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ORIGINAL ARTICLE

Coastal and riverine ecosystems as adaptive flood defenses under a changing climate

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Abstract Adaptation planning for flood risk forms a significant part of global climate change response. Engineering responses to higher water levels can be prohibitively costly. Several recent studies emphasize the potential role of ecosystems in flood protection as adaptive risk reduction measures while also contributing to carbon fixation. Here, we use a conceptual model study to illustrate the built-in adaptive capability of ecosystems to reduce a wide range of wave heights, occurring at different water levels, to a narrower range. Our model shows that wave height of waves running through a forested section is independent of initial height or of water level. Although the underlying phenomenon of non-linear wave attenuation within coastal vegetation is well studied, implications of reducing variability in wave heights for design of ecosystem and levee combinations have not yet been properly outlined. Narrowing the range of wave heights by a vegetation field generates an adaptive levee that is robust to a whole range of external conditions rather than only to a maximum wave height. This feature can substantially reduce costs for retrofitting of levees under changing future wave climates. Thereby, in wave prone areas, inclusion of ecosystems into flood defense schemes constitutes an adaptive and safe alternative to only hard engineered flood risk measures.

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1 Introduction

Rising sea levels, land subsidence, more extreme storms, and increasing river discharges will increase future flood risk and make future flood risk reduction more costly (Hallegatte et al. 2013). Uncertainty on how this risk will manifest requires flexible measures that can easily be adapted to changing external conditions (Ranger et al. 2013; van Wesenbeeck et al. 2014). Current flood risk mitigation strategies focus on hard engineering measures that are not adaptive and have additional negative impacts (Winterwerp et al. 2013; van Wesenbeeck et al. 2014). Typically, these defenses are designed to provide a specified standard of protection by withstanding flooding up to a certain water level and wave height (CIRIA et al. 2013). In coastal areas, rising sea levels will necessitate a corresponding increase in levee height to continue maintaining the same standard of protection. This can mean substantial future costs especially along coastlines that are now poorly defended and densely populated (Jonkman et al. 2013). Designing a flood defense system that can adaptively withstand a widening range of dynamic conditions, e.g., a spectrum of increasing water levels or wave heights, would help achieve more robust, cost-effective, and climate proof designs. Integration of ecosystems into levee designs and flood risk reduction strategies has the potential to achieve this.

Restoration and conservation of coastal and riparian ecosystems as alternatives to infrastructural measures are increasingly being explored (Barbier et al. 2008; Borsje et al. 2011). Ecosystems can help reduce flood risk in multiple ways by attenuating waves, stabilizing shorelines, and reducing current velocities (Gedan et al. 2011; Shepard et al. 2011). Additionally, they offer many co-benefits such as enhancing fisheries and recreation and tourism (Cheong et al. 2013; Spalding et al. 2014). Ecosystems can contribute actively to climate change mitigation by sequestrating and fixating carbon (Duarte et al. 2013). In the meantime, they can also enhance the adaptive capacity of the coastal system and as such form an important part of climate change adaptation measures (Cheong et al. 2013; Duarte et al. 2013). In this respect, the discussion on the role of coastal ecosystems has been mainly limited to their capacity to grow with rising water levels by trapping sediment (Borsje et al. 2011; Kirwan and Megonigal 2013).

Both mangroves and marshes can keep pace with rising sea levels through sediment trapping (Morris et al. 2002) (Fig. 1a), depending on sediment budgets and relative sea level rise (including subsidence) (McIvor et al. 2013; Lovelock et al. 2015). Basin mangroves can also keep pace with sea level rise through accumulation of organic matter mostly under nutrient poor conditions (McKee 2011). Besides soil elevation, some attention has been paid to the resilience of ecosystems and their capacity to self-repair after minimal to moderate disturbances (Borsje et al. 2011; Spalding et al. 2014) (Fig. 1b). Another useful feature of coastal ecosystems such as mangroves, marshes, and sea grass beds is their ability to dampen waves of different incoming heights over a certain distance to a narrow range (Fig. 1c). This mechanism is explained by the fact that wave attenuation within vegetation is a non-linear process (Barbier et al. 2008; Koch et al. 2009). The extent of wave attenuation is exponentially proportional to the incoming wave height. While the phenomenon of wave attenuation within vegetation has been widely studied, the implications of this process to flood defense design and functionality under a range of conditions have not yet been widely acknowledged. Here,

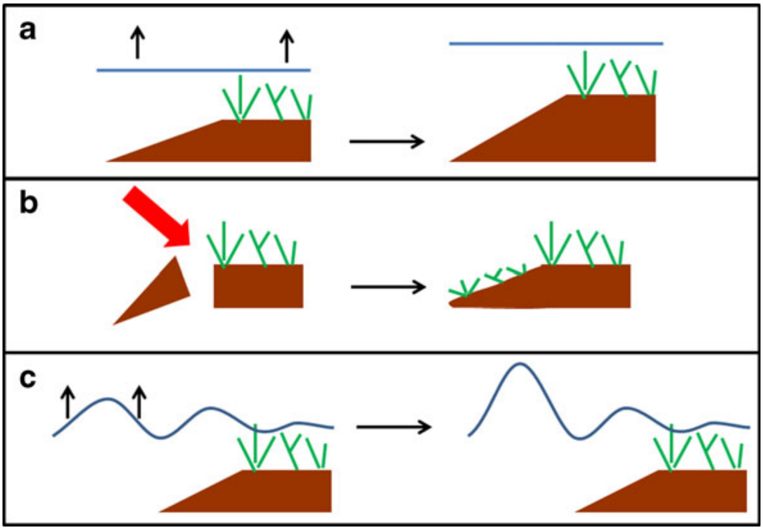

Fig. 1 Conceptual drawing showing three adaptive features of ecosystems that can contribute to flood risk mitigation. **a** Accretion with rising water levels. **b** Self-repair (resilience) after small disturbance events. **c** Reduction of waves with different heights to almost similar height

we illustrate with a simple modeling exercise how combinations of levees with fronting vegetation will create a levee that is more robust to external changes in wave climate and to rising water levels. Therefore, levee-vegetation combinations may become important adaptation options for climate change effects.

2 Methods

2.1 Model set up

To assess effects of vegetation on wave reduction with different wave heights and water levels, the third generation spectral wave model SWAN (Simulating Waves Nearshore) was used (Booij et al. 1999). SWAN is a single layer wave model and vegetation can be implemented using the Mendez and Losada (2004) formulation (Suzuki et al. 2012). This formulation accounts for the effects of vegetation on the wave attenuation in addition to regular wave attenuation processes. The vegetation is modeled as cylinders with a certain height (ε_v), diameter (b_v), density (N), and drag coefficient (C_D), based on Dalrymple et al. (1984). The overall effect of the vegetation on energy reduction can be expressed as the vegetation factor V_f, calculated by b_v*N*C_D (Suzuki et al. 2012). For further information on SWAN and SWAN-VEG, we refer to online manuals (link) and Booij et al. (1999) and Suzuki et al. (2012).

In SWAN-VEG, a horizontal field of 200 m long was implemented. No coastal slope was implemented as the main aim was to assess the sole effect of trees on wave reduction. Of the field, the last 170 m is covered with woody emergent vegetation. For vegetation parameters, we use an example of a well-developed forest that is over 5 years old. Tree height is set at 10 m for all types such that the vegetation is emergent for all scenarios. Tree density of 1 tree per m^2 and a stem diameter of 50 cm are assumed for all wave and water level scenarios. A drag coefficient of 0.9 was taken for each type as this evaluation is performed with woody vegetation that has little to no flexibility (Massel et al. 1999). Chosen values for vegetation parameters are representative of tropical coastal mangroves (for example, *Avicennia* sp.) as well as temperate riparian forests (for example, *Salix* sp.) (Naiman et al. 1998; Bao 2011). The vegetation factor (V_f) of this vegetation type is the product of the diameter, the density, and the drag coefficient and thus is 0.45 in this model.

The design implications of wave attenuation within vegetation depend on both vegetation and hydraulic parameters. For this study, we evaluated the effects of trees in attenuating regular waves of different heights (Hs) with a fixed steepness (ratio of Hs and wavelength) of 0.03 in different water levels. In the model, the default formulations and parameters settings for wave breaking and white capping are included. The effects of wind (growth) were ignored. The model was run with vegetation for six wave heights (1.5, 1.25, 1.0, 0.75, 0.5, and 0.25 m) and for three water depths (2, 3, and 4 m) to assess the influence of water depth on wave attenuation.

3 Results

3.1 Model output

Figure 2 shows the propagation of waves with different wave heights running through woody emergent vegetation. It can be seen that incoming waves of heights between 1.5 and 0.25 m are reduced to a range of 0.1 to 0.4 m after propagation through 170 m of vegetation. Larger waves show a steep and rapid decline in height whereas smaller waves show a smaller, more gradual decline in height. The rate of wave attenuation and the rate of convergence of absolute wave heights are highest within the first 40 m of the vegetation field. Similarly, effects of water level on wave attenuation are shown for three different water depths (2, 3, and 4 m) with an

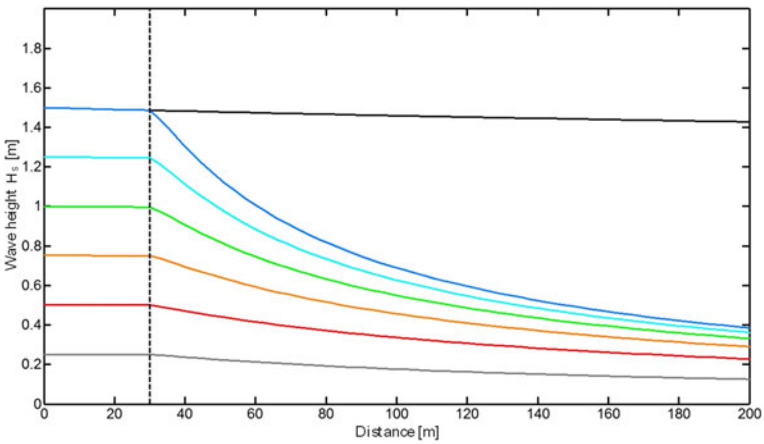

Fig. 2 Attenuation of waves with different wave heights through woody emerged vegetation. Vegetation starts at 30 m. Significant wave heights are shown on the *y*-axis and distance within the vegetation is depicted on the *x*-axis. The *black line* represents the reference situation without vegetation. The *different colors* indicate the different initial wave heights

incoming wave height of 1 m (Fig. 3). An increase in water depth reduces the rate of wave attenuation within the vegetation as the effects of bed friction are reduced. However, with emergent vegetation, the effect of water levels on the rates of wave attenuation is relatively small. At the lowest water levels, bottom friction still contributes to attenuation, which is visible in the wave height reduction before the vegetation.

The effect of vegetation on wave attenuation is mainly due to the energy dissipation of waves obstructed by a rigid object. Since wave energy is proportional to the square of the wave height, this results in a non-linear reduction of wave heights, with an increase in the rate of attenuation with increasing wave heights (Denny 1988). As a result, waves running over vegetation show asymptotical dampening which is empirically supported by numerous field and laboratory measurements on wave attenuation through mangrove forests (Mazda et al. 2006; Bao 2011) and over marshes (Möller and Spencer 2002). This phenomenon is also incorporated in a number of wave models (Mendez and Losada 2004). This model is also used in this study, and as a consequence, a broad range of incoming wave heights gets attenuated to a small range of wave heights when traveling through a vegetation field. Therefore, a levee designed for a 0.4 m wave can be robust for waves up to 1.5 m if a woody emergent vegetation field exists in front.

4 Discussion

A direct implication of the capacity of vegetation to reduce a broad range of wave heights to narrow ranges is that wave heights are considerably reduced at the levee, thus lowering the crest height requirement and/or structural requirements (i.e., an earth bund versus a concrete levee) for a given standard of protection. Fronting coastal or riparian vegetation can provide a significant portion of the reduction of wave overtopping that is traditionally provided by extra levee height. In this case, levee design criteria such as crest height and width can thus be limited to the minimum necessary to prevent inundation and structural (macro-stability) failure.

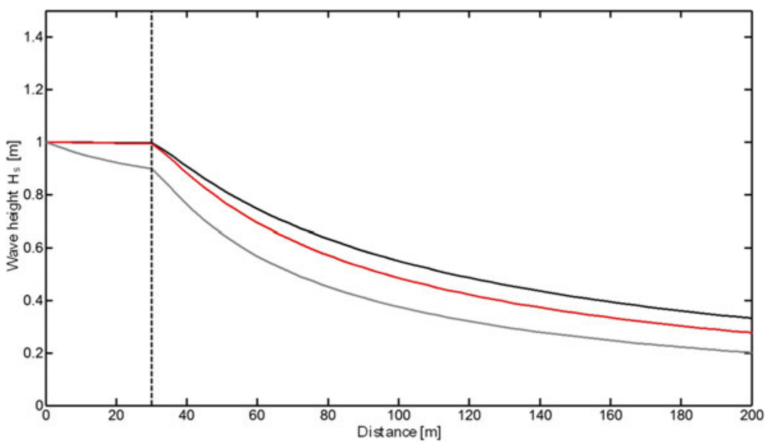

Fig. 3 Attenuation of waves of 1 m with different water levels through emerged woody vegetation. Vegetation starts at 30 m. Significant wave heights are shown on the *y*-axis and distance within the vegetation is depicted on the *x*-axis. The *different colors* indicate the different water levels (*gray* = 2 m, *red* = 3 m, *black* = 4 m)

Another implication for existing coastal defenses is that vegetation in front of an existing levee can extend the useful design life of the levee by limiting the upper range of wave heights at the toe of the structure (Hughes 2008). Thus, a levee designed for a certain standard of protection can provide this functionality for longer with fronting vegetation. This will help save the substantial costs associated with levee upgrades in high risk coastal areas that are faced with increasing sea levels and/or a changing wave climate. This is a valuable feature as it limits hydraulic loading on the levee even under dynamic conditions such as rising sea levels and higher waves.

The results from the numerical model simulations suggest that wave attenuation within emergent vegetation is not significantly affected by an increase in water depth. It is also likely that this functionality is enhanced by the well-documented adaptive capacity of coastal vegetation to keep pace with sea level rise through sediment accretion. Examples where these concepts are implemented are found in Vietnam where large areas of mangroves are restored to reduce levee maintenance (Reid and Swiderska 2008). In the Netherlands, a levee and willow combination is currently constructed as part of the Room for the River program and will be operational in 2016 (Borsje et al. 2011). The latter shows that vegetation levee combinations can be designed, constructed and tested.

In this study, we have focused on foreshores with stiff woody vegetation that are not fully submerged during high water levels as a proxy for mangrove or willow forests and on wave conditions up to 1.5 m. However, the wave attenuation will be less if vegetation is fully submerged (Möller et al. 2011), if the vegetation is more flexible such as grasses or reeds (Mendez and Losada 2004; Möller et al. 2011) or if waves are higher and, thus, have longer periods (McIvor et al. 2012a, b). Additionally, wave attenuation through vegetation increases with the distance that the wave travels over the vegetation and with vegetation height (Koch et al. 2009; Shepard et al. 2011). Longer and higher waves will require longer vegetation stretches for dampening. However, these waves may also cause structural damage to vegetation, which is repeatedly reported during hurricanes and tsunamis (Cochard et al. 2008).

Nevertheless, it is likely that flexible vegetation also has a significant reduction effect that will influence levee height (Möller and Spencer 2002; Möller et al. 2014). Yet, little research has specifically looked into the combination of flexible vegetation with levees. To get a better grip on the amount of reduction by flexible vegetation, species-specific and location-specific traits, such as the biomass per square meter, stem flexibility and stem density need to be known. Most of these factors are currently captured in the vegetation factor which includes a drag coefficient that functions as a calibration factor for each vegetation type (Mendez and Losada 2004). For mainstreaming vegetated foreshores into levee design and testing, further validation of the vegetation factor and a better physical understanding of the drag coefficient will improve reliability of modeling results. These improvements will allow us to better assess the effect of the width of designed or existing vegetated belts, especially under changing wave conditions.

Conventionally, coastal levees are designed to withstand a maximum wave height-water level combination that occurs with a certain probability. By recognizing wave dampening by vegetation as an adaptive capacity, levee designs can account for the non-linear wave reduction effects of fronting vegetation rather than assuming a uniform reduction factor for all incoming wave heights. Furthermore, due to the added safety level of this effect to existing dikes, the decision to upgrade a dike to new safety levels, caused by changing conditions or for instance subsidence, could be postponed, saving investments.

5 Conclusions

Levees and dikes combined with vegetated foreshores can be considered promising climate change adaptation measures due to their capacity to sequester and store carbon and to adapt to changing external conditions. For example, they may be able to keep pace with sea level rise (Kirwan and Megonigal 2013) and have a certain amount of self-repairing capacity by reducing a broad range of wave heights to a small range of wave heights. In this way, they have the potential to offer a cost-effective adaptation strategy that is relatively robust to changing external conditions. Achieved reduction of levee height will also allow for a smaller levee base, thereby needing less volume and decreasing the levee impact on subsoil compaction and on the surrounding landscape. Levees combined with fronting vegetation can also be used for simple and cheap, yet effective, flood risk reduction measures in areas where the level of risk does not make a convincing case for hard engineering measures and where wave impact is an issue.

Including ecosystems into flood risk mitigation designs is not possible everywhere. In urban areas, space is often a confounding factor and external conditions for suitable habitat creation, restoration, or conservation, such as sediment availability and wave climate, should be favorable. Further, in areas where levee height is determined by water level, fronting vegetation will provide little benefits. Like for any engineering structure, a concern regarding fronting vegetation for flood risk mitigation is to quantify uncertainties with regard to presence and functioning under extreme events. Tackling some of these questions through monitoring and experiments will allow wider implementation of vegetation and levee combinations and further mainstream flood risk mitigation measures that include coastal and riparian ecosystems.

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