the mass of sediment eroded in sand at high burrow densities. This study demonstrates that burrow builders influence sediment transport by more than just vertical particle mixing and highlights some of the complexities of small-scale sediment processes. Knowledge of different organism–sediment interactions among sediment types and spatial scales will enhance the accuracy of sediment transport models.

1. Introduction

Soft sediment ecosystems are the most extensive environments on the planet including large areas of the intertidal zone (Snelgrove, 1999). It has long been established that bioturbating fauna influence the flux of matter across the sediment–water interface through disruption of the geotechnical properties of the sediment matrix (Meadows and Meadows, 1991; Meysman et al., 2006; Murray et al., 2002) affecting sediment erosion and deposition rates by several orders of magnitude (e.g. Andersen et al., 2002, 2005; Grant, 1983; Paterson and Black, 1999; Widdows et al., 1998). This can have broad-scale effects on water turbidity, sediment transport and benthic community composition and ultimately influence the evolution of estuarine flat morphology. Such modifications to the benthic environment have the capacity to alter ecosystem functioning by influencing the rates and pathways of processes such as nutrient cycling, primary production, organic matter remineralisation and the redistribution of pollutants and contaminants (Banta and Andersen, 2003; Lohrer et al., 2004; Snelgrove, 1997; Thrush et al., 2006; Webb and Eyre, 2004). Despite biological interactions being highlighted as a key process in determining particle flux, relatively few studies have attempted to establish the links between bioturbation (biological perturbation) and sediment stability (Graf and Rosenberg, 1997 and references therein; Fernandes et al., 2006; Widdows et al., 2009). Studies on burrow building species are particularly lacking, considering the number of habitats in which they dominate in both number and biomass (Botto and Iribarne, 2000; Escapa et al., 2007, 2008; Needham et al., 2010; Widdows et al., 2009). Further understanding and quantification of how small-scale biotic processes can influence sediment stability at greater scales will enhance the predictive capabilities and realism of hydro and sediment dynamic models (Widdows et al., 2004).

Burrow construction modifies the structure of sediments as both the sediment matrix and interstitial porewater are mixed during the building process (Botto and Iribarne, 2000; Escapa et al., 2008; Graf and Rosenberg, 1997; Nowell and Jumars, 1984). The formation of water filled burrows often results in a reduction of bulk shear strength, bulk density (particularly in cohesive sediments) and erosion thresholds, increasing the mass of sediment eroded, especially where burrow densities are high (Grabowski et al., 2011 and references therein). Burrows are often surrounded by mounds and hummocks, as well as surficial

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deposits from feeding, defecating and burrow maintenance leading to complex sediment surface topography (Murray et al., 2002 and references therein). Such features may modify erosion rates through changes in bed roughness altering flow dynamics, turbulence and deposition (Botto et al., 2006; Friedrichs et al., 2009; Graf and Rosenberg, 1997; Yager et al., 1993). Biological processing of sediments also influences erodibility; faecal pellets colonised by microphytobenthos may act to stabilise sediments (Palomo and Iribarne, 2000), while those stripped of organic material through ingestion may be more easily eroded.

Differences in sediment stability between cohesive mud and non-cohesive sand occur naturally, irrespective of benthic biota, as transport is also heavily influenced by particle size, the strength of cohesive forces between particles, water content and hydrodynamics. Many studies have shown a correlation between erosion threshold and particle size (Grabowski et al., 2011 and references therein), however most have focussed on non-cohesive sediments as the transport dynamics of cohesive particles are much less predictable. As key bioturbating species often reside across broad sedimentary gradients, organism–sediment interactions may differ due to changes in the inherent sediment properties surrounding them, in turn affecting erodibility (Escapa et al., 2008; Widdows and Brinsley, 2002).

Attempts to group organisms into functional classifications such as ‘stabilisers’ or ‘destabilisers’, have been limited in success because of an oversimplification of the processes and interactions at work (Nowell and Jumars, 1984 and references therein). Few burrow builders have been classified in this way. However, the burrowing species *Nereis diversicolor* and *Corophium volutator* (herein *Nereis* and *Corophium*), were categorised as ‘stabilisers’ based on their ability to increase sediment shear strength (Meadows and Tait, 1989; Meadows et al., 1990) until direct measures of bed erosion also demonstrated that both species destabilise sediments under differing conditions such as changes in flow or season (de Deckere et al., 2001; Fernandes et al., 2006; Gerdol and Hughes, 1994). Widdows et al. (2009) also demonstrated density-dependent effects of burrowing and surface deposit feeding by *Nereis* on bed erodibility, while *Corophium* burrow caps have been shown to ‘armour’ the sediment, preventing erosion despite simultaneously increasing erosion potential due to increased bed roughness (Grant and Daborn, 1994). As organism–sediment interactions are complex and often context-specific, the capacity for individual species to influence sediment dynamics is poorly understood and often highly contested. This highlights the difficulties in predicting net effects on sediment transport over broader spatial scales (Jumars and Nowell, 1984).

The burrowing mud crab *Austrohelice crassa* (herein *Austrohelice*), is a key species in the regulation of ecosystem functioning in New Zealand estuaries (Gibbs et al., 2001; Needham, 2011; Thrush et al., 2003), and has been shown to exhibit some degree of functional plasticity mediated by the sediment environment (Needham et al., 2010). This shift in functionality is attributed to differences in burrow permanency and consequentially, sediment reworking rates between cohesive and non-cohesive sediments. These differences have been shown to modify the flux of nutrients to the overlying water column (Needham et al., 2011) and are also likely to create differences in the erodibility between sediment types. As *Austrohelice* burrows are less stable in non-cohesive sand than in cohesive muddy sediment (mean burrow permanency = 1.4 days and 26 days respectively, Needham et al., 2010), sediment is turned over much more frequently, particularly in areas of high crab density. Sediment in these areas will be less consolidated than areas without crabs and consequently microbial biomass, and hence cohesion, may be reduced. Surficial pellets of a similar grainsize and organic matter content as the sediment surface are often seen in this habitat (Needham et al., 2010). These pellets likely alter bed roughness but are often dispersed or somewhat flattened with each tide. In mud, far greater burrow densities are often observed due to both increased crab number and burrow longevity. Burrow openings are often sunken from the sediment surface and, due to their close proximity to one another, form undulations in the bed surface topography that may modify boundary layer dynamics (Baas and Best, 2000; Fries et al., 1999, 2000; Widdows and Brinsley, 2002; Widdows et al., 2000, 2004). However, surficial pellets are not formed in muddy sediment (H.R. Needham, *pers obs*) and therefore surface roughness may be less pronounced in mud than sand at equivalent burrow densities.

Here we explore the relationships between *Austrohelice* burrow density and sediment type in two key habitats, a fine to medium sand and a cohesive sandy-mud, to establish the role of *Austrohelice* burrows on sediment particle fluxes. Intact sediment cores containing burrows from these environments were subjected to a range of flow velocities in annular flumes. Burrow morphology is highly varied regardless of sediment type and organism density (Needham et al., 2010), therefore by using actual burrows instead of mimics we aimed to gain a greater appreciation of the structure–flow–sediment interactions in the natural environment. We hypothesised that with increasing burrow macropores, erosion thresholds would reduce, increasing sediment erodibility. Due to the differences in the inherent sediment properties between cohesive and non-cohesive sediments, as well as the more frequent disruption and modification of the surface topography in sand, we anticipated that the magnitude of the impact of *Austrohelice* burrows would differ between sediment types.

2. Methodology

2.1. Study site and experimental treatments

Sediments were collected from crab beds in the mid intertidal zone of Tairua estuary (36° 59′ 57.56″ S, 175° 51′ 04.09″ E), Coromandel Peninsula, New Zealand, during summer over a 3 week period. At the two selected locations, classed as a cohesive sandy-mud (herein called site SM) and a non-cohesive fine to medium sand (herein called site S; Table 1), burrow densities and burrow permanency have been shown to differ by over an order of magnitude (Needham et al., 2010). *Austrohelice* comprise the majority of macrofaunal biomass at both sediment types and very few other macrofaunal species greater than 1 cm in diameter reside within the burrowed beds (Needham, 2011), likely due to the high levels of crab-generated sediment disturbance (Botto and Iribarne, 2000). Small-scale variations in burrow density within each crab bed were used to create burrow density treatments of 0, 19 and 100 burrows m^{-2} in site S and 0, 100 and 400 m^{-2} in site SM, each replicated 3 times. *Austrohelice* density has been shown to correlate with increasing mud content (Thrush et al., 2003), and these selected densities reflect the natural range of adult burrows (>8 mm dia.) at the two sites (Needham et al., 2010). Adult crab burrows were targeted as these represent the dominant source of bioturbation and sediment mixing effects in both sites. Overlap of the highest burrow density in site S and the lowest density in site SM was deliberate, allowing comparison between sediments while still reflecting natural burrow densities for

Table 1
Sediment properties (0–1 cm) of the two selected sediment types in Tairua estuary. Three samples were collected and pooled on 6 sample dates interspersed throughout the three week study period. ±SD are given in parentheses. S: non-cohesive sand; SM: cohesive sandy-mud; Chl *a*: sediment chlorophyll *a* concentration; Phaeo: sediment phaeopigment concentration.

Sediment property	Site S	 SM
Chl *a* ($\mu g\ cm^{-3}$)	9.9 (0.8)	19.4 (2.0)
Phaeo ($\mu g\ cm^{-3}$)	2.1 (1.1)	4.3 (2.1)
Organics (%)	2.8 (0.1)	5.3 (0.9)
Water content (%)	30.1 (1.0)	59.7 (10.9)
Dry bulk density ($g\ cm^{-3}$)	1.5 (0.02)	1.05 (0.1)
Silt–clay (%)	5.9 (1.3)	63.5 (15.2)
Median grain size (μm)	226 (13.6)	119 (95.4)