Assessment of underwater vegetation to reduce coastal erosion

Effect of eelgrass (*Zostera marina*) on wave attenuation at Lomma Bay

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Project Leader: Eduardo Infantes Oanes, Assistant Professor at the Department of Marine Sciences, University of Gothenburg, Kristineberg Research Station.

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Cover photo taken on an eelgrass bed at Lomma Bay by Jonas Gustafsson.

Sammanfattning

Kusterosion är ett växande problem som förutses bli värre med klimatförändringar och tillhörande havsnivåökning och extrema väderhändelser. Länsstyrelsen Skåne är partner i ett Interreg projekt, ”Building with Nature” (BwN) som pågått sedan 2016. Projektets syfte är att med hjälp av naturliga skydd göra kuster, flodmynningar och avrinningsområden mer anpassningsbara och motståndskraftiga mot klimatförändringar. Projektet genomförs i Nederländerna, Tyskland, Belgien, Danmark, Storbritannien och Sverige. Länsstyrelsen i Skåne är projektpartner i Sverige.

Ålgräs diskuteras för närvarande som en hållbar naturlig metod för kustskydd jämfört med traditionell strandfodring, som är mindre hållbar. Det saknas dock storskaliga fältstudier som visar hur sjögräsängar påverkar transport av sand och stranderosion. Det är därför oklart om eller hur sjögräs påverkar vågdämpning och stranderosion, och under vilka förhållanden de kan minska stranderosion, och hur ängarnas egenskaper påverkar denna förmåga. Syftet med detta uppdrag är att utföra fältmätningar samt beräkna vilken effekt ålgräs har på vågdämpning och därmed indirekt på kusterosion. Uppdraget fokuserar på Lommabukten där det finns väl etablerade ålgräsängar samt att SGU har klassat kusten söder om Bjärred som en strand som idag har måttlig till betydande erosion.

För att kvantifiera hur ålgräsängar (*Zostera marina* L.) dämpar vågförhållandena placerades vågmätare och en strömmätare i Lommabukten under 3 månader (aug-okt 2019) på två platser med hög respetive låg täthet av vegetation. Ålgräsängarnas täthet mättes i fält med hjälp av en undervattensvideokamera. Tre stormar registrerades under mätperioden då havsnivån också var högre än medelvattennivån. Resultaten visar att våghöjderna minskar genom ålgräsängarna. Vågreduktionen under stormhändelser var i genomsnitt 35-40% i lokalen med hög vegetationstäthet, respektive 5-10% i lokalen med lägre vegetationstäthet. En enkel modell byggdes för att beräkna vågdämpningen över ängen, vars resultat tyder på att den främsta orsaken till vågreduktion var den skillnad i motstånd som orsakades av den täta och glesa vegetationen.

Resultaten visade också att sand från den konstgjorda stranden som ligger söder om Lomma hamn verkar ha transporterats 300 m till djupare vatten (3 m djup). I denna del av Lommabukten är vågdämpningen också mindre eftersom ålgräsängarnas täthet var låg. Denna sand kan potentiellt påverka ålgräsängarnas utbredning genom att begrava växterna. Ytterligare arbete behövs för att bedöma effekten av den konstgjorda sanden på ålgräsängarnas grunda utbredningsgräns.

Detta projekt ger stöd och information till kustförvaltare, som arbetar med kustskydd och bevarande av ålgräs, genom att visa på vilken betydelse ålgräsängar har för att dämpa vågor. Dessa resultat kan användas i utformningen av innovativa bevarande- och restaureringsstrategier för att minska erosionen vid kusten.

Abstract

Coastal erosion is a growing problem that is predicted to get worse with climate change and the associated sea-level rise and extreme weather events. Eelgrass is presently discussed as a natural sustainable new method for coastal protection compared to traditional not sustainable beach nourishment. However, large-scale field studies assessing how seagrass meadows affect transport of sand and beach erosion are currently lacking. It is therefore unclear if or how seagrass affect wave attenuation and beach erosion, and under what environmental conditions they can reduce beach erosion, and how meadow characteristics affect this capacity.

In this project, we quantify how eelgrass meadows (*Zostera marina* L.) attenuate wave conditions in Skåne, southern Sweden, a region with growing problems with coastal erosion. Wave gauges and a current flow meter were deployed in Lomma bay during 3 months (2-Aug to 5-Nov) in two sites with high and low plant density. In addition, eelgrass cover was measured in the field using an underwater drop-video camera. Three storms were recorded during the deployment where sea level also raised above average. Results show that wave heights decrease as it propagates through the meadow. The wave reduction during storm events was on average 35-40% at the eelgrass dense site while at the eelgrass sparse site was 5-10%. A simple model was built to calculate the wave decay over the meadow, suggesting that the main cause for wave reduction were the different drag effects caused by the dense and sparse vegetation.

Our results also showed that sand from the artificial beach located in the south of the Lomma port seems to have been transported 300 m to deeper water (3m depth). In this section of Lomma Bay, wave decay was also smaller since the eelgrass density was low. This sand could potentially affect the eelgrass shallow limit even further by burying the plants. Further work could be focus to assess the effect of the artificial beach on the shallow limit of eelgrass.

This project provides information to support coastal managers working with coastal protection and conservation of eelgrass to quantify the role of eelgrass meadows on wave damping. These results could be later implemented in the design of innovative conservation and restoration management strategies to reduce coastal erosion.

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Acknowledgements

We would like to acknowledge the participation of Henrik Möller and Nicolina Andersson in the field campaigns.

1. Background and objectives

The county administrative board of Skåne is the project partner in an Interreg project, "Building with nature" (BwN), which has been going on since 2016. The aim of the project is to make coastlines, estuaries and river basins more adaptable and resistant to climate change, using natural protection. The project is carried out in the Netherlands, Germany, Belgium, Denmark, the UK and Sweden. The county administrative board of Skåne is the project partner in Sweden.

Beach erosion is a natural process which means that sediments are removed by waves, currents and wind and accumulate elsewhere. Along the shores of Skåne, the most common beach type is sand and gravel beaches where erosion and accumulation occur alternately. Significant erosion has been assessed by SGU (Sweden's geological survey) on a smaller part of the coastal stretch (7%). Underwater vegetation has a stabilizing function on the bottom sediment through its root and rhizome system. The vegetation also serves to dampen waves and currents.

Underwater vegetation can consist of algae, seaweed and other seed plants such as seagrass. In Sweden, eelgrass (*Zostera marina*) is the most common seagrass, and alongside Skåne's shores there are several large eelgrass beds. Eelgrass grows in shallow areas and can withstand both high salinity and more exposed water. Eelgrass is also adapted to different wave exposure and sediment conditions. These are highly productive habitats with a number of functions, such as food bases, shelter and breeding grounds for many marine species.

Because eelgrass beds dampen wave energy, improve water quality and stabilize bottom sediment, it is interesting to study whether eelgrass in Skåne's coastal areas can slow down or reduce erosion. There are few studies in the world and along the Swedish coast.

The purpose of this assignment is to perform field measurements and calculate the effect eelgrass meadows has on wave damping and thus indirectly on coastal erosion. The assignment focuses on the Bay of Lomma (Fig. 1), which has been selected when there is a well-documented eelgrass bed and that SGU has classified the coast south of Bjärred as a beach that today has moderate to significant erosion.

1.1. Overview of the research area

Coastlines have traditionally been engineered to maintain structural stability and to protect property from storm-related damage, but their ability to endure climate change will be challenged over the next century. The increasing rate of global climate change seen in this century, is predicted to accelerate having large impacts such ad increasing sea-level rise and the frequency of large storm-events. For the most of Sweden's coastlines, rising sea levels will be offset by the land uplift. However, in southern Sweden, which mainly consist of low-lying sandy coastlines, the land uplift is close to zero. As a result, rising sea levels will increase the problems with coastal erosion and flooding, and create increasing damage to property and infrastructure (Hansen et al. 2012). Already today, in Skåne in southern Sweden, the problem with beach erosion is evident, and there is a growing interest to find sustainable methods for coastal protection. Traditional coastal protection with hard substrates such as breakwaters and groynes are criticized for only shifting the problem to neighboring areas and creating new long-term problems. There has been a shift towards "soft" coastal defense techniques, for example, in Skåne the method growing fastest is "beach nourishment", when sand is collected from subtidal habitats and spread on the shore line (Bontje 2016). Although the method has been successful, it has also been criticized for not being sustainable, as it requires continuous replenishment, and because of the negative impacts on fish and benthic fauna in areas where the sand is collected (Hanley et al. 2014).

There is a recent interest to use eelgrass meadows as a natural defense against beach erosion in southern Sweden, and small-scale attempts have started to transplant eelgrass as a measure for coastal protection. Although it is well established that seagrass meadows can attenuate waves and stabilize sediments (Ondiviela et al. 2014), and even though many authors have suggested that seagrasses may reduce beach erosion (Martinez & Moreno-Casasola 1996, Danielsen et al. 2005, Barbier et al. 2008, Tanaka et al. 2008), there is in fact a lack of field studies showing a clear link between the presence of seagrass vegetation and a reduction in beach erosion. Thus, there is a need for empirical field studies that assess this link and improve our understanding regarding the type of environments where seagrass meadows have the capacity to reduce beach erosion, and how meadow characteristics (eg. shoot-density, canopy height, water depth, size of the meadow) affect this capacity. This information is essential to understand if eelgrass beds affect beach erosion and if they do, which areas are more important to protect. In addition, this knowledge is also important before attempting eelgrass restoration as measure for coastal protection.

In Sweden, the Geological Survey of Sweden (SGU) and the Swedish Geotechnical Institute (SGI) has made a general assessment of the conditions for beach erosion along the country's coasts and develop a model for mapping erosion vulnerability, eg. effects on buildings and infrastructure (Rydell et al. 2012, Malmberg et al. 2016). This model is based on coastal parameters such as soil type, slopes, exposure and sediment dynamics, which are used to calculate an index for erosion sensitivity (see Gornitz et al. 1991, Shaw et al. 1994, Ramieri et al. 2011). But this index does not include the presence of coastal vegetation such as eelgrass, which could be an important component determining beach erosion. Eelgrass play a key role in the coastal ecosystems by enhancing local biodiversity and providing several critical ecosystem functions, which in turn extends to many important ecosystem services and human benefits (Cole & Moksnes 2016). However, eelgrass is a threatened species and over 60% of the eelgrass meadows have vanished from the Swedish NW coast since the 1980s and losses continue today, which make protection of eelgrass a priority in Swedish and in European waters (Moksnes et al. 2016). With the predicted future climate scenarios, increase of sea-levels and storm frequency, eelgrass meadows along the exposed coasts of southern Sweden may be threatened. Increasing our knowledge of the ecology and resilience of these population has been identified as key research area in a recent national action plan for eelgrass (Moksnes 2017).

1.2. Aims and objectives

Coastal erosion is a growing problem that is predicted to get worse with climate change and the associated sea-level rise and extreme weather events. Eelgrass is presently discussed as a natural sustainable new method for coastal protection compared to traditional not sustainable beach nourishment. However, large-scale field studies assessing how seagrass meadows affect transport of sand and beach erosion are currently lacking. It is therefore unclear if or how seagrass affect beach erosion, under what environmental conditions they can reduce beach erosion, and how meadow characteristics affect this capacity.

This project aims to assess if eelgrass meadows (*Zostera marina* L.) attenuate wave conditions in Skåne, southern Sweden, a region with growing problems with coastal erosion. It also aims to increase the knowledge of eelgrass meadows in high energy environments, which are threatened by climate change, but understudied today. We will address these aims through 3 main objectives:

- Measure waves and currents in an eelgrass meadow using field measurements in Lomma bay in Skåne.
- Measure the effect of plant densities on wave damping.
- Calculate the potential wave damping effect of eelgrass beds.

3. Methods

To assess how an eelgrass meadow affect wave attenuation in high energy environments, field measurements were performed at Lomma Bay in Skåne between 1-August to 5-November of 2019 (Fig. 1). The selection of this site is based on an extensive inventory of eelgrass in Skåne by the County Administrative Board of Skåne (CABS 2017) who provided data and support in the selection of sites.

Figure 1. Approx. location of wave measurements at Lomma Bay. The effect of eelgrass density on wave propagation. Wave properties measured at two parallel transects with dense and sparse eelgrass of approx. 1000m.

3.1. Wave measurements

To quantify the effect of plant density on wave propagation, waves were measured at 2 sites near the port of Lomma (Table 1). The dense area was located approx. 2 km south of the port while the sparse area was located in front of the port. We used data from previous eelgrass surveys (Toxicon 2017) to select the deployment sites. At each site, two locations (deep and shallow) were selected. Waves were measured using wave gauges (RBR, Solo DIwave16). Every hour 4096 measurements were performed at 8Hz. Wave data such as significant wave height (H_s) and mean wave peak period (T_p) were calculated using Ruskin software (RBR).

An acoustic Doppler profiler (Nortek, Aquadopp) was deployed on the dense deep site to determine the incident deep-water wave conditions and flow velocities (Infantes et al. 2011). These wave conditions were assumed to be similar at both deep sites where the incident wave direction and current velocities were measured. The RBR wave gauges provided high resolution data used to calculate the wave decay, while the Aquadopp provided data on wave direction and flow velocity, which the wave gauges do not provide. In addition, the water temperature was also measured. Significant wave height (H_s), peak period (T_p) and wave direction (*Dir*) were processed using Nortek (QuickWave v.2.04) software (Nortek).

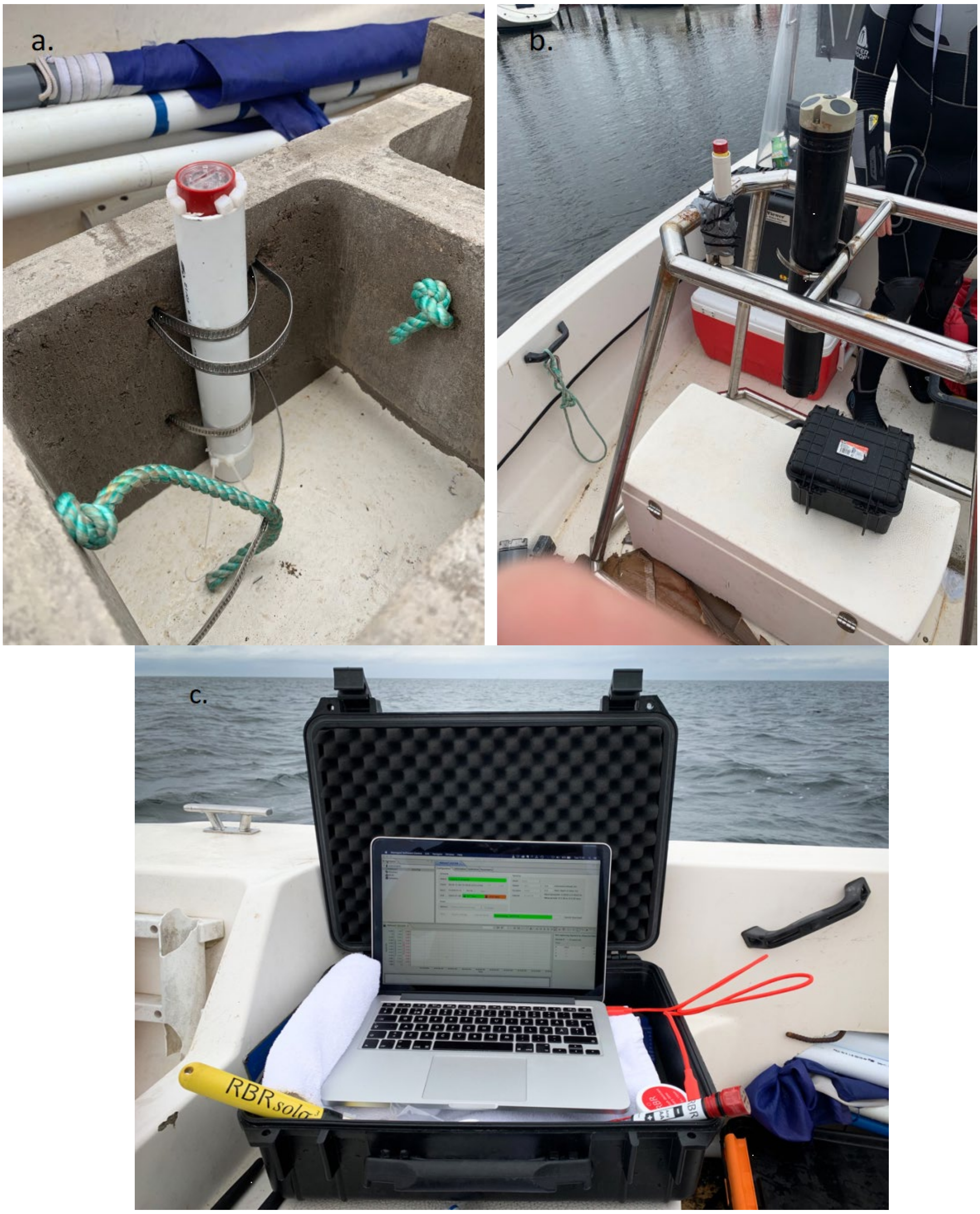

Figure 2. Wave measurements in Lomma Bay, a) deployment of RBR wave pressure gauge attached to concrete block, b) deployment of acoustic Doppler and

wave gauge in stainless mooring, c) wave data downloading after recovering the wave gauges.

Table 1. Locations of instruments deployed between 2-August to 5-November of 2019.

Site	Location	Depth (m)	Height from bottom (cm)	Model
Dense eelgrass	Deep	6.82	1.30	Nortek, Aquadopp
Dense eelgrass	Deep	6.82	1.20	RBRsolo Dlwave16
Dense eelgrass	Shallow	3.23	0.24	RBRsolo Dlwave16
Sparse eelgrass	Deep	6.93	0.24	RBRsolo Dlwave16
Sparse eelgrass	Shallow	3.39	0.24	RBRsolo Dlwave16

3.2. Meteorological data

Wind data series were obtained from SMHI station in Malmö (52350, Lat: 55.5715, Lon:13.0708). The weather station is located approx. 10 Km from the study site. Mean wind speed and wind direction were used to identify the dates of the storm events. Since Lomma Bay is exposed to waves from West and North-West, these events will generate the highest wave conditions in the bay.

3.3. Storm surge

The surge was calculated using the pressure data from the wave gauges. Surge is defined as the observed water level at sea minus the calculated astronomical tide. Storm surge refers to an extreme water level during a storm. The storm surge level in the Lomma is generally a result of wind set-up from West directions. Locally wave set-up can play a role. The inflow and overwash are in strong relation with the water level at Kattegat Sea, which is a function of wind set-up, barometric set-up, wave set-up and astronomical tide. Typically, the astronomical tide is not included in the calculation for the storm surge, considering its definition. It is nevertheless included in the absolute calculation of the water depth. Increased water levels due to sea level rise, precipitation and fresh water inflow is not included in the calculation for surge.

3.4. Eelgrass cover

A boat survey was carried out to identify the eelgrass cover at both transects (Fig 1). The eelgrass cover was assessed with a drop-video camera and a GPS. The drop-video camera had a real-time live remote viewing (SeaViewer Underwater Video Systems, Fig. 3ab), enabling an observer to rigorously record eelgrass cover as presence and cover of eelgrass (*Zostera marina*), and unvegetated bottom (sand). The location of each observation was recorded with a GPS (Garmin, GPSMAP 64s), (Fig. 3c). This surveying methodology is an established practice among seagrass research, being suitable for the objectives of this project. The team consisted in 3 persons: 1 person handled drop camera, 1 person took notes and marked the GPS positions, and 1 person was the skipper of the boat. The survey was carried out on 1-August of 2019.

At each site, the eelgrass cover was assessed by performing transects from between the locations where the instruments were deployed. The eelgrass cover was classified in 6 categories: 0-No seagrass (0% cover), 1-Very sparse (< 20% cover), 2-Sparse (20-40% cover), 3-Medium (40-60% cover), 4-Dense (60-80% cover) and 5-Very dense (>80% cover). Each category had a score of 1-5 depending on the vegetation cover. A total of 52 field observations were recorded, 26 for each site. To quantify the total eelgrass cover, the scores were added at each site. The dense site had a total score of 87, while the sparse site had a total score of 45 suggesting that the dense site had double the amount of plants that the sparse site.

Eelgrass samples were taken on both transect to measure the plant morphologies using snorkel. Ten eelgrass shoots were collected at shallow 3.5 m and deep water 6.5 m. The leaf lengths, leaf width and number of leaves per shoot were measured. The average for each parameter was calculated (Table 2). As expected, eelgrass leaf morphology changed with depth becoming larger, wider and with more number of leaves per shoot at the deeper location.

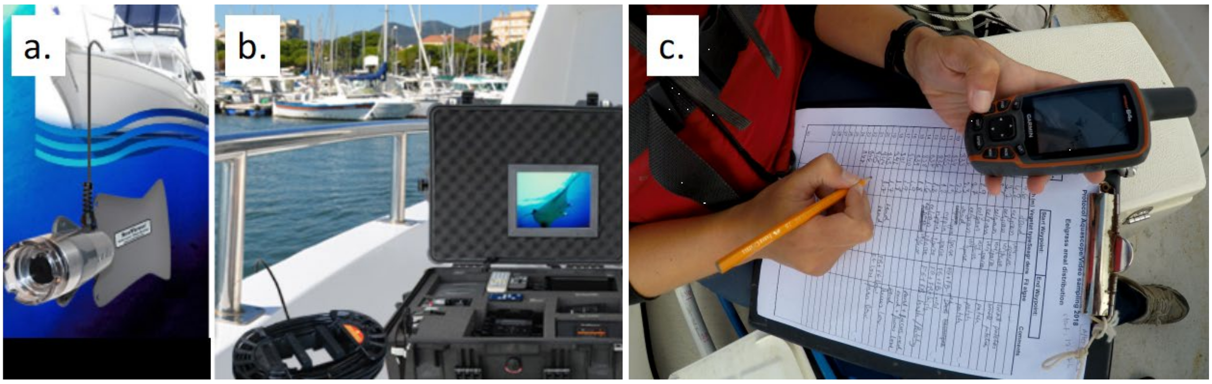

Figure 3. Eelgrass cover survey was performed using an a) drop-video camera, b) with real-time screening of bottom classification, while location and details of each observation were recorded c) with a GPS and a field protocol.

Table 2. Eelgrass morphologies variations at shallow (3.5 m) and deep water (6.5m) at Lomma Bay. Mean values with standard errors in brackets, n=10.

	Leaf length (cm)	Leaf width (mm)	N of leaves
Shallow	37.7 (2.6)	2.9 (0.3)	4.4 (0.2)
Deep	64.5 (4.9)	4.6 (0.2)	5.2 (0.2)
Mean	52.3 (3.7)	3.7 (0.2)	4.8 (0.1)

3.5. Simple wave decay model

Assuming that linear wave theory is valid and assuming straight and parallel bathymetric contours as is the case in Lomma Bay, the conservation of wave energy for random waves may be written as

$$\frac{\partial(Ec_g)}{\partial x} = -\varepsilon_D \qquad [1]$$

with the energy E being $E = \rho g H^2 / 8$, with g the acceleration of gravity, H the wave height [m], ε_D the energy dissipation, and C_g the wave group velocity given by

$$C_g = \frac{\omega}{2\mathrm{k}}\left\{1 + \frac{2\mathrm{k}h}{\sinh\,(2\mathrm{k}h)}\right\} \qquad [2]$$

with the constants $\omega = 2\,\pi/T_p$ is the wave radian frequency and $k = 2\pi/L$ is the wave number. L is the wave length [m] corresponding to T_p, the peak period [s], and h the local water depth [m]. Previous work on wave propagation over vegetated fields have dealt with the question of obtaining ε_D in order to integrate Eq. (1) (Luhar et al. 2017)

$$\frac{H}{H_0} = \frac{1}{1+K_D a_0 x} \qquad [3]$$

here a_0 is the initial wave amplitude [m] at $x = 0$ (defined as the start of the meadow). Wave decay K_D, is a constant defined in this study as a dimensionless parameter $K_D a_0 L$ to represent wave decay over the length of the eelgrass meadow (Luhar et al. 2017).

$$K_D a_0 L = \frac{4a_v a_0}{9}\, C_D \left[\frac{9\sinh kl + \sinh 3kl}{\sinh kh(\sinh 2kh + 2kh)}\right] \qquad [4]$$

where a_v is vegetation frontal area per unit volume and C_D is the drag coefficient. Using the morphological parameters of eelgrass collected in Lomma, the average for shallow and deep water morphologies were used and the constant a_v was calculated as

$$a_v = l_h \cdot l_w \cdot\, l_n \cdot S_d \qquad [5]$$

where l_h is the constant leaf length 0.4 [m], l_w is the constant leaf width 0.003 [m], l_n is the constant number of leaves per shoot set to 4, and S_d is the number of shoots per area [m^2]. In the sparse transect S_d was 100 while in the dense was 200, resulting in values for a_v of 0.9 and 1.8 for the sparse and dense eelgrass sites respectively.

Shoaling is the deformation of the waves, which starts when the water depth becomes less than about half the wavelength. The shoaling causes a reduction in the wave propagation velocity as well as shortening and steeping of the waves. To account for changes in wave height as a response to the variable bathymetry the shoaled wave heights (H) were calculated using linear wave theory as:

$$H = \left(\frac{h_0}{h_1}\right)^{0.25} H_0 \qquad [6]$$

where H_0 is the incident wave height, h_0 and h_1 are the water depths at the deep and shallow locations (Bradley & Houser 2009).

4. Results

4.1. Eelgrass cover and bathymetry changes

Both sites had a mild-slope bottoms which were very similar, covering approx. 1000 m from shallow depths between 2.9 and 3.1 m to deep depths of 6.5 and 6.6 m for the eelgrass dense and eelgrass sparse sites respectively (Fig. 4). The slope of the profiles ranged between 0.3% and 0.2% for the dense and sparse sites respectively. Eelgrass cover decrease with water depth at both locations but the cover was higher in the dense site. In particular, in the shallow areas, eelgrass cover was higher in the dense site than in the sparse site (Fig. 4).

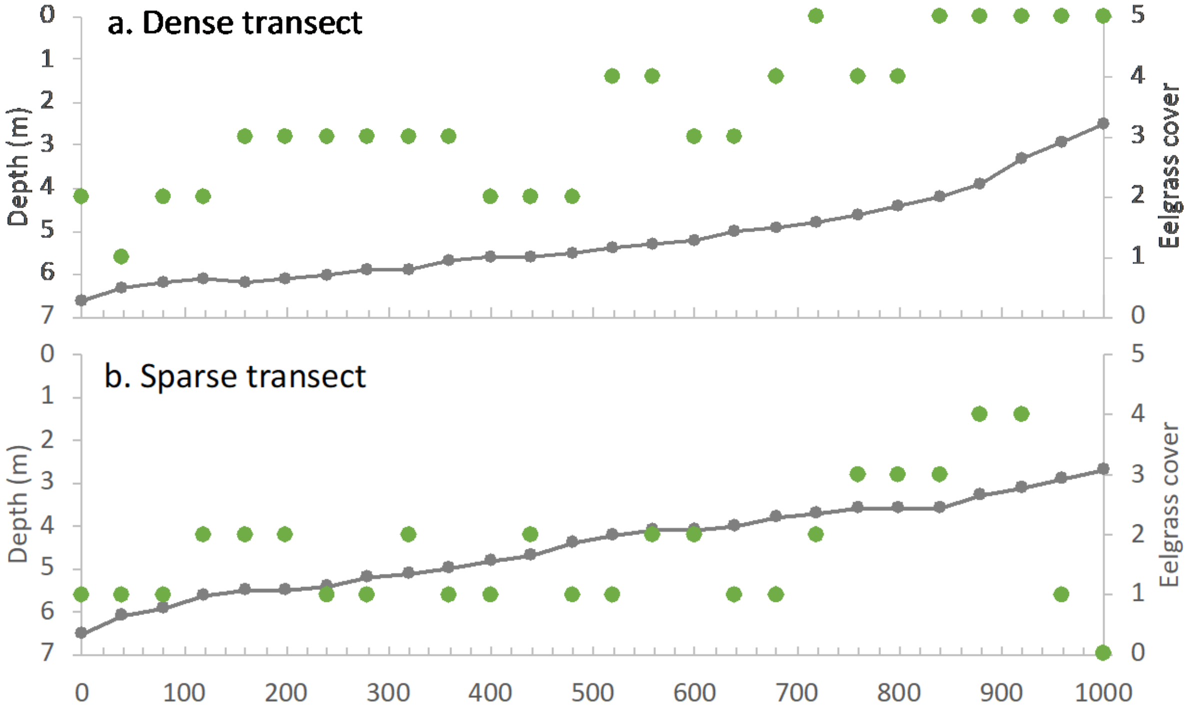

Figure 4. Bathymetric profile and eelgrass cover in Lomma Bay, a) Dense eelgrass transect and b) Sparse eelgrass transect. Depth profile shown in grey line and eelgrass cover measured with the drop-video camera in green circles.

4.2. Wave conditions

Wave conditions in Lomma Bay were recorded between August to November of 2019 covering a range of wave conditions from i) mild summer weather corresponding to waves generated by wind speeds below 10 m/s and ii) a storm event with high water levels above the mean sea level and winds of 15 m/s.

Three storm events were recorded between August to November of 2019. Storm events were defined as waves higher than 0.8 m, sharp and quick increase in water level, winds between 10-15 m/s and winds from NW direction (250-310 degrees). The first storm event was in 6-7 September, the second in 14-18 of September and the third in 1-2 October (Fig. 5).

- **Storm 1** (6-7 September), reached wave heights of 0.8 m and a water level of +0.2 m above the mean level at deep water. Mean wind velocities between 10-12 m/s and directions from NW (255°).
- **Storm 2** (14-18 September), reached wave heights of 0.9-1.0 m and water level of +0.7 m above the mean level at deep water. Mean wind velocities reached 15-16 m/s and directions from NW (265-305°).
- **Storm 3** (1-2 October), reached wave heights of 0.8-1.0 m and water level of +0.33 m above the mean level at deep water. Mean wind velocities reached 15-17.6 m/s and directions from NW (270-280°).

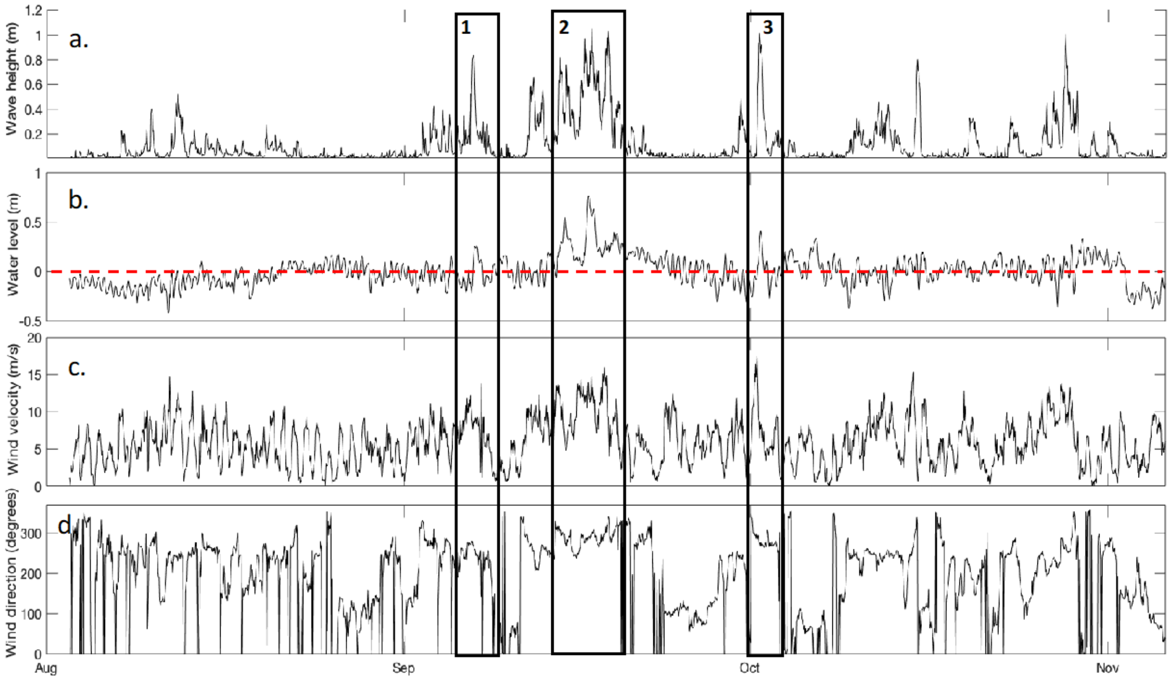

Figure 5. Wind and deep-water wave conditions between August and November 2019, a) significant wave height, b) water level, c) mean wind velocity and d) mean wind direction. Three storms are indicated in grey boxes.

More details on each storm event can be obtain in the Appendix, figures S1, S2 and S3.

The maximum wave heights in the study area during the deployment were between 0.5 m to 1.1 m with maximum flow velocities reaching 0.25 m/s in the eelgrass dense deep site (Fig 6ab). The current generated during the storm events was not higher than during less intense wave conditions, showing no clear trend or correlation between flow velocity and wave heights. This could be due to local currents might also influence the direction and velocity at these locations.

The water temperature ranged from approx. 18-21^{o}C during August and dropping to 14-15^{o}C in September (Fig 6c). Sharp drops in water temperature of 2-3^{o}C occurred on four occasions suggesting that deep water masses moved close to the surface. These temperature drops were not clearly correlated to wave heights or current velocities suggesting that large scale processes from the Baltic or Skagerrak-Kattegat are affecting conditions at Lomma Bay.

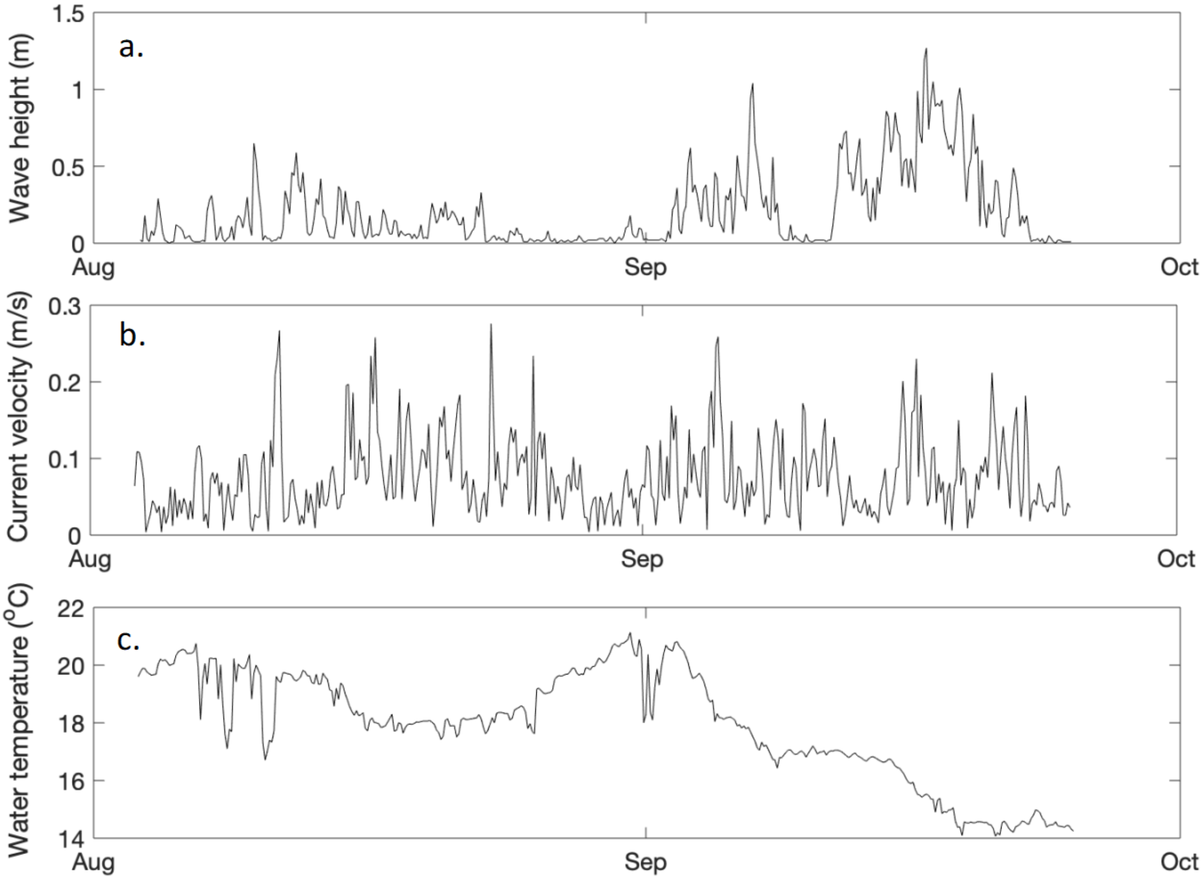

Figure 6. Wave, current and water temperature conditions during the deployment using the acoustic doppler (Nortek, Aquadopp). a) Wave height (m), b) current velocities at (m/s) and water temperature (degrees). Note that the Aquadopp deployed only lasted until the (24-Sep-2019) since the battery autonomy of the instrument is more limited than the RBR wave gauges.

Wave decay was higher in the dense eelgrass site than in the sparse site (Fig.7). The wave decay (H/H_0) over the dense eelgrass site was about 35-45% while at the sparse eelgrass site was between 5-10%. The wave decay estimated using eq. 3 showed a good agreement between the computed and measured wave field (Fig. 8) but with an average over prediction of the field wave decay of 10%.

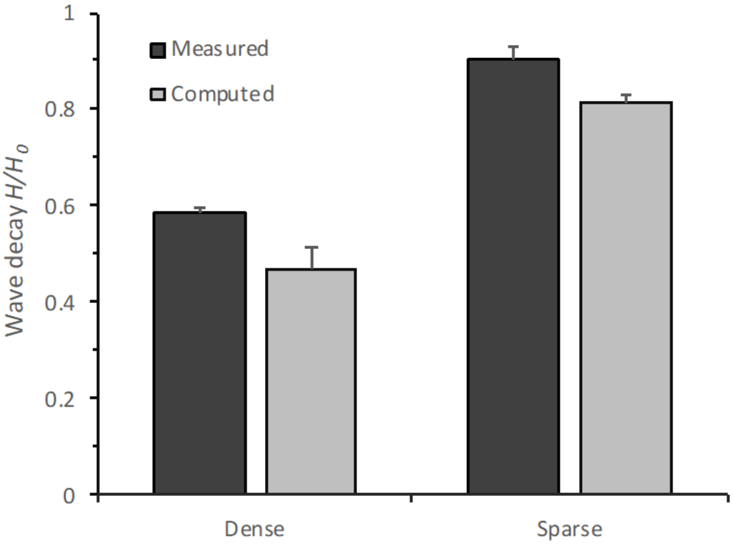

Figure 7. Wave decay at the eelgrass dense and eelgrass spare sites. *H/H₀* calculated using measured at Lomma Bay and calculated using eq. 3.

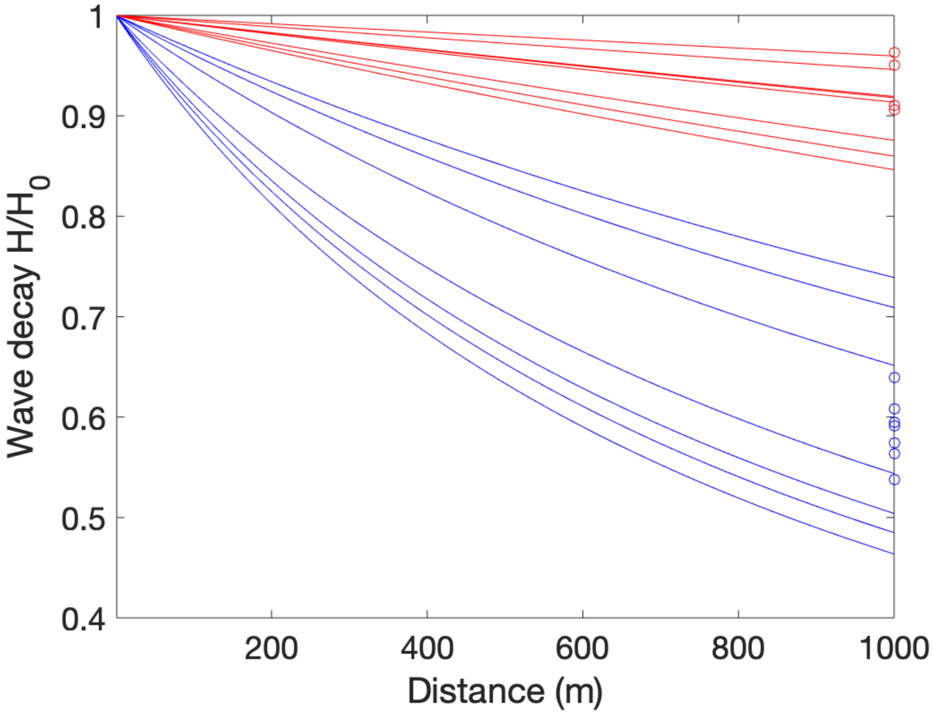

Figure 8. Wave decay calculated over 1000 m distance of the eelgrass bed. The lines correspond to the wave decay H/H_0 calculated using eq. 3. while the circles are the field measurements at Lomma Bay. The blue lines indicate the dense eelgrass site while red lines indicate the sparse site.

5. Discussion

5.1. Effect of eelgrass on wave propagation

This study shows that wave propagation is affected by eelgrass vegetation. The wave reduction over the 1,000 m of eelgrass bed was higher at the eelgrass dense site than at eelgrass sparse site. Wave heights crossing the dense eelgrass bed at Lomma Bay were reduced on average 40% of the initial wave height. In contrast, the wave heights crossing the sparse eelgrass bed only were reduced an average of 10% of the initial wave height. A simple model was built to calculate the wave decay over the meadow, suggesting that the main cause for wave reduction were the different drag effects caused by the dense and sparse vegetation. Wave attenuation by seagrass canopies has been measured at coastal systems where canopies occupy a large fraction of the water column with a ratio of 1:1 to 1:3 seagrass length to water depth. In this study at Lomma Bay, the seagrass canopy occupied a small fraction of the water column with a ratio of 1:6 to 1:12, showing that wave decay due to vegetation is still possible at these ratios (Fonseca & Cahalan 1992, Koch 2001, Chen et al. 2007, Bradley & Houser 2009). This results is similar to a previous study carried out in the Mediterranean seagrass *Posidonia oceanica* with a ratio of 1:7 to 1:20 seagrass length to water depth (Infantes et al. 2012). Submerged plants increase bottom roughness, thus reducing near-bed velocity (Koch et al. 2006) and increasing wave attenuation (Kobayashi et al. 1993, Mendez & Losada 2004).

Natural seasonal variations in the eelgrass cover might affect the wave propagation (Koch et al. 2009). Eelgrass densities in the west coast of Sweden vary across the year, being lowest in during the winter months (50-100 shoots per m^2) and higher in summer months (200-300 shoots per m^2, Infantes personal observation). This seasonal change in shoot density could have an impact on wave propagation. Storms are common in autumn and winter months (Sep-Apr) when the vegetation cover is lower. Nevertheless, this study shows that even if the effect of eelgrass on wave attenuation is lower in autumn, eelgrass still provides an important role on wave height reduction. On the other hand, the effect of eelgrass on reducing storm surges might be minimal since the slow change in water level might not be significantly reduced by eelgrass vegetation.

This study quantifies the wave decay over a 1km of eelgrass meadow. Wave propagation in the absence of vegetation will be dominated by wave shoaling, which is the deformation of the waves when the water depth becomes less than about half the wavelength (Dean & Dalrymple 1984). The shoaling causes a reduction in the wave propagation velocity as well as shortening of the wave length and increase of the wave height (Fig 9a). In the presence of vegetation, the wave friction coefficient in the bottom and drag coefficient increases reducing the wave height (Fig. 9b). When the vegetation is dense, the friction and drag becomes larger than the shoaling effect, which sets a clear effect on the wave height as it is reduced as it propagates through the vegetation (Fig. 9c). The simple wave propagation model, simulated the wave decay when using a drag coefficient (C_D) of 0.8 in the eelgrass dense site and a C_D of 0.3 in the eelgrass sparse site.

In Lomma Bay, the vegetation frontal area, a_v, changes with water depth (Table 1). In the shallow area, 3.5 m, eelgrass plants are generally shorter (0.3-0.4 m), thinner (2-3 mm), with a lower number of leaves per shoot (4-5) and very dense (200-300 plants per m^2). In contrast, at deeper water, 6.5 m, eelgrass plants are larger (0.6-0.7m), wider (4-5 mm), with a larger number of leaves per plant (5-6) and lower densities (50-100 plants per m^2). These values might change between sites and are also affected by wave exposure (Boström et al. 2014). In the simple wave decay model used in this study, a constant value was used for the entire wave propagation transect. All parameters such as l_h, l_w and l_n in eq. (5) were maintained constant using the average for shallow and deep, while the plant density, S_D, was adjusted to 200 (dense eelgrass) and 100 (sparse eelgrass). The model could be further improved by adjusting the vegetation frontal, a_v, to the water depth.

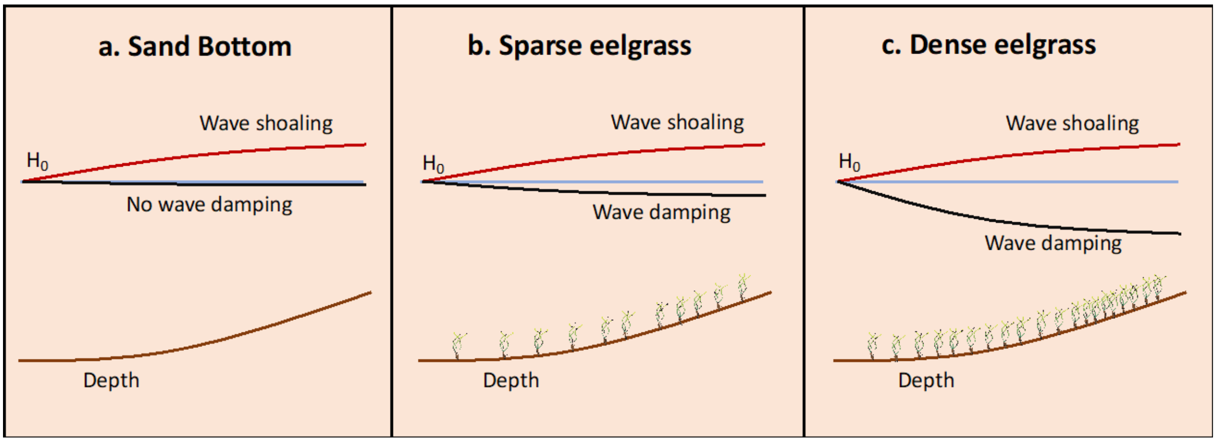

Figure 9. Effect of depth and vegetation on wave height (H_0) due to shoaling and damping. a) wave height increases with shoaling over a sand bottom, b) wave heights are slightly damped by sparse vegetation, and c) wave heights are highly damped by dense vegetation.

5.2. Sand transport in front of Lomma port

A large movement of sand was recorded during the instrument deployment. The wave sensor deployment structure located in the sparse-shallow location (3.4 m depth) was covered with sand on the 5-November, when it was recovered (Fig. 10). The structure was 20 cm height above the sea bottom when deployed on the 2-Aug (Fig. 10a), but after three months, the structure was buried with sand with only the sensor above the sediment (Fig. 10b). The eelgrass around the wave gauge seemed to be buried under the sand. We propose two main reasons that could have caused this sand movement.

The first is the larger wave heights recorded in the sparse transect which generated higher bottom orbital flow velocities initiating the sand transport. This study shows that waves heights were larger in the sparse transect than in the eelgrass dense transect. When flow velocities reach a critical shear stress, sediment particles will start transporting along the bottom until velocities are reduced. At these low velocities, the particles settle in the bottom. In Lomma Bay, the high flow velocities in the shallow areas where the sand was artificially placed, seems to have shifted to deeper locations where velocities are lower.

The second is the artificial sand nourishment of the beach in the south of Lomma port. The artificial addition of sand to build a beach could be potentially harmful for the eelgrass meadow if the sand is transported to deeper water. Sand could affect the shallow eelgrass limit if sand is accumulated on top of the meadow. The distribution of seagrass in the shallow areas is limited by hydrodynamic conditions (Infantes et al. 2009) while in the deep areas is limited by sunlight (Duarte 1991). Eelgrass is vulnerable to sediment burial and erosion caused by waves and currents. In the study area in front of the Lomma port, eelgrass does not occur shallower than 3 m depth. Using historical aerial images available from Google Earth is not possible to identify if the shallow eelgrass limit has been modified during the last 14 years (2005 to 2019), but sand nourishment of the Lomma beach could be potentially affecting the shallow limit (Fig. 11).

Further work using historical aerial images or earlier field surveys could be focus to determine the impact of sand nourishment in the shallow eelgrass limits in front of the Lomma port. In addition, we suggest a careful monitoring of the eelgrass bed near the port and in particular the location of the shallow eelgrass limit since the sand from the artificial beach could be affecting the meadow.

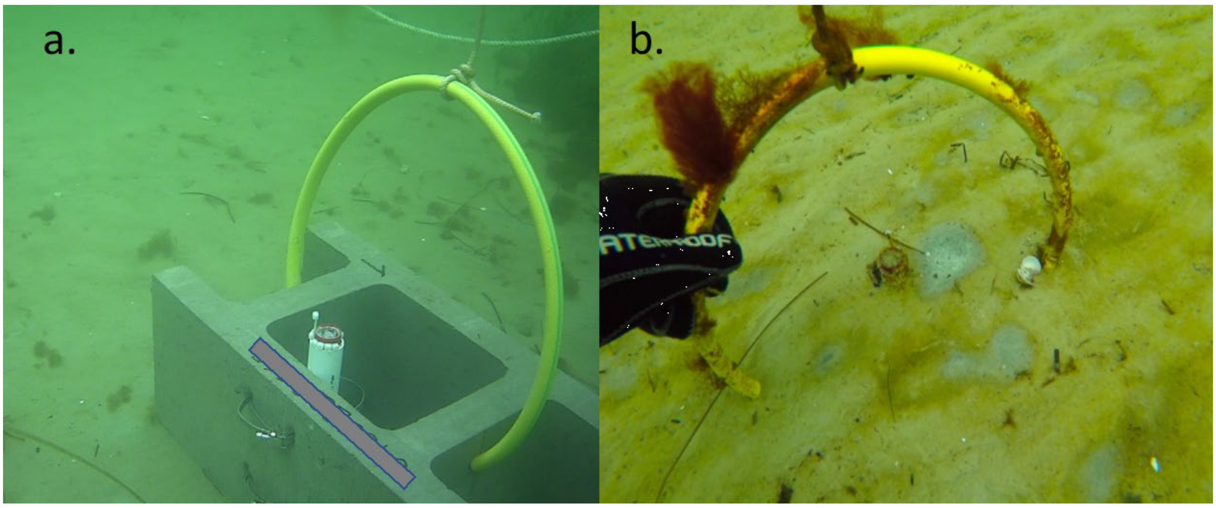

Figure 10. Burial of wave gauge in front of Lomma port due to sand movement, a) Concrete structure in the sea bottom at the start of the deployment (2-Aug) in the sparse-shallow location, b) Structure buried in the sediment after 3 months deployment (5-Nov). The height of the concrete block from the sea bottom is 20 cm.

Figure 11. Evolution of Lomma beach between 2005 to 2019. The beach located in the south of the port of Lomma is nourished with sand. The sand seems to shift locations during storm events and could potentially affect the meadow and shallow limit of eelgrass which is located today at about 300m from the beach. Images from Google Earth Pro.

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Apendix. Wave conditions during storms events

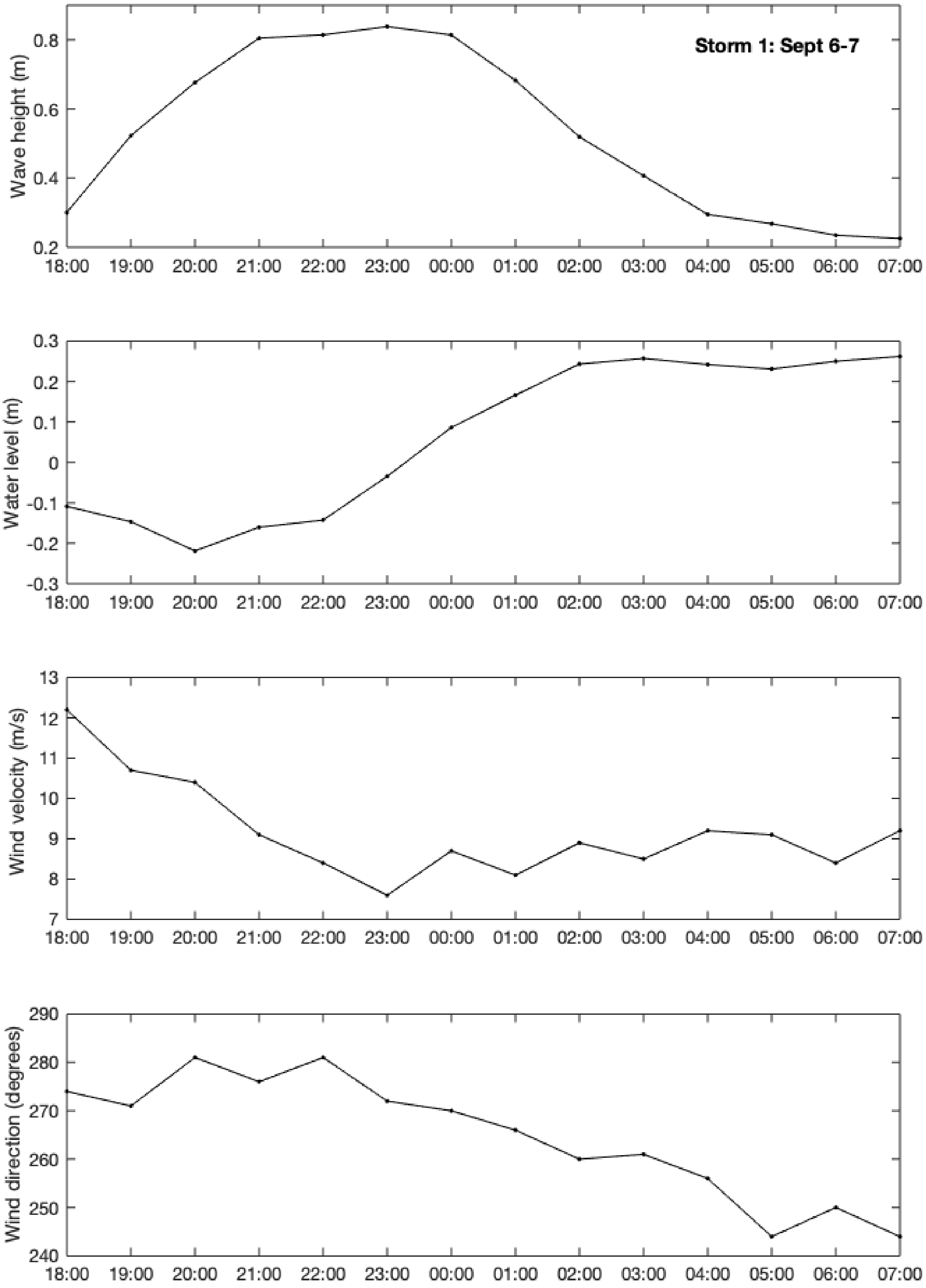

Figure S1. Wind and wave conditions at storm 1, between 6-7 September 2019, a) significant wave height, b) water level, c) wind velocity and d) wind direction.

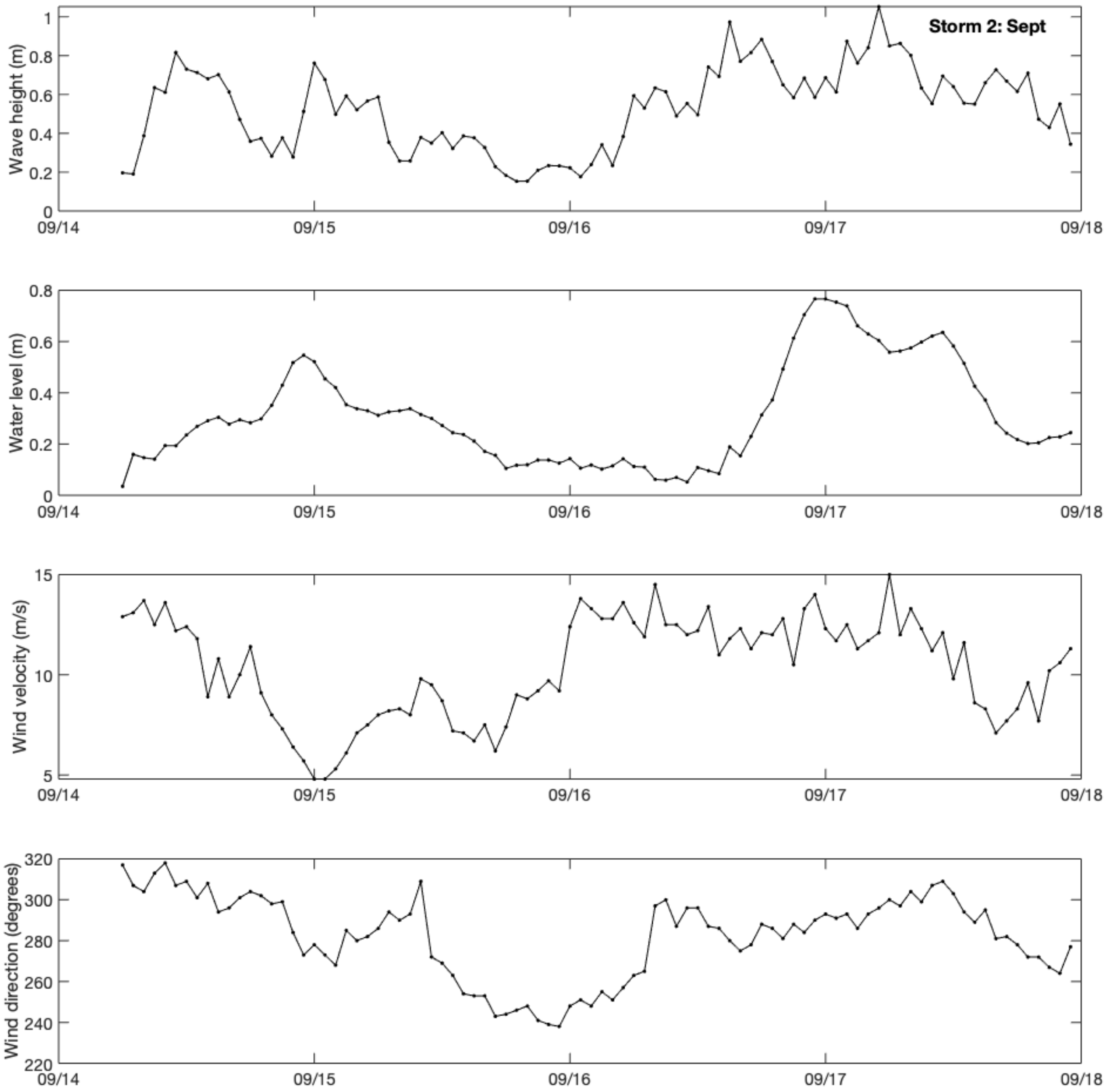

Figure S2. Wind and wave conditions at storm 2, between 14-18 September 2019, a) significant wave height, b) water level, c) wind velocity and d) wind direction.

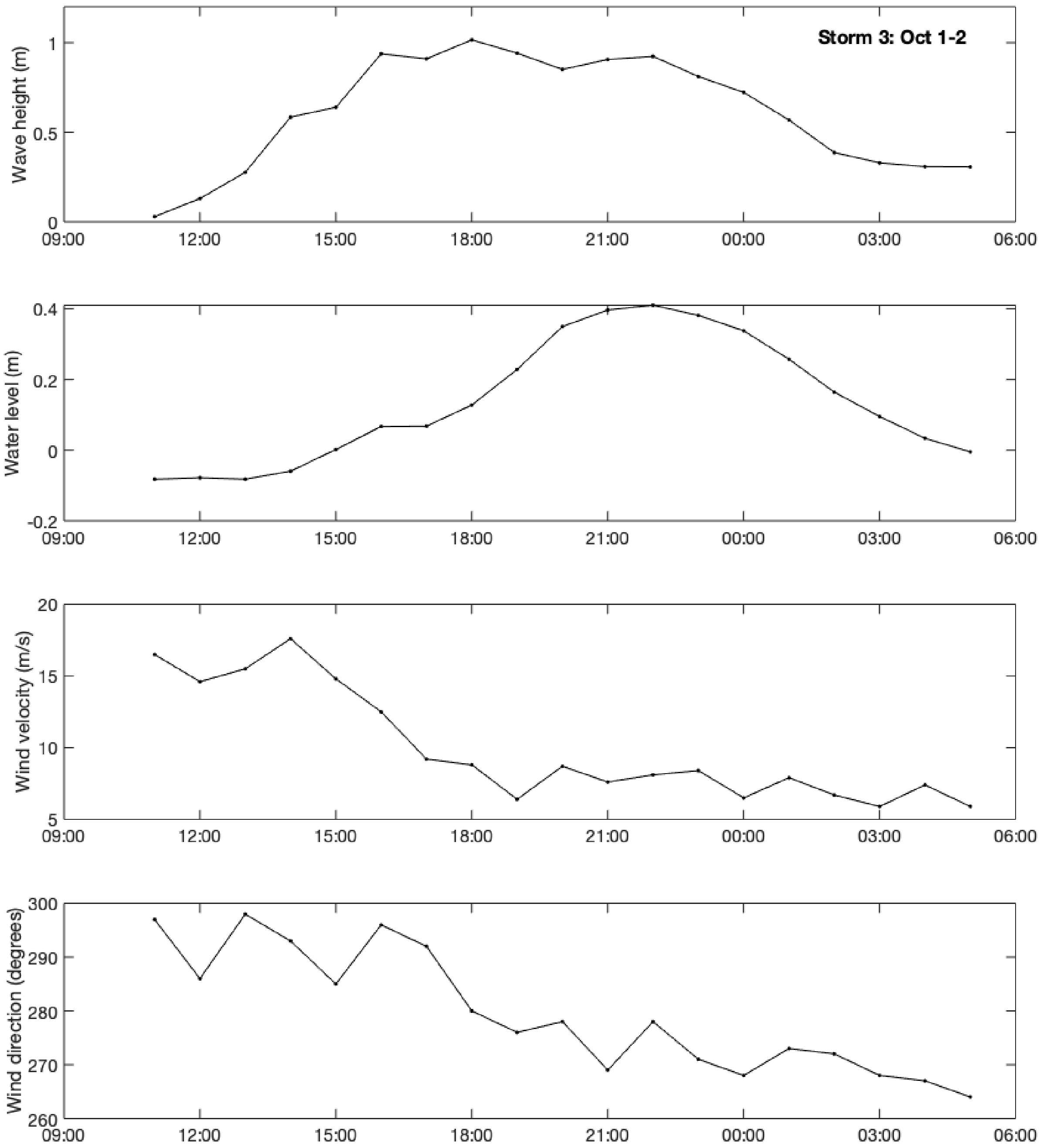

Figure S3. Wind and wave conditions at storm 3 between 1-2 October 2019, a) significant wave height, b) water level, c) wind velocity and d) wind direction.