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Aquaculture induced erosion of tropical coastlines throws coastal communities back into poverty

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ABSTRACT

Shallow tropical coastlines harbour unique mangrove ecosystems, which support livelihoods and provide a natural barrier against coastal flooding. Non-sustainable land-use practices, such as large-scale clear cutting of mangroves for aquaculture, ground water withdrawal and alteration of river flows, result in rapid subsidence. The collapse of aquaculture production, due to pollution and disease, is followed by coastal erosion, damage to infrastructure, intrusion of salt water and coastal flooding. Standard engineered interventions for protection often fail or are extremely expensive in these soft muddy environments. Subsidence and erosion render re-planting of mangroves in front of retreating coastlines impossible. Short-term solutions should focus on restoration of abiotic conditions, such as hydrology and sediment fluxes, to facilitate rapid establishment of protective mangrove belts. However, to ensure long-term sustainability, improved governance frameworks are required that put in place criteria for sustainable aquaculture, guide coastal infrastructure designs and limit ground water extraction.

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Large-scale erosion and subsidence of tropical muddy coastlines following the establishment of aquaculture ponds and development of hard infrastructure is observed in several countries in South East Asia, such as Thailand and Indonesia (Fig. 1) (Marfai, 2011; Saengsupavanich, 2013), and along Latin American coastlines. Characterization of Landsat images of the coastline of Northern Java shows a total loss of 55 km^2 of land between the beginning of the 21st century and 2014. Areas that suffer most of subsidence and erosion are in proximity of large urban agglomerations, such as Jakarta and Semarang on Java and near Bangkok in Thailand (Fig. 1). In these urban agglomerations subsidence levels are large due to ground water extraction from deep wells. In Bangkok subsidence was around 12 cm/year in the 1980's (Phienwej et al., 2006). In Semarang subsidence rates of up to 15 cm/year were measured between 1979 and 2006 (Kuehn et al., 2010). Also in certain areas in Jakarta subsidence exceeds 10 cm/year (Abidin et al., 2001). Subsidence from groundwater pumping has mainly been considered a problem of urban areas, yet intensive aquaculture in rural areas is often also accompanied by groundwater pumping and resulting land subsidence (Higgins et al., 2013). Additionally, little is known yet on the extension of urban subsidence into rural areas. Further analyses of ground water extraction and resulting subsidence in rural areas are required to support implementation of mitigation measures and policies.

1. Mangrove conversion to intensive aquaculture

One of the largest threats to coastal safety is the rapid conversion of mangroves into fish and shrimp ponds (Pattanaik and Prasad, 2011; Primavera, 2006). Such conversion across the entire intertidal zone sets off cascading effects that contribute to further subsidence and erosion of the coastline. Removal of mangrove forests diminishes their capacity to attenuate waves, trap sediment and accumulate organic matter. Additionally, in aquaculture pond systems, rivers are disconnected from the natural floodplain, thereby depriving the floodplain from new sediment input. Further,

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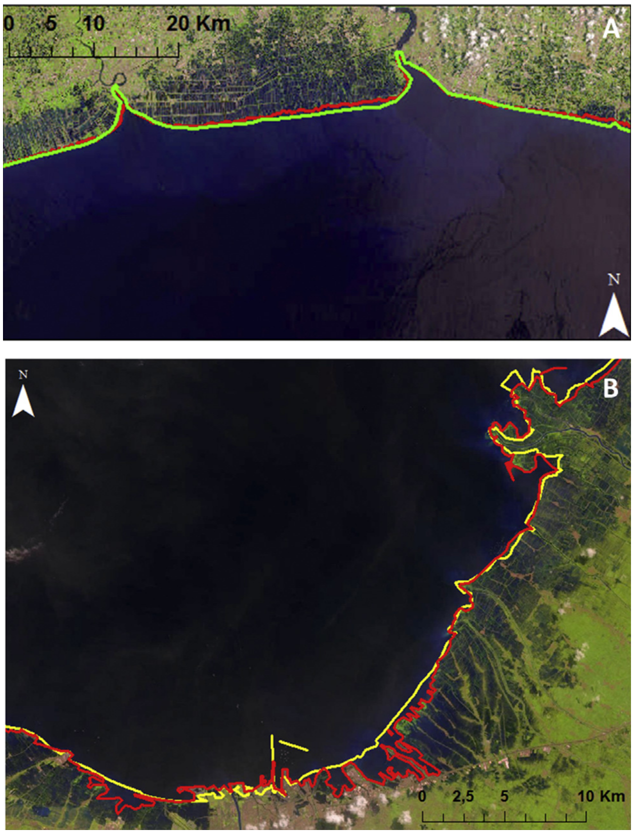

Fig. 1. Landsat Images from 2013 of A. Gulf of Bangkok (Thailand) with coastline in 2013 (red) and 1972 (green) and B. Semarang area (Central Java, Indonesia) with coastline in 2013 (red) and 1994 (yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

subsidence makes coastlines more vulnerable to erosion by increasing wave heights through increasing water depths. In muddy coastal environments this will rapidly enhance the erosive force of the waves, which is augmented by the erection of pond bunds that cause wave reflection (Winterwerp et al., 2013). As a result erosion is initiated and salinity levels start to rise in remaining ponds, thereby jeopardizing healthy aquaculture production (Dewalt et al., 1996). Moreover, rising salinity levels also affect agriculture production along the coast, where for example Nipa palms and coconut trees are exposed to lethal salinity levels (Marfai, 2011). This loss of derived ecosystem services is not a linear process (Fig. 2). Coastal safety provided by mangroves is exponential with the area of mangrove present (Barbier et al., 2008). So, the loss of coastal protection services will not be notable first, but will then be sudden. Similarly, the loss of resources triggered by high salinity levels will not be a gradual process but is more likely to be abrupt once salinity tolerance levels are exceeded.

2. Who profits?

The profits derived from the aquaculture boom have been considerable. In the beginning of the 21st century over 2 million people were working in the aquaculture sector in Indonesia alone (http://www.fao.org/fishery/countrysector/naso_indonesia/en).
With a growing population in many countries in South East Asia where fish constitutes an important protein source the demand for aquaculture products is rising rapidly and the production of this sector has increased rapidly in the last ten years (FAO, 2014). However, in many areas the main profits end up with large-scale

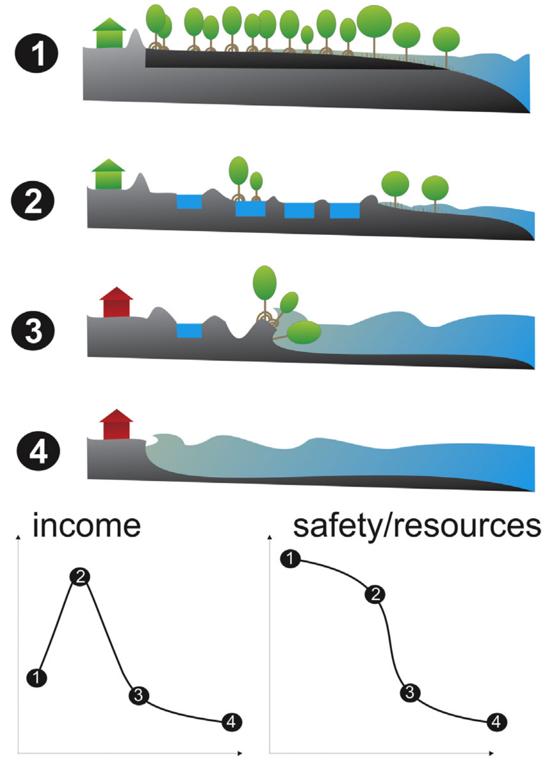

Fig. 2. Development of income, flood safety and resources for communities along mud-mangrove coasts. 1. Natural mangrove forest with small fishing or agricultural communities, 2. Large-scale mangrove cutting and intensive aquaculture, 3. Reduction of pond yield and start of coastal erosion, 4. Large-scale coastal erosion and increasing salinity intrusion.

investors and local community members do not always reap the benefits as they are only hired for low payment jobs, such as guarding and maintenance of ponds (Dewalt et al., 1996; Huitric et al., 2002; Swapan and Gavin, 2011). Further, intensive aquaculture ponds are only profitable for a short period of time. Management regimes are known to induce serious adverse environmental effects, such as contamination and salinization of surrounding surface and ground water (Avnimelech, 2006; Primavera, 2006). This causes a collapse of aquaculture productivity as well as damage to agricultural crops further inland (Marfai, 2011; Primavera, 1998) (Fig. 2). Many large companies abandon the ponds once their profits decrease, turning to pristine mangrove areas for development of new and more productive ponds (Huitric et al., 2002). Local communities are left behind in a devastated landscape. Once ponds collapse or get inundated due to subsidence or coastal erosion, people often revert to small-scale off-shore fishery practices. However, fish stocks may also be declining because of loss of the nursery function of mangroves (Nagelkerken et al., 2002) and increasing turbidity levels may result in loss of adjacent habitats, such as sea grasses and coral reefs. This chain of events leaves coastal communities in a very vulnerable situation, which is further exacerbated by sea level rise (Fig. 2).

3. Response by construction of infrastructure and mangrove planting

The classical response to coastal erosion includes construction of levees, seawalls, coast-parallel breakwaters and other hard defence structures. However, these hard infrastructural measures are difficult and expensive to construct on the soft mud layers that characterize mangrove coasts (Saengsupavanich, 2013). Many hard engineered constructions become unstable and collapse (Marfai, 2011). Additionally, these constructions may further disturb sediment flows towards the coast and hydrology (Winterwerp et al., 2013), thereby exacerbating erosion. Another response to coastal erosion along these deforested coastlines is the replanting of mangrove trees. Many rehabilitation efforts have not been successful as they failed to consider limiting factors for mangrove growth such as wave exposure and tidal inundation (Balke et al., 2011). Generally the most successful rehabilitation projects focus on restoring favourable abiotic conditions for natural mangrove growth, as opposed to haphazard active planting of mangrove seedlings (Lewis III, 2005).

In central Java a large-scale pilot project has started by the Indonesian Ministry of Marine Affairs, the Indonesian Ministry of Public Works and Dutch research institutes, private sector parties and international NGO's. This large-scale coastal restoration effort aims to restore several kilometres of eroded coastline by shifting erosion processes towards accretion processes. This is done by making use of permeable dams, preferably built from natural materials, aiming to create benign conditions for sediment accretion (Winterwerp et al., 2013). First results show successful accretion of sediments (around 50 cm in the first year after placement of the structure). Once elevation is suitable natural settlement of *Avicennia* seedlings has already been observed. Ultimate regeneration of mangrove forests is targeted. To conserve restored mangrove forests a community awareness program focussing on alternative livelihoods will be implemented.

4. Future perspective

Current intensive aquaculture practices in the tropics contribute to a number of the most severe societal problems in these regions today, such as poverty, water quality problems, loss of valuable ecosystems and their resources and increasing carbon emissions (Donato et al., 2011). Short-term profits from aquaculture developments are far outweighed by longer-term costs to local communities and governments. Exacerbated by projected sea level rise, this poses a rapidly growing threat to millions of people that live in lowland coastal areas, and will jeopardize future growth of the aquaculture sector. Short-term solutions lie in combinations of traditional engineering measures with ecosystem restoration, both based on strong system understanding. An example is restoration of protective mangrove belts along the coast and rivers to reduce wave impact and halt coastal erosion but also to purify water supply and run off from aquaculture (Robertson and Phillips, 1995). This can be combined with construction of small earthen levees that limit inundation of villages and houses.

Knowledge on restoration of mangrove forests in environments that are heavily degraded is limited. Mangrove planting often fails and currently simple techniques focussing on restoration of abiotic conditions for mangrove colonization are gaining popularity (Lewis III, 2005). Construction of permeable dams of bamboo or wood, which reduce wave impact and allow for precipitation of sediment, show promising results (Saengsupavanich, 2013; Schmitt et al., 2013; Winterwerp et al., 2005; Winterwerp et al., 2013). However, even if these localized efforts turn an eroding coast into an accreting coast and allow for mangrove re-establishment, under current sea level rise projections other immediate actions are required to secure conservation of lowland areas throughout South East Asia. To sustain aquaculture as a pillar to economic prosperity, new land use models that honour ecological and hydrological integrity of the landscape should be developed in close collaboration with local communities and the aquaculture sector. These models should include rehabilitation of deserted and unproductive shrimp pond areas and regulation of new aquaculture exploitation. Less extensive aquaculture practices, restrictions on deep ground water withdrawal, strong system understanding and increasing community resilience through income diversification will be crucial for success of this model. Internationally recognized criteria for sustainable aquaculture can function as a catalyst and opportunities to transform aquaculture landscapes through the market should be explored. Especially, since the complex cross-sectorial measures required are hard to enforce in areas with little institutional capacity and decentralized control, which is often the case along tropical soft sediment coasts.

Author contributions

HW developed theory and methods for coastal restoration. BvW and HW did analyses of natural systems and causes of erosion. ER, HS, FT and PvE developed socio-economic framework and aquaculture context. TB, HW and BvW explored EO images for erosion. Initial set-up of manuscript was done by BvW. All authors contributed to and approved the final manuscript.

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