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Ecosystem engineering potential of the gastropod *Terebralia palustris* (Linnaeus, 1767) in mangrove wastewater wetlands – A controlled mesocosm experiment

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Terebralia palustris high ecosystem engineering potential in constructed mangrove wetlands.

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ABSTRACT

The effect of different sewage concentrations (0, 20, 60 and 100%), vegetation (Bare, *Avicennia marina* or *Rhizophora mucronata*) and immersion periods (immersion/emersion period of 12/12 h or 3/3 days just for 100%) conditions were studied for 6 months on survival and growth rates of *Terebralia palustris* (Linnaeus, 1767). Gastropods' activity and ecosystem engineering preformed at bare and *A. marina* planted cells and 3 sewage conditions (0, 20 and 60%) were determined. Survival rates were higher than 70% in all treatments. Growth rate decreased significantly with increasing sewage concentrations (mainly at unplanted conditions) and longer immersion periods. A complete shift (from immersion to emersion periods) and a significant decrease in mobility and consequently its engineer potential, due to sewage contamination, lead to a 3–4 fold decrease in the amount of sediment disturbed. Sewage contamination, primary producers' abundance and environmental conditions may have influenced the gastropods survival, growth and its ecosystem engineering potential.

1. Introduction

Mangrove forests are known to provide important ecosystem goods and services such as nursery areas for several important aquatic species, and a variety of food, timber and chemicals for local communities (Duke et al., 2007). These systems have recently shown a potential as natural wastewater treatment facilities, thus preventing coastal pollution (Wong et al., 1997a). Field trials have shown that sediments of these ecosystems are very efficient in removing nutrients from sewage (Tam and Wong, 1995, 1996), without apparent impacts on mangrove trees (Wong et al., 1997a) or significant effect on the benthic invertebrate communities (Yu et al., 1997).

Sewage filtering of constructed mangrove wetlands is now addressed worldwide, mainly due to low running cost and high efficiency potential (PUMPSEA, 2008; Yang et al., 2008), although it was shown that wastewater loadings above the system capacity and under weak hydrodynamic conditions usually lead to eutrophication and consequently hypoxic conditions (Gray et al., 2002). Low oxygen levels may decrease faunal diversity and biomass due to emigration of mobile species or high mortality of less mobile species in natural mangroves (Diaz and Rosenberg, 1995) or lower survival rates in constructed wetlands (Penha-Lopes et al., accepted). This could significantly affect ecosystem functioning (Biles et al., 2002; Le Hir et al., 2007), and coupled with a potential decrease in activity and behaviour of the more resistant species (Diaz and Rosenberg, 1995) potentially reduce the mangrove health and filtration efficiency.

Most studies on sewage filtration have focussed on the role of plants and sediment with associated microbes and microalgae (e.g., Wong et al., 1995, 1997a; Tam, 1998) and only few have dealt with macrofaunal performance under severe conditions. Mangrove fiddler crabs maintained survival rates near 50% and efficient bioturbation via feeding and burrowing for 6 months in severe organic contaminated mangrove mesocosms (Penha-Lopes et al., accepted). Most infauna species such as crabs and polychaetes are key players

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in healthy ecosystems by increasing mineralization processes and nutrient cycling through burrowing and irrigation activities (Kristensen and Kostka, 2005), mainly in organic-rich systems (Hansen and Kristensen, 1998; Nielsen et al., 2003; Kinoshita et al., 2008; McHenga and Tsuchiya, 2008; Lindqvist et al., 2009).

Among all benthic species, gastropods are considered very resistant to low oxygen levels (Gray et al., 2002). They generally maintain high survival during hypoxic events (Stickle et al., 1989; Das and Stickle, 1993; Sagasti et al., 2001) and are among the first colonizers of previous anoxic environments (Gamenick et al., 1996). Nevertheless, they respond to low oxygen concentrations by decreasing their crawling and feeding activities, and consequently diminish metabolic rate and growth (Stickle et al., 1989; Das and Stickle, 1993; Cheung et al., 2008; Riedel et al., 2008). Gastropods play an important ecological role in natural systems through organic matter consumption (Slim et al., 1997; Fratini et al., 2004), bioturbation effects on nutrient cycling (Biles et al., 2002), regulation of meiofauna and microphytobenthos biomass (Carlén and Ólafsson, 2002; Pape et al., 2008), changes in the dynamics of suspended material (Kamimura and Tsuchiya, 2004) and effects on sediment stability (Orvain et al., 2003, 2004, 2006).

The mudwhelk *Terebralia palustris* (Linnaeus, 1767) is a key epifaunal species in East African mangrove forests. Studies have shown that it is important for the nutrient cycling by consuming large amounts of *Avicennia marina* (Forsk.) and *Rhizophora mucronata* Lam. litter. It can also regulate microphytobenthic primary productivity through feeding and crawling activities (see Cannicci et al., 2008; Lee, 2008). However, this species disappeared completely following organic contamination of mangrove areas in Mozambique, Kenya and Zanzibar (Cannicci et al., in press) suggesting an upper tolerance limit to the conditions present in those areas.

It is therefore fundamental to investigate the direct and indirect effects of severe sewage contamination on species like *T. palustris* to comprehend the effect of organic discharges on natural mangrove forests as well as to develop a sustainable and more efficient mangrove wastewater wetland. The major goal of this study was to determine survival and growth of *T. palustris* under different domestic sewage loading, immersion periodicity and vegetation conditions. Further, its behaviour and bioturbation activities, and thus ecosystem engineering potential, were evaluated at different sewage concentrations in the presence or absence of mangrove trees.

2. Materials and methods

2.1. Experimental setup

A mesocosm system consisting of 27 cells (9 m^2 each) was constructed at the upper *A. marina* (Forsk.) belt of the Kunduchi mangrove forest (Jangwani Beach) located at longitude 39°12′–39°13′E and latitude 6°39′–6°41′S, about 18 km from Dar es Salaam City Centre, Tanzania (see system description in Penha-Lopes et al., accepted). The 27 cells were divided as follows: "vegetation" treatment, with nine unvegetated cells, nine cells planted with *A. marina*, and nine with *R. mucronata* Lam. saplings. Sediment was laid and saplings planted (at a density of 2.8 m^{-2}) on selected plots in early February 2006. The system was initially inundated exclusively with seawater and sewage discharge was initiated in early October 2006. For each vegetation treatment, three replicate cells were exposed to sewage loading of 0, 20 and 60% in seawater for the first 6 months period (October 2006–April 2007). A diurnal tidal rhythm was simulated with 12 h immersion to 0.1 m depth starting at 23:00. The sewage concentration was increased to 100% during the second 6 months period (April 2007–October 2007) with 12/12 h (100_{12h}) and 3/3 days (100_{3d}) immersion/emersion periods for all vegetation conditions (only 2 replicates). The basic chemical and biological characteristics of sewage–seawater mixtures are presented in Tables 1 and 2 (adapted from PUMPSEA, 2008). *A. marina* and *R. mucronata* were 50.30 ± 1.17 and 55.3 ± 0.5 cm (±SE) tall, respectively, and litter fall from the young trees was absent when sewage discharge was initiated. They grew to 223.9 ± 18.0 and 133.0 ± 13.2 with litter fall of 1.17 ± 0.20 and 2.8 ± 0.7 g m^{-2} day^{-1} (for *A. marina* and *R. mucronata*, respectively) in October 2007 (PUMPSEA, 2008).

T. palustris individuals were introduced to each cell in August 2006 together with individuals of abundant fiddler crab species found in East African mangrove forests, *Uca annulipes* (H. Milne Edwards, 1837) and *Uca inversa* (Hoffmann, 1874). All fauna was randomly collected from the Jangwani mangrove forest near the mesocosm system. The chosen abundance of *T. palustris* (5 ind m^{-2}) was in the lower range of natural densities (Cannicci et al., in press). Fauna adapted to the system for almost two months before sewage discharge was initiated. At that time the gastropods had an average size (±SE) of 62.49 ± 0.31 mm.

2.2. Gastropod survival and growth

T. palustris survival and size increment (also denominated as growth from now on) in 0, 20 and 60% sewage concentrations was followed for the first 6 months. At this time, survival and growth rates were calculated based on the difference of the average value obtained for each cell with initial conditions. The survival and growth rates in 100% sewage (both 100_{12h} and 100_{3d}) were calculated from the fraction of individuals that stayed alive during the second 6 months period. For gastropod survival and size analysis (shell height), all individuals in each mesocosm were collected, checked for life activity, counted and measured (maximum linear dimension of the shell from the apex to the anterior edge of the lip) at each sampling period (immediately before, and 6 months and 12 months after starting sewage discharge), and then returned to the respective cell.

2.3. Gastropod behaviour and bioturbation

This set of experiments was done during an intensive campaign from March to April 2007. Due to similar survival and growth results between both planted cells, 3 replicates of 0%, 20% and 60% sewage in bare and *A. marina* cells were used. Temporal replication was conducted during half (except for 20%) and full moon, which coincides with neap and spring tides in the surroundings.

2.3.1. Environmental conditions

Top-sediment temperature, porewater content and dissolved oxygen (DO) of sewage mixtures were measured on one occasion in all cells receiving 0% and 60% sewage. Temperature was measured every 2 h (except at night, 02.00–07:00) in 5 replicates per cell. Sediment for porewater content (determined as weight loss after drying sediment samples at 100 °C for at least 12 h) was sampled in 5 replicates per cell every 2 h during the emersion period (12:00–22:00). Dissolved oxygen was measured right after immersion (24:00), before sunrise (6:00) and just before flushing out (11:00) twice in every cell using a dissolved oxygen probe (WTW Oxi 330i with an associated WTW CellOx 325 electrode).

2.3.2. Behaviour

Due to the considerable differences in behaviour between 0% and 60% sewage treatments during the first temporal replication, it was decided to include 20% sewage treated cells during the second replication period. At each period, the position of 8 marked gastropods of different sizes in each examined cell was noted every 2 h over a 24 h cycle. The total daily movement of each individual was estimated as the sum of all 2 h events, which were measured as the straight line between the initial and final position. Whenever possible ($N = 66$, approximately 10% of all 2 h events), the real path of each individual was measured from tracks in the surface sediment to obtain a correction of the straight line estimate. Individuals were located and identified by a buoy with a specific colour code attached to the shell during immersion and a specific colour code painted on their shell during emersion. Flags with the same colour codes were used to mark the 2 h positions.

2.3.3. Bioturbation

The amount of sediment displaced by different sized *T. palustris* individuals during movement was determined in the laboratory and extrapolated to the mesocosm results. Sediment displaced by the track area of individuals in different sediment types (i.e. porewater content) was measured and calculated under flooded, wet and dry conditions. Wild animals were collected from the same location as those used in the mesocosm experiment, while sediment was collected from cells receiving no sewage. Sediment was transferred to 40 × 40 × 10 cm plastic boxes to a depth of 4 cm and seawater was added in excess. To simulate flooded periods 4 cm of water column were maintained, for wet conditions (21.9 ± 0.4% of porewater) excess of water was removed only, and for dry conditions (6.9 ± 0.9% of porewater) sediment was in addition placed at the sun for 1 h. Gastropods with fresh weights ranging from 2.2 to 42.3 g were used. Individuals were placed on the sediment at flood, wet and dry conditions and allowed to move at least 30 cm. The displaced sediment was estimated on 5 cm subsections of the 30 cm track by assuming that, the cross section of tracks approximated half of an ellipse area ($A_{section} = 1/4 \times \pi \times a \times b$). Measured track width is equivalent to a and maximum depth represents b. Using these laboratory based results, the total sediment displaced by individuals of known weight in the mesocosms during a 24 h cycle was estimated.

2.4. Statistical analysis

2.4.1. Survival and growth experiments

A two-way ANOVA was used to compare *T. palustris* survivorship (using ArcSin transformed data) and average height increment for the two 6 months periods, under different vegetation conditions and sewage loading (0, 20 and 60% for the first