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# Seasonal modification of tidal flat sediment dynamics by seagrass meadows of *Zostera noltii* (Bassin d'Arcachon, France)

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## Abstract :

The Arcachon lagoon (Atlantic coast, SW France) is a mesotidal embayment where seagrass beds colonize the majority of intertidal areas. In recent years, the surface area of Zostera noltii meadows has considerably decreased, with possible consequences for the sediment balance of the lagoon. However, such interactions are poorly understood, and knowledge of the relationship between hydro-sedimentary processes and small intertidal meadows, such as Z. noltii, is limited.

An intertidal mudflat, with variable meadow coverage, was studied during an annual survey. The study consisted in continuous high-frequency monitoring of bed altimetry, tidal elevation and waves. Sediment parameters and meadow characteristics were analyzed using samples collected monthly. Acoustic altimetry was validated as an efficient method to measure bed elevation in a vegetated environment, despite the presence of leaves under the transducer. The acoustic altimeter was also shown to have the potential to accurately estimate canopy height in a submerged environment.

Our survey data showed centimetric bed accretion at all vegetated stations. Accretion was positively correlated with seasonal growth of themeadows. During seasonal degeneration, themeadow prevented erosion of the sea bed. These results highlight the important role of seagrasses as ecosystem engineers.

**Keywords** : Ecosystem engineer, Zostera noltii, Growth dynamics, Sediment level, Biometric survey, Arcachon lagoon, Acoustic altimetry

## Introduction

In coastal shallow waters, seagrass meadows dampen the hydrodynamic energy of tidal currents (Fonseca and Fisher, 1986; Gambi et al., 1990; Verduin and Backhaus, 2000; Hendriks et al., 2008; Hendriks et al., 2010) and waves (Koch, 1999; Koch and Gust, 1999). Consequently, seagrass meadows are also believed to enhance sediment deposition (Gacia et al., 1999; Gacia and Duarte, 2001; Gacia et al., 2003; Hendriks et al., 2008) and to protect the sediment bed from erosion (Gacia and Duarte, 2001; Amos et al., 2004; Bos et al., 2007), with direct consequences for the long-term sediment balance. Seagrass meadows comprise a wide variety of species, and many studies have been undertaken to assess their role in ecosystem engineering by modifying hydro- and sediment dynamics. However, most of these studies focused on tall subtidal species, like *Posidonia oceanica* (Gacia et al., 1999; Granata et al., 2001; Hendriks et al., 2008), *Zostera marina* (Fonseca and Fisher, 1986; Gambi et al., 1990; Fonseca and Koehl, 2006) or *Thalassia testudinum* (Fonseca and Fisher, 1986; Koch, 1999; Koch and Gust, 1999). Much less attention has been paid to intertidal short-leaf species, such as *Zostera noltii* (Widdows et al., 2008). Because of their seasonal growth cycle, these species cause strong time-dependent variability of the interactions between the seagrasses, tidal flows and sediments. Their presence in the intertidal zone may also affect the morphodynamics of wide tidal flat areas through significant seasonal and long-term modifications. Knowledge of the interactions between hydro-sedimentary processes and seasonal variations of *Zostera noltii* is still limited (Bos et al., 2007; Widdows et al., 2008). Additionally, in many European coastal areas, a major decline in the surface area of seagrasses has been reported during the last century (Giesen et al., 1990; Bernard et al., 2005; Orth et al., 2006; Bernard et al., 2007; Waycott et al., 2009) and the consequences of this decline remain to be determined.

With a total surface area of 174 km$^2$, the Arcachon lagoon is a triangular-shaped mesotidal embayment located along the Aquitaine Atlantic coast (South-West France, Fig. 1). The tidal range varies from 0.8 m at neap tides to 4.6 m at spring tide. Wide intertidal areas (117 km$^2$) are extensively colonized by perennial seagrass meadows of *Zostera noltii*, and are the largest seagrass meadows in Europe (Auby and Labourg, 1996). Comparison of maps made in 1989 and 2007 showed that the surface area of these meadows has decreased by 33% from 68.5 km$^2$ to 45.7 km$^2$ (Plus et al., 2010). This decline has consequences not only for the ecology of the lagoon, but also for its management. At the same time as the reduction in area, the inner lagoon's channels are tending to fill in, increasing the need for dredging. Such events suggest that the decline in meadows will have significant consequences for the sediment balance. For this reason, *in situ* continuous monitoring of the bed altimetry, coupled with monthly determination of seagrass development and surficial sediment characteristics, was performed over a period of one year. Using this dataset, the aim of the present study was to understand how seasonal changes in the meadows are linked to the sediment dynamics of tidal flats. In addition, this is the first demonstration of the use of acoustic altimetry in a vegetated environment. When evaluating the data, we focused on observed seasonal trends, with emphasis on the interaction between the seasonal growth of *Zostera noltii* meadows and sediment dynamics. Finally, the possible long term consequences for the lagoon are discussed.

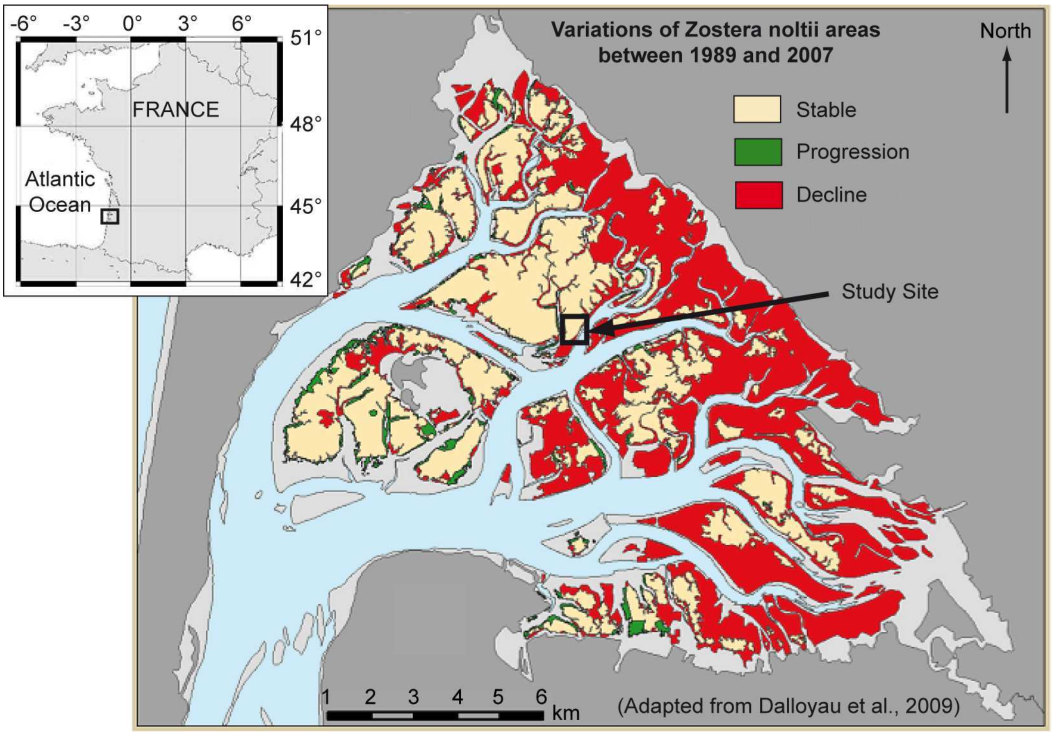


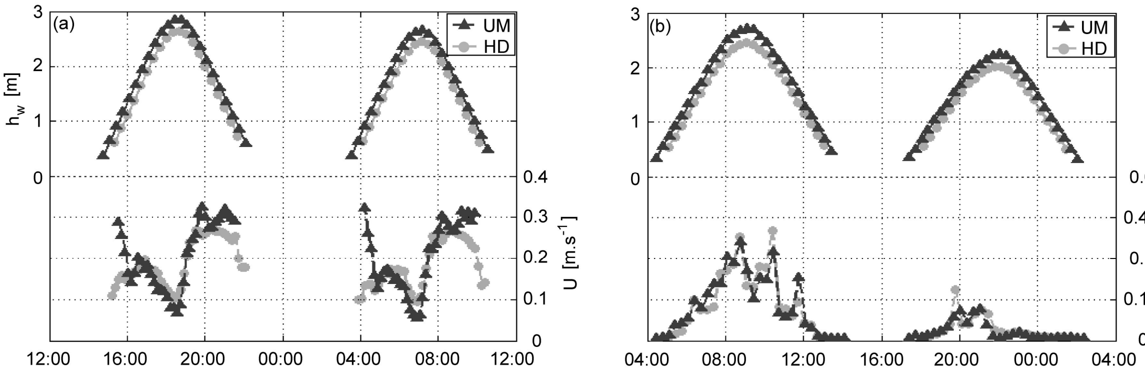
*Figure 1: General location of the Arcachon lagoon and the study site. Channels and subtidal areas are in sky blue. The interannual variation of Zostera noltii on intertidal flats highlights the decline of meadows in the inner parts of the lagoon.*

## Materials and Methods

### *Site description*

Field research was conducted from February 2009 to March 2010 on an intertidal flat located in the central part of the Arcachon lagoon (Fig. 1). The site was selected based upon the relative stability of the meadows throughout the year (Plus et al., 2010). The experimental site consists of three vegetated stations comprising meadows with different densities of *Zostera noltii*. The leaf cover was estimated visually before the beginning of the survey, and stations were identified as “high-density” (HD), “medium-density” (MD) and “low-density” (LD) meadows. The stations were located 60 m apart. Bathymetry (nautical chart datum) for the three stations ranged from 1.78 m (LD) to 1.82 m (HD), and the average emersion time ranged from 3 h 45 min (LD) to 3 h 50 min (HD). A fourth station was located in a bare mud area closest to the HD station. This bare mud station was denoted the “unvegetated mud” (UM) station. Because of the natural heterogeneity in meadow morphology and distribution in the field, this station had a slightly lower bathymetry (1.69 m) than did the vegetated stations, and it was located closest to the channel edge (40 m). However, the average emersion time (3 h 38 min) was only 12 minutes less than that of the highest station (HD).

Current velocity measurements were recorded simultaneously at the stations with the highest and lowest bathymetry (respectively, the HD and UM stations). These measurements were made from August 18, 2009 to September 2, 2009 and from January 28, 2010 to February 12, 2010 using ADCPs (Acoustic Doppler Current Profiler, RD Instruments). Computed depth-averaged current velocities under fair weather conditions (*U*, Fig. 2a) were of the same order of magnitude at both stations. During the first 40 minutes of inundation, slightly higher velocities were recorded at the unvegetated mud station (UM), but they decreased rapidly to reach the values recorded at the vegetated HD station. Moreover, under windy conditions (Fig. 2b), wind-induced waves of significant wave height ($H_s$), measured with an ALTUS pressure sensor (see below), exhibited comparable growth and decay at both the UM and HD stations. We can thus safely assume that each station was subject to similar hydrodynamic forcing.



Tides from the 20th to the 21th August 2009
(tidal ranges: 4.15 m and 3.97 m)

Tides from the 9th to the 10th November 2009
(tidal ranges: 2.85 m and 2.63 m)

*Figure 2: Comparison of hydrodynamic measurements at the vegetated high-density (HD) and unvegetated mud (UM) stations. Water depth ($h_w$, left axis) and depth-averaged velocities (U, right axis) were recorded during a spring tide (a); water depth ($h_w$, left axis) and significant wave height ($H_s$, left axis) were recorded during a storm event (b).*

### *Eelgrass sampling*

A biometric analysis was performed at each vegetated station (HD, MD and PD) following a protocol adapted and calibrated for the European Water Framework Directive (Hily et al., 2007). Mini-core samples (98 mm in diameter and 70 mm in length) of eelgrass were collected monthly. Nine samples were collected at each station. Samples were washed with fresh water on a sieve (mesh size 1.25 mm) to separate seagrasses from sediments and shell fragments. The seagrasses were frozen until analysis. For biometric analysis, the seagrasses were first separated into individual plants, and then divided manually into above- and below-ground biomass. When the rhizomes and roots were soft and dark brown in color, they were considered to be dead and removed. The number of shoots per mini-core was recorded, providing the shoot density ($D_{shoot}$, in shoot.m$^{-2}$). Using digital photography, the length and width of a leaf from ten randomly selected shoots were measured. Using these measurements, the mean leaf length ($L_{leaf}$, in mm) and the leaf area index ($LAI$, total leaf area per ground area unit in m$^2$.m$^{-2}$) were calculated. For each of the three vegetated stations (9 samples per station), the mean and standard deviation of each parameter were computed.

### *Surficial sediment sampling*

At each station, surface sediments (the uppermost 5 mm) were collected monthly in triplicate by skimming the surface of the sediment with a spatula. Pre-weighed pill boxes of known volume (3.2 cm$^3$) were used to collect samples for the determination of dry density. The samples were weighed before and after drying for 20 days at 60 °C. Dry density ($\rho_{dry}$, in kg/m$^3$) was computed as $\rho_{dry} = (W_{dry}-W_p)/V_t$, where $W_{dry}$ is the dry weight (in kg), $W_p$ is the tare weight of the pill box (in kg), and $V_t$ is the total volume of the pill box (in m$^3$).

Smaller pill boxes (1.5 cm$^3$) were used to collect samples for grain size analysis. Analyses were performed using a Malvern laser particle sizer that measures a size range from 0.06 to 880 µm. To prevent obstruction of the Malvern device, samples were first sieved (1000 µm) to remove fragments of shells and seagrasses. Sediment particles were then classified as mud ($C_{mud}$, <63 µm) or sand ($C_{sand}$, >63 µm), and particle composition was recorded as a percentage.

### *Bed level from ALTUS altimeters*

#### *Main features of ALTUS*

The ALTUS altimeter is an autonomous device that couples a 2-MHz acoustic transducer with a pressure sensor (Jestin et al., 1998; Bassoullet et al., 2000; Deloffre et al., 2007; Verney et al., 2007; Bassoullet et al., 2010). These devices provide bed altimetry and water level measurements at a resolution of 0.6 mm and 20 mm, respectively. The transducer was fixed on a large stainless-steel tripod, which limits undermining, while a separate container, holding the datalogger, the pressure sensor and the power supply, was buried down to the surface of the bed (Fig. 3a). The vertical distance between the sediment and the transducer ($H_{sed}$) was measured manually at each site inspection.

For each station, the ALTUS sampling rate consisted of 2-Hz bursts applied for 4 minutes every 20 minutes. This high-frequency sampling allowed the calculation of significant wave height ($H_s$) according to $H_s = 4 \cdot m_0^{0.5}$, where $m_0$ is the variance of the water surface elevation, previously corrected from depth attenuation, as described in (Neumeier and Amos, 2004).

In the standard mode, ALTUS devices are able to record four simultaneous signals (*H1* to *H4*), each based on a different threshold of the returned acoustic energy. Multiple threshold signals can provide qualitative information about the nature of the bed, for instance, the presence of fluid mud over consolidated sediments (Bassoullet et al., 2000; Bassoullet et al., 2010). In this study, we only used the maximum and the minimum threshold with values set at respectively 75% (*H1*) and 10% (*H4*) of the returned acoustic energy. These threshold values were chosen for their ability to provide reliable bed level measurements, which was demonstrated in several previous ALTUS surveys conducted in a wide range of coastal environments (Bassoullet et al., 2000; Deloffre et al., 2005; Deloffre et al., 2006; Deloffre et al., 2007; Verney et al., 2007).

#### *ALTUS altimetry within vegetation*

ALTUS altimeters have mainly been used on muddy or sandy-mud flats without vegetation (Bassoullet et al., 2000; Deloffre et al., 2007; Verney et al., 2007). In the case of vegetated beds, the acoustic response may be strongly influenced by the presence of leaves (Fig. 3b). In the case of unvegetated beds, the sediment bed constitutes a unique high-energy reflector, while in the presence of seagrass meadows, leaves also act as reflectors. In this case, the intensity of the reflected acoustic signal results in a double peak; the first peak being caused by the leaves and the second by the sediment bed. However, in some cases, the intensity of the peak caused by the leaves can be so strong that it masks the peak caused by the bed. Indeed, at vegetated stations, we observed that across 480 measurements, the sediment bed was not always detected. Therefore the *H1* maximum distance ($H1_{max}$) along the burst was considered to correspond to the bed sediment. Under similar considerations, the *H4* minimum distance ($H4_{min}$) along the burst should correspond to the top of the canopy.

To confirm the reliability of the data, the root mean squared deviation (*RMSD*, Eq. 1) was used.

$$RMSD = \sqrt{\frac{\sum_{t}^{n}(x_t - y_t)^2}{n}} \qquad \text{(Eq. 1)}$$

where $x_t$ represents manual measurements (e.g., $h_{sed}$, $L_{leaf}$, see below), $y_t$ represents ALTUS measurements (e.g., $h1_{max}$, $h_{canopy}$, see below), and n is the number of site inspections.

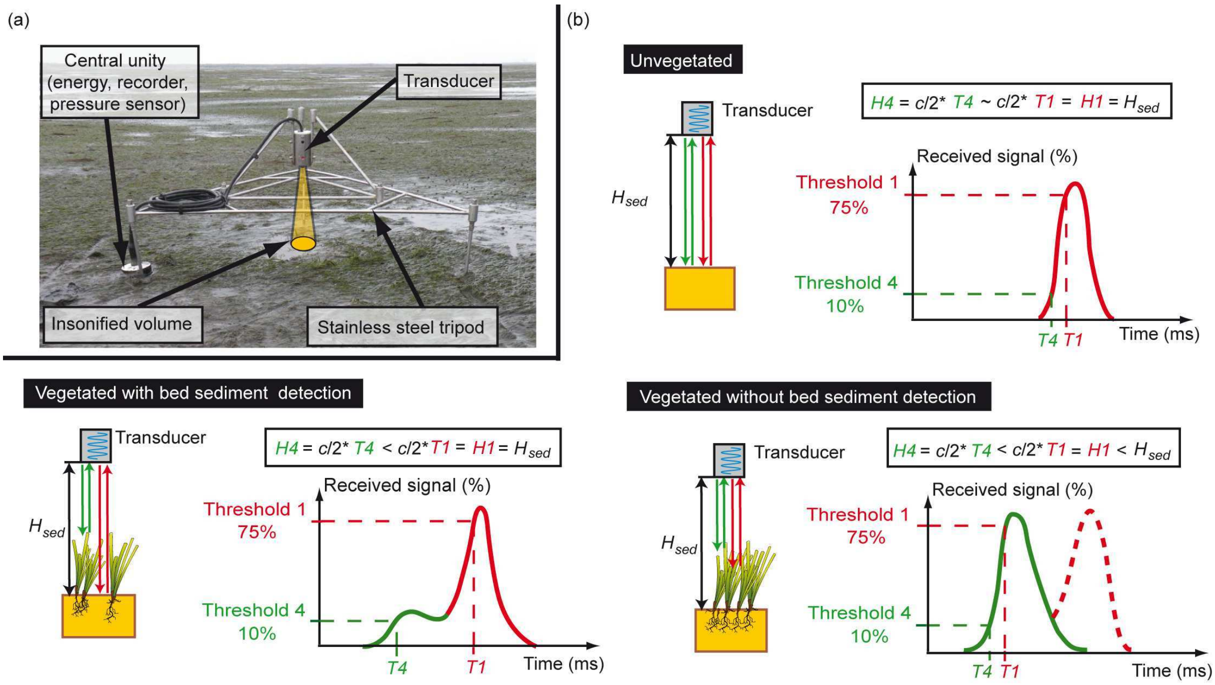


*Figure 3: Features of the ALTUS device. (a) Photograph of the ALTUS device deployed on a flat. (b) Sketches showing three typical cases of interface detection using two threshold values. $H_{sed}$ is the real transducer/sediment distance, T1 and H1 are double-time and distance, respectively, measured for the threshold 1 (75 %); T4 and H4 are double-time and distance, respectively, measured for the threshold 4 (10 %); and c is sound velocity in sea water.*

## Results

### Evaluation of the methodology

#### Sediment altimetry

Prior to comparisons between manual and ALTUS measurements, transducer-sediment distances for $H_{sed}$ and $H1_{max}$ were converted into sediment levels, relative to the initial sediment level, at time $t_0$, as $h_{sed}(t) = -[H_{sed}(t) - H_{sed}(t_0)]$, and $h1_{max}(t) = -[H1_{max}(t) - H_{sed}(t_0)]$, where $t$ corresponds to time. As manual measurements of sediment level ($h_{sed}$) were made on the emerged flat, they were compared with the converted ALTUS $h1_{max}$ measurements made using the first available measurement after the tidal flat became wet (Fig. 4a). At all stations, the ALTUS $h1_{max}$ measurements enabled satisfactory detection of the bed sediment. Indeed, the bed detection errors (RMSD ≤ 2.2 mm) were in the same order of magnitude as the accuracy of the ALTUS altimeters (2 mm). Furthermore, at vegetated stations, detection of bed sediments was better at the LD station than at the HD station (Fig. 4a). However, on the $h1_{max}$ annual time-series (Figs. 5b to 5e), the acoustic signal was found to be subject to more noise interference at the vegetated stations (Figs. 5b to 5d) than at the unvegetated mud station (Fig. 5e).

### *Canopy height*

At some site inspections, seagrass leaves located under the ALTUS transducer were cut back to keep the insonified volume as clear as possible and to prevent the leaves from covering the transducer. A visual inspection of leaf size and density determined how many leaves to cut back from the transducers. The time and site of these cuttings are indicated by arrows in Figure 5.

Mean leaf lengths ($L_{leaf}$) were compared with the computed ALTUS measurement of canopy height ($h_{canopy}$). Canopy height was computed as $h_{canopy}(t) = H1_{max}(t) - H4_{min}(t)$, where $H1_{max}$ and $H4_{min}$ are the last ALTUS measurements recorded before the intertidal flat dried out (Fig. 4b). A relatively good correlation was observed between $h_{canopy}$ and $L_{leaf}$ at the HD and MD stations ($RMSD$ = 19.7 mm and 13.6 mm, respectively), while a lower correlation was observed at LD station ($NRMSD$ = 34 mm ). The canopy height computed from ALTUS measurements, $h_{canopy}$, was slightly lower than the leaf length, $L_{leaf}$ (Fig. 4b).

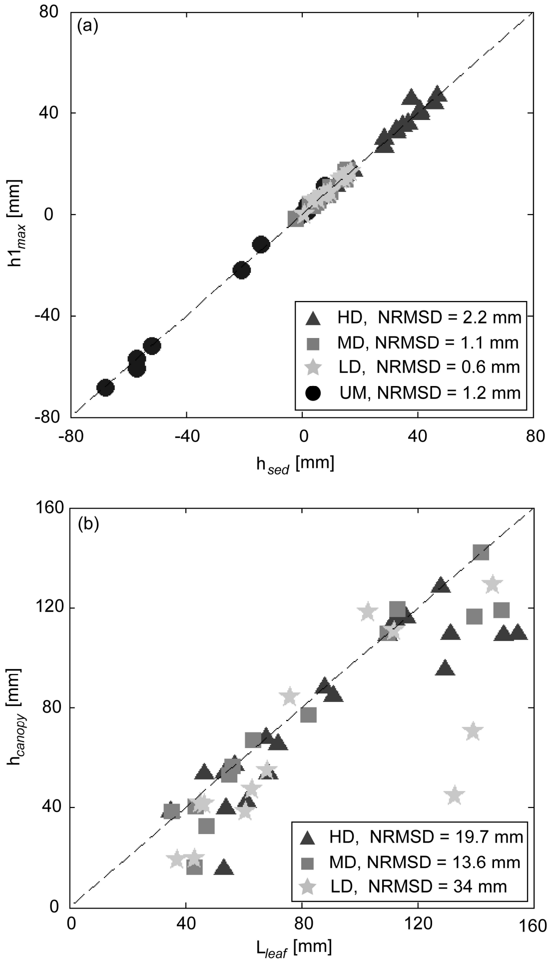


*Figure 4: Evaluation of the reliability of ALTUS measurement for the detection of the bed sediments and canopy height. Manual measurements of sediment level ($h_{sed}$) and corresponding acoustic measurement of sediment level ($h1_{max}$) for both the vegetated (HD, MD and LD) stations and the unvegetated mud (UM) station (a); mean leaf length ($L_{leaf}$) and corresponding acoustic estimation of canopy height ($h_{canopy}$) for all vegetated stations (HD, MD and LD) (b).*

### *Seasonal dynamics of sediment and seagrass*

During the first month of the survey (February 2009), measurements of wind wave height recorded at the HD station were relatively low, and $H_s$ was nearly equal to 0.1 m (Fig. 5a). From March to June, the wave climate was more energetic with several wave height events of over 0.2 m. The summer period (June to August) was characterized by fair weather conditions, while the period from September to November was characterized by only few energetic events during which $H_s$ reached 0.3 m. The period between November 2009 and March 2010 was characterized by a continuous succession of storm events, where $H_s$ ranged from 0.4 m to more than 0.6 m.

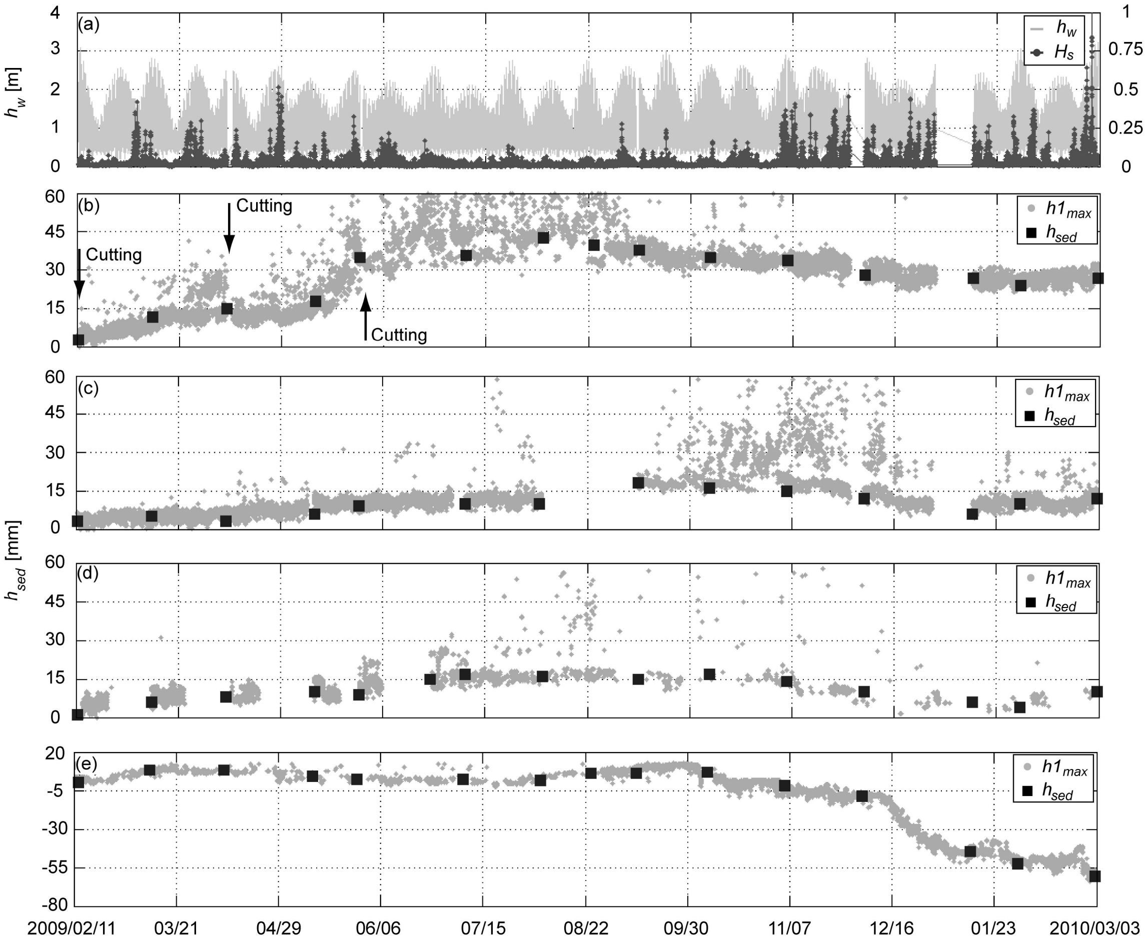


*Figure 5: One year of ALTUS records on the mudflat of the Arcachon lagoon. (a) Water depth ($h_w$, left axis) and significant wave height ($H_s$, right axis) recorded at the high-density (HD) station. Continuous ALTUS sediment level data ($h1_{max}$) and monthly manual measurements ($h_{sed}$) recorded at the HD (b), MD (c), LD (d) and UM (e) stations. Cutting dates are indicated by arrows.*

Between February and September 2009, sediments were consistently accreted at all vegetated stations (+41 mm, +16 mm and +15 mm at HD, MD and LD, respectively; see Figures 5b to 5d), whereas the unvegetated mud showed minimal changes in sediment height (+3 mm, Fig. 5e). During this period, accretion was maximal at the stations with the highest vegetation density and coincided with the seasonal development of vegetation at all vegetated stations (Fig. 5b to 5d, and Fig. 6a). At all vegetated stations, shoot density increased from April 2009 to May 2009 (from 9 500 shoot.m$^{-2}$ to 24 800 shoot.m$^{-2}$ at the HD station), and then decreased slightly until August (Fig. 6a). The *LAI* increased from 0.8 m$^{2}$.m$^{-2}$ at the start of the survey (February) to 9.8 m$^{2}$.m$^{-2}$ in September, with growth acceleration in April.

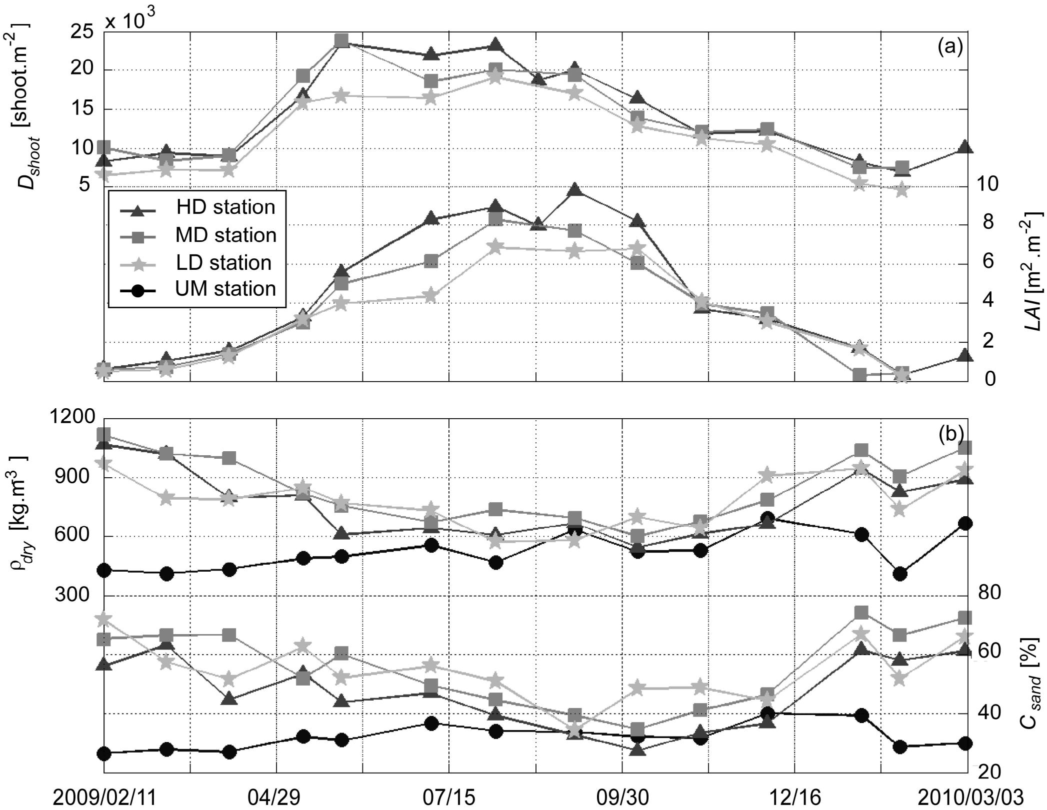


*Figure 6: Seasonal fluctuations in biometric and surficial sediment characteristics. Shoot density ($D_{shoot}$, left axis) and leaf area index (LAI, right axis) sampled at all the vegetated (HD, MD and LD) and unvegetated mud (UM) stations (a). Dry density ($\rho_{dry}$, left axis) and sand content ($C_{sand}$, right axis) sampled at all the vegetated (HD, MD and LD) and unvegetated mud (UM) stations (b).*

Between September 2009 and February 2010, the sediments were weakly eroded at all vegetated stations (-9 mm, -6 mm and -7 mm at HD, MD and LD, respectively; Fig. 5b to 5d), whereas the UM station showed strong erosion (-54 mm, Fig. 4e), marked by strong erosion in early October and late December 2009. At all vegetated stations, $D_{shoot}$ and $LAI$ gradually decreased from an average of respectively 24 800 shoot.m$^{-2}$ and 9.8 m$^2$.m$^{-2}$ in September 2009, to 8 000 shoot.m$^{-2}$ and 0.5 m$^2$.m$^{-2}$ in February 2010.

Surficial characteristics of the vegetated sediments exhibited contrasting seasonal variability. During the seagrass growth period (February to September 2009), dry density ($\rho_{dry}$) and sand content ($C_{sand}$) decreased by an average of 1 150 kg.m$^{-3}$ to 650 kg.m$^{-3}$ and by an average of 72% to 36%, respectively (Fig. 6b). However, during the seagrass degeneration period (September 2009 to February 2010), $\rho_{dry}$ and $C_{sand}$ increased from respectively 650 kg.m$^{-3}$ to 850 kg.m$^{-3}$ and from 36% to 72% on average. However, at the unvegetated station, changes in the surficial sediment characteristics revealed no significant seasonal trend. Within one year, from February 2009 to 2010, both $\rho_{dry}$ and $C_{sand}$ at the unvegetated station decreased only slightly, from 430 kg.m$^{-3}$ to 410 kg.m$^{-3}$, and from 27% to 30%, respectively (Fig. 6b).

## Discussion

### *ALTUS altimeter capability*

#### *Sediment levels in vegetated areas*

For long-term surveys, which may span days or weeks, the ALTUS device demonstrated reliable measurements of fluctuations in the sediment level, despite the presence of seagrass leaves. However, it was not possible to efficiently measure short-time fluctuations in sediment level, such as those occurring within hours or within tidal cycles when seagrass beds were fully developed. At the HD and MD stations, when the seagrass meadows were fully developed (e.g., $LAI > 6$ $m^2.m^{-2}$), the data were affected by superimposed scattering (up to 30 mm, Figs. 5b and 5c); the scattering was attributed to eelgrass leaves. In these cases, the bed position corresponds to the base of the $h1_{max}$ signal scattering. Filamentous algae (*Enteromorpha* spp.), mainly trapped by the ALTUS tripod supports at the HD and MD stations, were observed in varying quantities and for different lengths of time and caused additional noise interference in the ALTUS signal (Fig. 5b and 5c). Furthermore, short-time fluctuations of approximately 10 mm in bed level in the $h1_{max}$ signal scattering were observed at the UM station (Fig. 5e) and when seagrass development was limited (e.g., $LAI < 6$ $m^2.m^{-2}$) at the vegetated station (Figs. 5b to 5d).

Finally, cutting back the leaves under the transducer at the HD station (Fig. 5b) caused appreciable decay in the $h1_{max}$ signal scattering. Although leaf cutting allowed better detection of the sediment beds, it was not necessary to cut back the leaves when the vegetation cover was low because signal scattering at the MD and LD stations was of the same order of magnitude as at the UM station.

### *Estimation of canopy height*

The ALTUS was able to detect the canopy. Canopy height was underestimated compared with leaf length (Fig. 4b). This can be explained largely by the flexibility of seagrass leaves. While biometric measurements give the true leaf length, the ALTUS provides measurements of canopy height and takes into account the fact that seagrasses are submerged and thus subject to tidal currents. Canopy height was compared simultaneously with the water level during two tidal cycles at the HD station (Fig. 7a) and at the MD station (Fig. 7b); the water level gradient was used as an approximation of tidal currents above the tidal flat (Plus et al., 2006). Despite the irregular time variability of $h_{canopy}$, a trend was observed in two situations; during the flow and ebb tide, the leaves bent and thus decreased the canopy height by 50%. During high water slack, canopy height increased and reached 77% of the estimated leaf length confirming that the ALTUS satisfactorily evaluates canopy height, which is of potential interest for numerical modeling. Mathematical formulations used to simulate flow in the presence of submerged vegetation, require this parameter, although it is often determined empirically from flume experiments (Stephan and Gutknecht, 2002; Abdelrhman, 2003; Green, 2005; Nepf et al., 2007; Wilson, 2007).

## ***Implications of the seasonal growth cycle of meadows for sediment dynamics***

### *Sediment retention by seagrass meadows*

Evaluation of the altimetry data revealed strong trends in sediment accretion during the seagrass meadow growth season, and surficial sediments tended to become finer. Relative sand content decreased by a factor of two between February 2009 and September 2009. The accretion rates obtained in this study (ranging from 8 to 32 mm/year, respectively, for lower and higher shoot densities) were higher than those obtained for subtidal, perennial *Posidonia oceanica* beds (2 mm/year; (Gacia et al., 1999; Gacia and Duarte, 2001)) and for *Zostera marina* meadows in the Wadden Sea (Bos et al., 2007), where the accretion rate did not exceed 5 to 7 mm/year. In the Arcachon lagoon and in the Wadden Sea, the sediment supply is higher than in the Mediterranean Sea, where the sediment is sandy. Furthermore, considering differences in sediment supply and environmental characteristics, the difference in accretion rate appears to be of the same order of magnitude between these environments.

### *The balance between erosion and deposition*

Accumulation of sediments above a seagrass bed results from a balance between two competing processes. On one hand, deposition of suspended sediments increases (Gacia and Duarte, 2001; Gacia et al., 2003; Hendriks et al., 2008) and resuspension decreases (Gacia et al., 1999; Gacia and Duarte, 2001); these processes are caused by a reduction in flow energy near the bed (Verduin and Backhaus, 2000; Hendriks et al., 2008; Widdows et al., 2008; Hendriks et al., 2010). On the other hand, resuspension may be increased due to locally increased turbulence caused by the presence of shoots (Verduin and Backhaus, 2000; Fonseca and Koehl, 2006; Widdows et al., 2008; Hendriks et al., 2010). Depending on the plant development stage as well as on local conditions (such as sediment composition and hydrodynamics), one of these processes will dominate. One study (van Katwijk et al., 2010) observed a relationship between seagrass cover and surficial sediment composition. These authors found predominantly fine sediment deposition in a dense meadow, particularly in sandy beds with relatively high hydrodynamic energy. Conversely, dominant resuspension leading sandification was observed in muddy sediment in a lower density meadow because fine particles were more easily resuspended, and turbulence could be increased in low meadow densities (van Katwijk et al., 2010).

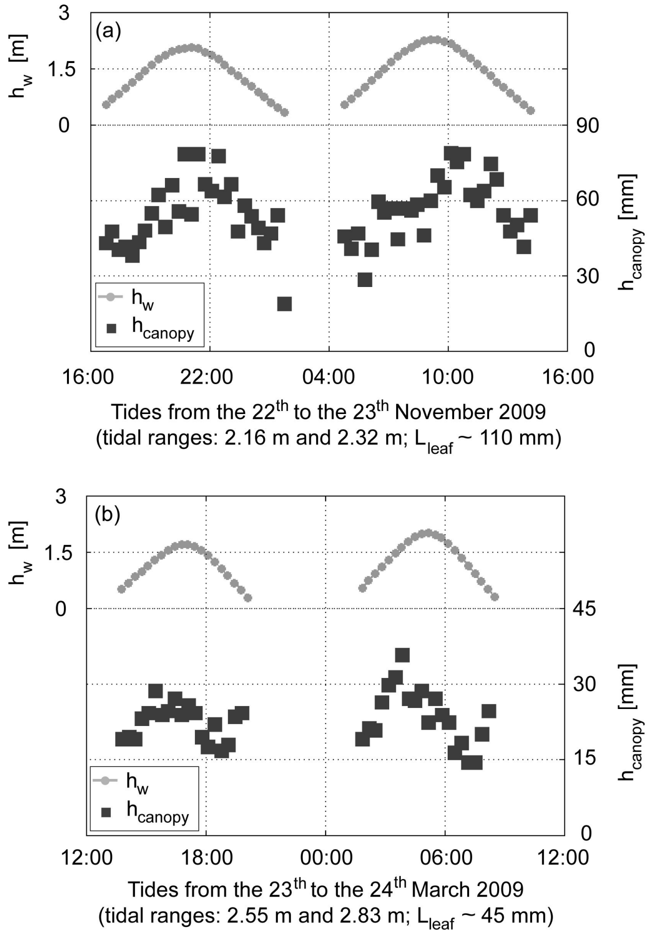


*Figure 7: Estimation of canopy height under tidal currents and fair weather conditions. Water depth ($h_w$, left axis, used as a proxy for tidal currents with maximum velocities expected at $h_w < 1.5$ m and minimal current velocity at the highest water level) and ALTUS canopy height ($h_{canopy}$, right axis) were recorded at the high-density (HD) station (a) and at the medium-density (MD) station (b). The approximate leaf length ($L_{leaf}$), corresponding to the time of plotted tides, is also reported.*

Results of the present study showed a similar, but time-varying pattern, correlated with the development of meadows. Accretion and reduction of the bed grain size from spring to summer may be correlated with a decrease in turbulence near the bed (due to higher shoot densities). From autumn to winter, erosion and sandification of surficial sediments was due to a decrease in meadow density. An increase in the sand fraction may have been caused by the erosion of fine particles.

Several storm events occurred during the course of the survey; however, the impact of waves on sediment dynamics differed during meadow growth and degeneration periods. From February 2009 to June 2009, many storm events occurred, but no significant erosion was recorded above the vegetated sites. During the same period, the unvegetated site underwent no accretion and sandification occurred. This was attributed to the high meadow density, which prevented sediment resuspension. Accretion on the vegetated flats which occurred during spring 2009 when wave activity was high, could be explained by higher levels of fine sediment resuspended at more exposed flats around the lagoon, which was transported and then efficiently trapped by meadows. Conversely, the weak erosion (<10 mm) associated with the sandification of surficial sediments, recorded from October 2009 to December 2009, could be explained by storm-induced resuspension of fine particles, coinciding with the thinning of the vegetation due to end-of-season die off. From January 2010 to the end of our data collection in March 2010, sediment levels remained stable despite the prevailing stormy conditions and low meadow density. The absence of erosion during the final months of the survey (whereas the unvegetated station eroded considerably) was attributed to: (1) the modification of the surface sediment and the increase in sand content in the muddy substratum, thus increasing bed strength (Mitchener and Torfs, 1996; Ganthy et al., 2011), and (2) the stabilizing effects of the root system, which reached the surface of the bed and prevented erosion of sediments (Ganthy et al., 2011).

### *Long term implications*

The net annual accretion of colonized tidal flats, induced by the meadow-enhanced mud deposition, would be expected to lead to continuous accretion of these tidal flats. However, this process is subject to self-regulating mechanisms. *Z. noltii* is sensitive to: (1) burial by high and rapid levels of accretion (Cabaço and Santos, 2007) and (2) desiccation, freezing and wave exposure increased by high bathymetric levels (Ramirez-Garcia et al., 1998; Huong et al., 2003; Shafer et al., 2007).

As unvegetated flats were found to be less resistant to erosion (Ganthy et al., 2011) than vegetated areas, the decline of meadows would be expected to lead to higher erosion of bed sediments. Higher concentrations of suspended sediment would decrease the light available for photosynthesis and lead to a further decline in meadows, thus providing negative feedback (van der Heide et al., 2007; van der Heide et al., 2011).

Due to the world-wide decline in seagrass over the last century (Giesen et al., 1990; Figueiredo da Silva et al., 2004; Bernard et al., 2005; Orth et al., 2006; Waycott et al., 2009), and more recently in the Arcachon lagoon (Plus et al., 2010), significant geomorphological modifications may occur in such vegetated areas, and the damage may be long-term. Decline of *Zostera noltii* meadows in the Arcachon lagoon will likely cause a drastic decrease in sediment deposition fluxes. Moreover, reduced consolidation time and hydrodynamic protection may significantly increase sediment resuspension in unvegetated areas. Resuspended sediment will likely be transported and redeposited in low energy channels, primarily in the inner regions of the lagoon, where the residual transport is controlled by the flood tide (Plus et al., 2006). Local authorities (SIBA, Intercommunal Union of Arcachon Lagoon) responsible for lagoon management have observed a simultaneous decline in meadows and an increase in dredging requirements in shallow channels located in the eastern part of the lagoon (SIBA, personal communication). However, it is important to emphasize that these pluriannual extrapolations were based on a one-year study and that a long-term evaluation is required to confirm this analysis.

## Conclusion

A one-year field survey was conducted in the Arcachon lagoon. Acoustic altimetry (using ALTUS devices) was performed on a tidal flat at sites with different densities and coverage of *Zostera noltii* meadows. Surficial sediments and seagrass development characteristics were recorded monthly. A specific post-processing technique for bed altimetry was developed to provide reliable measurements despite the presence of the vegetation. The following conclusions can be drawn from this study:

(1) ALTUS acoustic altimeters can provide reliable measurements of sediment level despite the presence of seagrass meadows. However, a specific post-processing method is required.

(2) ALTUS altimeters can also assess the real canopy height that is subject to hydrodynamics. The real canopy height is an important parameter to assess the effects of submerged vegetation on hydrodynamics in numerical modeling; this feature is often determined empirically *in situ* or from flume experiments.

(3) The presence of meadows modifies the balance between particle trapping and protection against erosion processes, depending upon the seasonal growth stage of seagrass.

- During the growth period (February to September), particle trapping dominates and is linked with muddification of surficial sediments, thus leading to centimetric accretion of colonized areas.
- During the degeneration period (September to February), erosion occurs, but less than in unvegetated flats. Protection against erosion dominates and is related to the sandification of surficial sediments. This sandification is probably induced by the resuspension of fine surficial sediments, while sandy sediments remain trapped in the meadows.

(4) The annual sediment balance of seagrass colonized tidal flats is positive, while unvegetated flats exhibit a strongly negative sediment balance. The decline of meadows in the Arcachon lagoon may lead to strong morphological modifications of the lagoon.

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## References

Abdelrhman, M.A., 2003. Effect of eelgrass *Zostera marina* canopies on flow and transport. Marine Ecology Progress Series 248, 67-83.

Amos, C.L., Bergamasco, A., Umgiesser, G., Cappucci, S., Cloutier, D., DeNat, L., Flindt, M., Bonardi, M., Cristante, S., 2004. The stability of tidal flats in Venice Lagoon---the results of in-situ measurements using two benthic, annular flumes. Journal of Marine Systems 51, 211-241.

Auby, I., Labourg, J.-P., 1996. Seasonal dynamics of *Zostera noltii* Hornem. in the bay of Arcachon (France). Journal of Sea Research 34, 269-277.

Bassoullet, P., Le Hir, P., Gouleau, D., Robert, S., 2000. Sediment transport over an intertidal mudflat: field investigations and estimation of fluxes within the "Baie de Marennes-Oléron" (France). Continental Shelf Research 20, 1635-1653.

Bassoullet, P., Verney, R., Kervella, Y., Kervella, S., Jestin, H., Voineson, G., 2010. Utilisation d'un altimètre (ALTUS) destiné à la quantification des dépôt/érosion en domaine littoral pour l'étude des corrélations avec les caractéristiques de vagues et les interfaces de dépôt. La Houille Blanche 5, 81-86.

Bernard, G., Bonhomme, P., Bouduresque, C.F., 2005. Recovery of the seagrass *Zostera marina* in a disturbed Mediterranean lagoon (Etang de Berre, Bouches-du-Rhône, Southern France). Hydrobiologia 539, 157-161.

Bernard, G., Bouduresque, C.F., Picon, P., 2007. Long term changes in Zostera meadows in the Berre lagoon (Provence, Mediterranean Sea). Estuarine, Coastal and Shelf Science 73, 617-629.

Bos, A.R., Bouma, T.J., de Kort, G.L.J., van Katwijk, M.M., 2007. Ecosystem engineering by annual intertidal seagrass beds: Sediment accretion and modification. Estuarine, Coastal and Shelf Science 74, 344-348.

Cabaço, S., Santos, R., 2007. Effects of burial and erosion on the seagrass *Zostera noltii*. Journal of Experimental Marine Biology and Ecology 340, 204-212.

Deloffre, J., Lafite, R., Lesueur, P., Lesourd, S., Verney, R., Guézennec, L., 2005. Sedimentary processes on an intertidal mudflat in the upper macrotidal Seine estuary, France. Estuarine, Coastal and Shelf Science 64, 710-720.

Deloffre, J., Lafite, R., Lesueur, P., Verney, R., Lesourd, S., Cuvilliez, A., Taylor, J., 2006. Interactions between intertidal mudflat and turbidity maximum in macrotidal estuarine context. Marine Geology 235, 151-164.

Deloffre, J., Verney, R., Lafite, R., Lesueur, P., Lesourd, S., Cundy, A.B., 2007. Sedimentation on intertidal mudflats in the lower part of macrotidal estuaries: Sedimentation rhythms and their preservation. Marine Geology 241, 19-32.

Figueiredo da Silva, J., Duck, R.W., Catarino, J.B., 2004. Seagrass and sediment response to changing physical forcing in a coastal lagoon. Hydrology and Earth System Sciences 8, 151-159.

Fonseca, M.S., Fisher, J.S., 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. Marine Ecology Progress Series 29, 15-22.

Fonseca, M.S., Koehl, M.A.R., 2006. Flow in seagrass canopies: The influence of patch width. Estuarine, Coastal and Shelf Science 67, 1-9.

Gacia, E., Duarte, C.M., 2001. Sediment Retention by a Mediterranean *Posidonia oceanica* Meadow: The Balance between Deposition and Resuspension. Estuarine, Coastal and Shelf Science 52, 505-514.

Gacia, E., Duarte, C.M., Marbà, N., Terrados, J., Kennedy, H., Fortes, M.D., Tri, N.H., 2003. Sediment deposition and production in SE-Asia seagrass meadows. Estuarine, Coastal and Shelf Science 56, 909-919.

Gacia, E., Granata, T.C., Duarte, C.M., 1999. An approach to measurement of particle flux and sediment retention within seagrass (*Posidonia oceanica*) meadows. Aquatic Botany 65, 255-268.

Gambi, M.C., Nowell, A.R.M., Jumars, P.A., 1990. Flume observations on flow dynamics in *Zostera marina* (eelgrass) beds. Marine Ecology Progress Series 61, 159-169.

Ganthy, F., Sottolichio, A., Verney, R., 2011. The Stability of Vegetated Tidal Flats in a Coastal Lagoon Through Quasi In-Situ Measurements of Sediment Erodibility. Journal of Coastal Research SI 64 (Proceedings of the 11th International Coastal Symposium), 1500-1504, Szczecin, Poland.

Giesen, W.B.J.T., van Katwijk, M.M., Den Hartog, C., 1990. Temperature, salinity, insolation and wasting disease of eelgrass (Zostera marina L.) in the Dutch Wadden Sea in the 1930's. Netherlands Journal of Sea Research 25, 395-404.

Granata, T.C., Serra, T., Colomer, J., Casamitjana, X., Duarte, C.M., Gacia, E., 2001. Flow and particle distribution in a nearshore seagrass meadow before and after a storm. Marine Ecology Progress Series 218, 95-106.

Green, J.C., 2005. Velocity and turbulence distribution around lotic macrophytes. Aquatic Ecology 39, 1-10.

Hendriks, I.E., Bouma, T.J., Morris, E.P., Duarte, C.M., 2010. Effects of seagrasses and algae of the *Caulerpa* family on hydrodynamics and particle-trapping rates. Marine Biology 157, 473-481.

Hendriks, I.E., Sintes, T., Bouma, T.J., Duarte, C.M., 2008. Experimental assessment and modeling evaluation of the effects of the seagrass *Posidonia oceanica* on flow and particle trapping. Marine Ecology Progress Series 356, 163-173.

Hily, C., Sauriau, P.-G., Auby, I., 2007. Protocoles suivi stationnel des herbiers à zostères pour la Directive Cadre sur l'Eau (DCE). IFREMER, p. 10.

Huong, T.T.L., Vermaat, J.E., Terrados, J., van Tien, N., Duarte, C.M., Borum, J., Tri, N.H., 2003. Seasonality and depth zonation of intertidal *Halophila ovalis* and *Zostera japonica* in Ha Long Bay (northern Vietnam). Aquatic Botany 75, 147-157.

Jestin, H., Bassoullet, P., Le Hir, P., L'Yavanc, J., Degres, Y., 1998. Development of ALTUS, a high frequency acoustic submersible recording altimeter to accurately monitor bed elevation and quantify deposition or erosion of sediments, Ocean Conference Record (IEEE).

Koch, E.W., 1999. Sediment resuspension in a shallow *Thalassia testudinum* banks ex König bed. Aquatic Botany 65, 269-280.

Koch, E.W., Gust, G., 1999. Water flow in tide- and wave-dominated beds of the seagrass *Thalassia testudinum*. Marine Ecology Progress Series 184, 63-72.

Mitchener, H., Torfs, H., 1996. Erosion of mud/sand mixtures. Coastal Engineering 29, 1-25.

Nepf, H.M., White, B., Ligthbody, A., Ghisalberti, M., 2007. Transport in aquatic canopies, in: Gayev Y.A., Hunt J.C.R. (Eds.), Flow and Transport Processes with Complex Obstructions, pp. 221-2250.

Neumeier, U., Amos, C.L., 2004. Turbulence Reduction by the Canopy of Coastal *Spartina* Salt-Marshes. Journal of Coastal Research, 433-439.

Orth, R.J., Carruthers, T.J.B., Dennison, W.C., Duarte, C.M., Fourqurean, J.W., Heck, K.L.J., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Olyarnik, S., Short, F.T., Waycott, M., Williams, S.L., 2006. A Global Crisis for Seagrass Ecosystems. BioScience 56, 987-996.

Plus, M., Dalloyau, S., Trut, G., Auby, I., de Montaudouin, X., Emery, E., Noël, C., Viala, C., 2010. Long-term evolution (1988-2008) of *Zostera* spp. meadows in Arcachon Bay (Bay of Biscay). Estuarine, Coastal and Shelf Science 87, 357-366.

Plus, M., Maurer, D., Stanisière, J.-Y., Dumas, F., 2006. Caractérisation des composantes hydrodynamiques d'une lagune mésotidale, le Bassin d'Arcachon. IFREMER, p. 54.

Ramirez-Garcia, P., Lot, A., Duarte, C.M., Terrados, J., Agawin, N.S.R., 1998. Bathymetric distribution, biomass and growth dynamics of intertidal *Phyllospadix scouleri* and *Phyllospadix torreyi* in Baja California (Mexico). Marine Ecology Progress Series 173, 13-23.

Shafer, D.J., Sherman, T.D., Wyllie-Echeverria, S., 2007. Do desiccation tolerances control the vertical distribution of intertidal seagrasses? Aquatic Botany 87, 161-166.

Stephan, U., Gutknecht, D., 2002. Hydraulic resistance of submerged flexible vegetation. Journal of Hydrology 269, 27-43.

van der Heide, T., van Nes, E.H., Geerling, G.W., Smolders, A.J.P., Bouma, T.J., van Katwijk, M.M., 2007. Positive Feedbacks in Seagrass Ecosystems: Implications for Success in Conservation and Restoration. Ecosystems 10, 1311-1322.

van der Heide, T., van Nes, E.H., van Katwijk, M.M., Olff, H., Smolders, A.J.P., 2011. Positive Feedback in Seagrass Ecosystems - Evidence from Large Scale Empirical Data. PLoS ONE 6, e16504.

van Katwijk, M.M., Bos, A.R., Hermus, D.C.R., Suykerbuyk, W., 2010. Sediment modification by seagrass beds: Muddification and sandification induced by plant cover and environmental conditions. Estuarine, Coastal and Shelf Science 89, 175-181.

Verduin, J.J., Backhaus, J.O., 2000. Dynamics of Plant-Flow Interactions for the Seagrass *Amphibolis antartica*: Field Observations and Model Simulations. Estuarine, Coastal and Shelf Science 50, 185-204.

Verney, R., Deloffre, J., Brun-Cottan, J.-C., Lafite, R., 2007. The effect of wave-induced turbulence on intertidal mudflats: Impact of boat traffic and wind. Continental Shelf Research 27, 594-612.

Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck, K.L.J., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T., Williams, S.L., 2009. Accelerating loss of seagrasses across the globe threaten coastal ecosystems. PNAS 106, 12377-12381.

Widdows, J., Pope, N.D., Brinsley, M.D., Asmus, H., Asmus, R.M., 2008. Effects of seagrass beds (*Zostera noltii* and *Z. marina*) on near-bed hydrodynamics and sediment resuspension. Marine Ecology Progress Series 358, 125-126.

Wilson, C.A.M.E., 2007. Flow resistance models for flexible submerged vegetation. Journal of Hydrology 342, 213-222.