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Aeolian transport of seagrass (*Posidonia oceanica*) beach-cast to terrestrial systems

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ABSTRACT

The annual export of the Mediterranean seagrass (*Posidonia oceanica*) litter to adjacent beaches and coastal dunes was quantified by examining the fortnight evolution of seagrass beach-cast volume on two beaches in the NW Mediterranean (Son Real and Es Trenc, Mallorca Island, Spain) for two years and analyzing the wind speed and direction obtained from the closest Meteorological Spanish Agency surface weather stations. The decomposition stage of the deposits was examined by analyzing the total hydrolysable amino acids, its percentage distribution and derived degradation indexes. Prevalent winds exceeding 6 m s^{-1}, the coastline morphology and type of terrestrial vegetation determine the annual dynamics of the seagrass beach-cast. In the most protected beach (Son Real) the seagrass beach-cast remained nearly stationary during the two studied years while it exhibited wide annual fluctuations in the less protected one (Es Trenc). The amounts of *P. oceanica* wrack washed on Son Real and Es Trenc beaches, respectively, were estimated at 309 kg DW m $coastline^{-1}$ yr^{-1} and 1359 kg DW m $coastline^{-1}$ yr^{-1}. They supplied between 20 kg $CaCO_3$ m $coastline^{-1}$ yr^{-1} and 47 kg $CaCO_3$ m $coastline^{-1}$ yr^{-1}. Between 54% (Son Real) and 70% (Es Trenc) of seagrass beach-cast, respectively accounting for 1.5 kg N m $coastline^{-1}$ yr^{-1} and 8.6 kg N m $coastline^{-1}$ yr^{-1}, were annually exported from the beaches to adjacent dune systems. Our results reveal that Mediterranean seagrass meadows might be an important source of materials, including sand and nutrients, for adjacent terrestrial systems, able to support their functioning.

1. Introduction

Coastal areas are at the interface between marine and terrestrial ecosystems, constitute approx. 8% of the Earth's surface (Ray and Hayden, 1992), and are highly productive (Duarte et al., 2005). The functioning of coastal ecosystems is partly subsidized by the flow of materials from land to the sea (Colombini and Chelazzi, 2003). Conversely, the role of marine productivity to systems beyond the sea boundary has only been occasionally quantified (see Coupland et al., 2007; Heck et al., 2008).

Seagrasses inhabit marine coastal areas down to 40–50 m water depth (Duarte, 1990) and rank amongst the most productive ecosystem worldwide (Duarte and Chiscano, 1999). Part of seagrass production can be exported to adjacent beaches where beach-cast accumulates forming up to a few meters thick deposits, named *banquettes* (Boudouresque and Meinesz, 1982; Jeudy de Grissac, 1984). Seagrass beach-cast prevents coastal erosion, by attenuating wave energy and protecting the shoreline (Boudouresque and Meinesz, 1982; Hemminga and Nieuwenhuize, 1991; Roig et al., 2009; Vacchi et al., 2016), although it depends on the residence time of the banquettes (Gómez-Pujol et al., 2013). Moreover, seagrass beach-cast can also prevent erosion though its role as a sand source. Seagrass meadows provide habitat for fauna and algal species that grow epiphytically on leaves and rhizomes. Many of these species have calcium carbonate skeletons (Holmer et al., 2003). In coastal carbonate-rich areas with no riverine sedimentary inputs, benthic communities can be the main source of sediment particles and seagrass meadows may produce 50–75% of

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them (Canals and Ballesteros, 1997). Seagrass material washed to shore can be loaded with carbonate rich epiphytes which become part of the sand pool of coastal areas as seagrass beach-cast decomposes. Furthermore, seagrass beach-cast supports marine-land food webs (Heck et al., 2008) and it supplies materials and nutrients to adjacent land systems beyond the beach (Hemminga and Nieuwenhuize, 1990; Colombini and Chelazzi, 2003; Cardona and García, 2008). Yet, the coastal functions of seagrass beach-cast have barely been quantified due to the limited knowledge on the magnitude of beach-cast production, dynamics and fate.

Seagrass beach-cast deposits have been reported on sandy beaches worldwide, from the tropics (e.g. Kenya, Mauritania; Hemminga and Nieuwenhuize, 1990) to temperate regions (e.g. Mediterranean, Mateo et al., 2006; Western Australia, Lavery et al., 2013). The magnitude of beach-cast deposits varies largely across beaches and seasons depending on the life cycle of seagrass meadows nearby (Gómez-Pujol et al., 2013), beach morphology (Simeone and De Falco, 2012), consumers (e.g. Heck et al., 2008) and environmental forcing acting at local (Simeone et al., 2013) and global (Ochieng and Erftemeijer, 1999) scales. Seagrass beach-cast accretes mainly by the influence of the waves generated when the prevailing coastal winds are perpendicular towards the shore (Ochieng and Erftemeijer, 1999; Hammann and Zimmer, 2014; Simeone et al., 2013; Gómez-Pujol et al., 2013) if there is sufficient seagrass litter in the water. The same mechanism is responsible for the erosion of seagrass beach-cast, particularly during severe storm events characterized by the presence of high waves and precipitation in the coastal region (Mateo et al., 2003). Wind speeds over 6 m s^{-1}, in addition to contributing to the generation of waves above 1 m height (Cavaleri, 2005), allow for aeolian transport (Nordstrom et al., 2011) of beach-cast material back to the sea or further inland (depending on wind sense) and, thus, it also drives seagrass beach-cast erosion. Therefore, the characterization of weather conditions can help to quantify the transport terms in the mass balance of seagrass beach-casts in those areas where aeolian transport drives the export terms.

The decomposition of seagrass debris may also contribute to variability in the magnitude of beach-cast deposit. The geochemical characterization of the deposits can give insights on the decomposition stage of the individual beach-cast deposits. Amino acids are the most labile class of organic biochemicals and are a critical substrate for microbial growth in marine environments (Keil et al., 2000). The relative molecular distribution of amino acids changes as the microbial degradation of organic matter proceeds. This observation can be used to assess the extent of degradation of organic matter in the beach-cast deposits, as has been done in other environments (Dauwe et al., 1999; Keil et al., 2000).

The size of seagrass beach-cast deposits has been assessed in the past by different methodologies, such as video-monitoring (Almar et al., 2008; Nieto et al., 2010; Gómez-Pujol et al., 2013), photographs (Simeone et al., 2013), quantification of the amount of the seagrass beach-cast removed in touristic beaches (De Falco et al., 2008; Simeone and De Falco, 2013) and *in situ* measurements (Ochieng and Erftemeijer, 1999; Nordstrom et al., 2011; Hammann and Zimmer, 2014). However, these studies are built on single or short temporal observations, preventing the quantification of stocks, inputs and fate of seagrass beach-cast at annual scale.

This work amied to examine the temporal dynamics of the seagrass beach-cast to estimate the annual amount of it washed to shore and its subsequent fate (towards the sea, remaining on the beach or towards the dune system) considering aeolian and marine transport (both generated by prevailing winds) and decomposition as the main drivers. We did so by (1) biweekly quantifying the dimensions of seagrass beach-cast deposits and (2) evaluating the fate of seagrass beach-cast by coupling the observed temporal volumetric changes, after excluding those attributed to decomposition, with the analyses of prevailing winds. We conducted this study during two years on two beaches in Mallorca Island (Mediterranean Sea) where beach-casts are formed by debris of the dominant, Mediterranean endemic seagrass *Posidonia oceanica*.

2. Methods

2.1. Description of the study sites

The study was conducted on two beaches in the NW Mediterranean Sea (Mallorca Island, Fig. 1) adjacent to extensive meadows of *P. oceanica* (Fig. 1a). *P. oceanica* is the dominant marine coastal ecosystem in sandy Mediterranean coastal areas, with an estimated Mediterranean extension of 50000 km^2 (Bethoux and Copin-Montégut, 1986). The production of *P. oceanica* fluctuates seasonally and this species sheds most of its leaves in late summer and early fall (e.g. Romero et al., 1992).

The topography of Mallorca consists of a high and continuous northwest mountain range and a lower and discontinuous one at the east. Between these two mountain ranges, the island height is fairly homogeneous with an elevated area in the center that determines the shape of the three main basins: Palma at the west, Campos at the southwest and Alcúdia at the northeast. The coastline of the basins has long sandy beaches while beaches in the rest of the island are smaller, in coves surrounded by cliffs. The sand of Mallorca beaches is typically fine, carbonate-rich and biogenic, with bioclasts accounting for 72%–99% of sand particles (Gómez-Pujol et al., 2007).

One selected beach is located in the Alcúdia basin (Son Real) and the other one in the Campos basin (Es Trenc), both placed in natural protected areas (Fig. 1) and representative of the coastal features of each basin. Within each basin, the studied beaches were selected according to the following criteria: (1) seagrass beach-casts are not manually removed along the year (since in touristic areas they are often considered a nuisance and non-aesthetic and are thus removed (De Falco et al., 2008; Roig et al., 2009)); (2) beaches are far from urban or touristic developments to reduce anthropogenic disturbances; and (3) beaches are easy access to perform the measurements.

The beach of Son Real (Fig. 1b) has a northeast orientation and is about 170 m long. It is a sandy beach limited by rocks at both ends. The dune zone is colonized by a mature *Pinus halepensis* forest together with other coastal trees such as *Tamarix* sp and *Juniperus phoenicea*. About 100 m away from the coastline there is a 10 m diameter flat island (Illa des Porros, see location in Fig. 1b) that protects the shore from wind and wave action.

Rocks are also present at both ends of Es Trenc beach (270 m long, Fig. 1c). The backshore of Es Trenc is characterized by a dune system colonized by low grass and typical Mediterranean dune vegetation (*Eryngium maritimum, Pancratium maritimum, Juniperus* sp *phoenicea turbinata, Phillyrea angustifolia and Tamarix* sp.) followed by a *Pinus halepensis* forest. Es Trenc is more exposed to wind and wave action than Son Real because of the low dune vegetation and the absence of near shore geomorphological barriers.

2.2. Beach-cast measurements

Fortnightly measurements of the dimensions of the seagrass beach-cast were performed in the two beaches during the period of February 2013–January 2015. We defined 4 and 5 transects (depending on the extension of the beach-cast) in Son Real and Es Trenc, respectively, perpendicular to the shoreline that were kept fixed during the whole study period (Fig. 2a). The distances between two consecutive transects were measured at the beginning

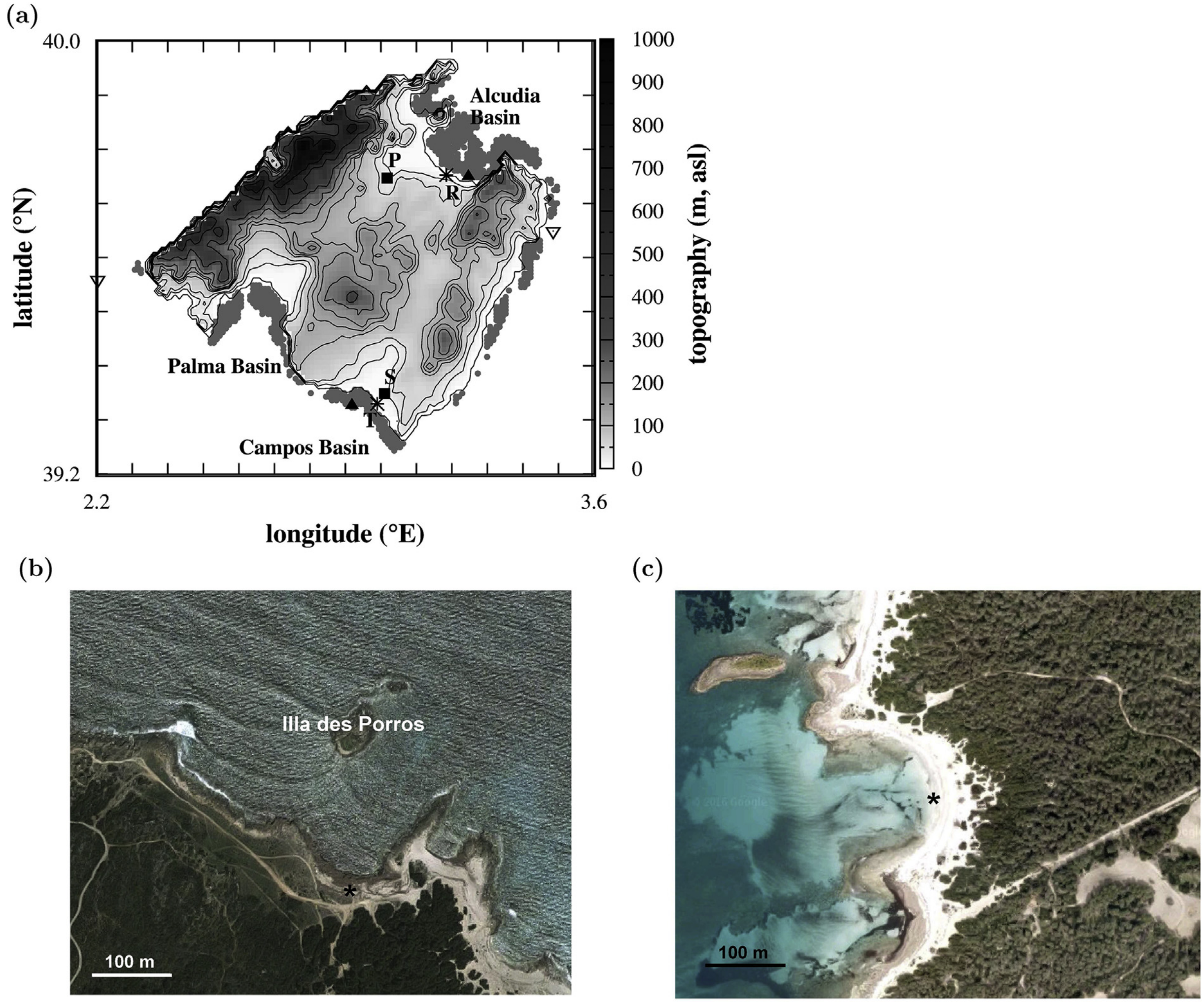

Fig. 1. **(a)** Topography of the island of Mallorca together with the location of the automatic surface weather stations of the Spanish Meteorological Agency (AEMET, in dots) used in this study at Ses Salines and Sa Pobla, indicated with a square and a letter S and P aside, respectively. The beaches where measurements of the dimensions of the beach-cast are made (Son Real and Es Trenc) are indicated with an asterisk (and a letter R and T aside, respectively). The locations of the buoys and SIMAR-44 points (Puertos del Estado) are shown with empty and solid triangles. The grey dots over the sea indicate the seagrass meadows surrounding Mallorca Island. The aerial images (google earth) of the studied beaches are shown in **(b)** and **(c)**, corresponding to Son Real and Es Trenc, respectively (indicated with an arterisc).

of the study ($D_{i,i+1}$ in Fig. 2a). During each sampling event we measured the landward extension of the beach-cast along each transect (d_i, in Fig. 2b) and the height of the beach-cast at the closest to the shoreline end of transects (h_i, in Fig. 2b). In addition, we measured the distance between the easterly and westerly limits of the beach-cast (A and B, respectively, in Fig. 2a) to the nearest transect (D_{5A} and D_{1B}).

2.2.1. Beach-cast volume

From the measured distances (d_i and $D_{i,i+1}$ in m, Fig. 2) and heights (h_i, in m, Fig. 2) we estimated the total volume of the seagrass beach-cast assuming that the volume between two consecutive horizontal transects corresponds to that of a rectangular prism ($V_{prism,i}$ in m^3),

$$V_{prism,i} = area_i \cdot height_i$$

where,

$$area_i = \frac{d_i + d_{i+1}}{2} \cdot D_{i,i+1}$$

and

$$height_i = \frac{h_i + h_{i+1}}{2}$$

In addition, the volume of beach-cast in between the most distal transects and the eastern (or western) limits of the deposit was calculated assuming a square pyramid ($V_{pyramid,A}$, in m^3),

$$V_{pyramid,A} = \frac{area_A \cdot D_{5,A}}{3}$$

where $area_A = d_5 \cdot h_5$ and the same for the western limit (B).

Integrating $V_{prism,i}$ and $V_{pyramid,i}$ over the different horizontal transects (here assuming 5), the total volume of seagrass beach-cast deposit was estimated as

$$V_{all} = V_{pyramid,A} + \sum_{i=1}^{4} V_{prism,i} + V_{pyramid,B}$$

Because only half of the computed volume corresponds to seagrass beach-cast, since the height of the beach-cast is maximum near the coast and decreases (up to zero) in the limits of the beach-cast

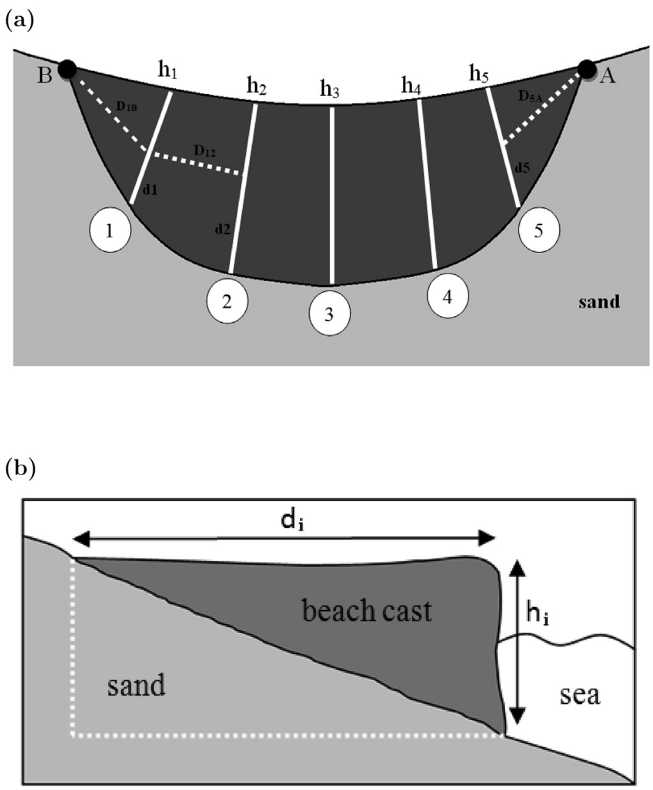

Fig. 2. Measurements of the beach-cast dimensions taken in the two selected beaches every two weeks from February 2013 to December 2014 for (a) horizontal and (b) vertical planes.

(Fig. 2b), the volume of seagrass beach-cast deposit was estimated as,

$$V_{beach-cast} = \frac{V_{all}}{2}$$

2.2.2. Beach-cast density, organic carbon, nitrogen and carbonate concentration

At each studied beach, we collected 3 samples of beach-cast (without sand) close to the shoreline and 3 additional samples close to the dune zone of a volume 25 cm × 13 cm x 8 cm in spring (only in Es Trenc) and summer (in Es Trenc and Son Real). The samples were weighed after drying at 60 °C until constant weight.

We analysed the concentration of total carbon and nitrogen in dried ground subsamples of summer seagrass beach-cast collected at each beach using a CHN auto-analyzer. We measured elemental concentration of beach-cast material only in summer samples because seasonal changes in organic carbon and nitrogen concentration would be negligible given the slow decomposition rates (Mateo et al., 2003; Romero et al., 1992). We similarly analysed the concentration of inorganic carbon in beach-cast samples where organic matter was previously removed by combustion at 550 °C for 4 h. We estimated the concentration of $CaCO_3$ (in %DW) in beach-cast samples by multiplying the concentration of inorganic carbon (% DW) by $CaCO_3$ molecular weight (100.0869 g mol^{-1}) and dividing by that of carbon (12 g mol^{-1}).

2.2.3. Total hydrolyzable amino acid (THAA) analysis, individual molar percentage (mol %) and degradation index (DI)

Samples collected in each location during July 2013 were analyzed for total hydrolyzable amino acid (THAA), molar percentage and degradation index (DI). The measurements were performed by hydrolysis for individual AA using triflouroacetyl/isopropyl ester (TFA) derivatives, following previously published procedures (McCarthy et al., 2007; Silfer et al., 1991). Briefly, 0.5 g of subsamples were hydrolyzed (6N HCl) for 20 h at 110° C. Hydrolysates obtained were filtered, evaporated to dryness under a stream of N_2, and stored in a vacuum desiccator overnight. Individual AA were then converted to TFA derivatives according to a modified protocol after Silfer et al. (1991). After derivatization individual amino acid concentrations and molar percentage (mol%) were measured by gas chromatography coupled to quadrupole mass spectrometry (GC-qMS) an on a Thermo Finnigan system fitted with DPX-5 column (SGE, 50 m, 0.32 mm ID, 1 μm film thickness). Concentrations and molar percentage were measured for alanine (Ala), glycine (Gly), valine (Val), isoleucine (Ile), leucine (Leu), proline (Pro), methionine (Met) and phenylalanine (Phe). Aspargine and glutamine are deaminated during acid hydrolysis protocols, and so are quantified as combined peaks: aspartic acid + Aspargine (Asx) and glutamic acid + Glutamine (Glx). THAA concentration in each sample was calculated as the sum of all identified amino acids divided by the subsample dry weight (mmol g DW^{-1}).

The degradation indexes (DI), proposed by Dauwe and Middelburg (1998), were calculated using all the mol% amino acid composition measured in each sample. DI was determined according to the formula proposed by Dauwe et al. (1999):

$$DI = \sum_i \left[\frac{var_i - AVGvar_i}{STDvar_i}\right] \times fac \cdot coef_i$$

where DI is the degradation index, var_i is the mol percentage of amino acid *i*, AVG var_i and STD var_i are its mean and standard deviation in our data set, and fac.coef.$_i$ the factor coefficient for amino acid *i* based on the first axis from Table 1 in Dauwe et al. (1999). The DI essentially distils the subtle and complex changes in amino acid distributions into one value that decreases with increasing degradation.

2.3. Meteorological data

We used meteorological data provided by AEMET (Spanish Meteorological Agency) from the closest surface weather station to the studied beaches (see locations in Fig. 1a). Specifically, we used wind speed and direction data from the stations of Sa Pobla, 10 km away from Son Real, and Ses Salines, at about 4 km away from Es Trenc (Fig. 1a). Previous studies demonstrated that surface wind conditions at the studied beaches are similar to those observed by the chosen surface weather station (Cuxart et al., 2007, 2014). Under clear-skies and weak-pressure gradient conditions, sea/land breezes are reported during day/night, respectively, with wind directions perpendicular to the coastline. Therefore, both weather stations capture local winds observed in the beaches. On the other

Table 1
Mean values and standard error (N = 6) of the measurements of the Degradation Index (DI) and the concentration of organic carbon (C_{org}), total nitrogen (TN), total hydrolyzable amino acid (THAA), mol% Gly, and carbonates (CaCO3) in *P.oceanica* beach-cast present in summer in two Mallorca beaches (Son Real and Es Trenc).

	SON REAL	ES TRENC
density (kg DW m^{-3})	45 ± 5	39 ± 4
C org (% DW)	34.71 ± 0.47	34.10 ± 0.50
TN (% DW)	0.91 ± 0.05	0.78 ± 0.03
THAA (mmol gDW^{-1})	24.21 ± 4.03	36.49 ± 6.10
mol % Gly (%)	25.63 ± 1.33	24.48 ± 1.08
Degradation Index	0.61 ± 0.27	0.69 ± 0.10
$CaCO_3$ (% DW)	6.46 ± 1.27	3.47 ± 0.32

hand, each weather station is exposed to the same strong large-scale winds as the corresponding beach since both sites are close and within the same basin.

Wind speed and direction at a frequency rate of 10 min were analyzed during two years starting in January 2013 for both surface weather stations. Moreover, the same analysis was done for Ses Salines considering a broader period (2008–2015), the only weather station with available observations back to year 2008.

The wind rose was computed annually and seasonally to determine the wind direction of the most frequent winds and their intensity. The wind rose was built classifying the observations of the wind direction during a certain temporal interval (annually or seasonally) in different groups. In this study, eight categories were taken every 45° corresponding to N (0° or 360°), NE (45°), E (90°), SE (135°), S (180°), SW (225°), W (270°) and NW (315°). The wind rose shows the percentage of the winds that fall in each category. Afterwards, the mean wind speed for each wind direction category was computed. Also, to further explore the wind conditions favourable for beach-cast aeolian transport (Nordstrom et al., 2011), the wind rose was built considering only winds stronger than 6 m s^{-1}.

2.4. Wave data

Wave observations from the Organismo Público Puertos del Estado (OPPE) are only available in Mallorca for two locations (see open triangles in Fig. 1a on the east and west sides of the island). However, these observations were not used here since the features of the waves measured by these buoys are not representative of the ones at the study beaches. Therefore, wave data obtained through numeral modelling by OPPE and AEMET were used, corresponding to the WANA system (starting in 1996 to the present and prior to 1996 it is called SIMAR-44). Modelled hourly data (wave height, frequency and direction among others) were obtained from the coupling of the 10-m wind from the atmospheric model HIRLAM (Navascués et al., 2013) and the WAve Model (WAM, Günther et al., 1992). The WANA closest points to the studied beaches were taken (Fig. 1a) and monthly and annual averaged data were freely downloaded from the OPPE web page. Data analysed here consist of monthly wave height (mean and maximum) and frequency of the annual wave height for each wind direction for the studied years.

Although the winds and waves that influence both beaches are inspected, a deeper analysis has been done for the wind observations because (1) wind data corresponds to measurements whereas wave data are obtained from models, (2) waves are generated by winds and therefore similar results are found from the analysis of both sources of data.

2.5. Estimation of mass balance of the seagrass beach-casts at the shoreline

The amount of seagrass beach-cast annually accumulated and the subsequent amounts exported towards the dune system or back to the sea were estimated by examining the annual mass balance of seagrass litter on the beach. The mass balance considered four contributions (1) the transport from seabed to shore (input); (2) the decomposition; (3) the aeolian transport to backshore and near shore (export), and (4) the net change (residual) and it was expressed by the equation:

$$\text{input} = \text{decomposition} + \text{aeolian transport} + \text{net change}$$

The transport from the seabed to shore (input) was computed from the increments of seagrass beach-cast between the sampling events for the whole study period.

The *in situ* decomposition of the seagrass beach-cast was estimated according to Romero et al. (1992) considering a rate of 0.0066 d^{-1}. We applied this beach-cast decomposition rate to the increment of seagrass litter mass between sampling events as well as to the beach-cast mass remaining on the beach since the previous sampling event. For those sampling periods when the mass decreased, we assumed that only the remaining seagrass beach-cast decomposed. The computed DI (section 2.2.3) informs about the degree of degradation (adimensional) but it is not a rate as the formulation of Romero et al. (1992).

We estimated the aeolian transport (export) of beach-cast towards adjacent terrestrial and marine systems as the amount of seagrass litter lost from the beach between consecutive sampling events for the entire study period. The amount of beach-cast exported was computed on the beach-cast pool remaining after decomposition; despite decomposition losses in between sampling events were small. The fate (i.e. towards adjacent dunes or the sea) of the computed export of seagrass beach-cast was estimated considering the direction and intensity of the prevailing winds.

The net change was computed as the difference between input, decomposition and aeolian transport. If the net change is zero, this indicates that all seagrass litter washed on shore annually goes to decomposition and aeolian transport. If net change differs from zero, the seagrass litter on the beach accretes (positive) or erodes (negative) during the studied years.

The mass balance of *P. oceanica* beach-cast is examined in terms of beach-cast mass (kg DW m^{-1} yr^{-1}), organic carbon (kg C_{org} m^{-1} yr^{-1}), nitrogen (kg N m^{-1} yr^{-1}) and calcium carbonate (kg $CaCO_3$ m^{-1} yr^{-1}). The different components of the mass balance for $C_{org,}$ N and $CaCO_3$ were calculated from beach-cast mass fluxes and beach-cast concentrations of $C_{org,}$ N and $CaCO_3$, respectively.

3. Results

The dimensions of the seagrass beach-cast significantly differed between the two beaches (Fig. 3). Mean heights at Son Real were larger (1.5–2 m) than those at Es Trenc (on average, 1 m). Conversely, the average width of beach-cast deposits was similar at both beaches, although during the periods of maximum accretion deposits could be twice as wide at Es Trenc as Son Real (Fig. 3). The seagrass beach-cast dimensions at Son Real were nearly constant over time whereas those at Es Trenc presented a clear annual cycle with maximum width and height during spring and fall. The shape of the beach-cast deposit at both beaches varied along the year as reflected by the annual variability in the mean value and the standard deviation (Fig. 3). The standard deviation reflects the heterogeneity of the beach-cast deposit height and width along the beach. The width of beach-cast deposit was more heterogeneous at Es Trenc than at Son Real. Conversely, the height at Es Trenc was more homogeneous than in Son Real (Fig. 3).

The mean volume of beach-cast deposit per metre of coastline over the study period was larger at Son Real (6.4 ± 1.7 m^3 m coastline^{-1}) than at Es Trenc (4.9 ± 5.4 m^3 m coastline^{-1}). Provided the density of seagrass beach-cast at each beach (Table 1), the average mass of seagrass litter at Son Real was 292.8 ± 73.2 kg DW m coastline^{-1} whereas it was 209.4 ± 228.6 kg DW m coastline^{-1} at Es Trenc.

Despite the temporal heterogeneity in the shape of the deposit at Son Real (Fig. 3), its volume remained rather constant over the entire study period (Fig. 4a), revealing a redistribution of seagrass litter deposit on the beach over time. On the contrary, the volume and mass of beach-cast deposit on Es Trenc exhibited wide seasonal fluctuations, particularly during 2013 (Fig. 4b). For both years, beach-cast volume and mass on Es Trenc peaked in autumn (between November and December, 20 m^3 m coastline^{-1}, 800 kg DW

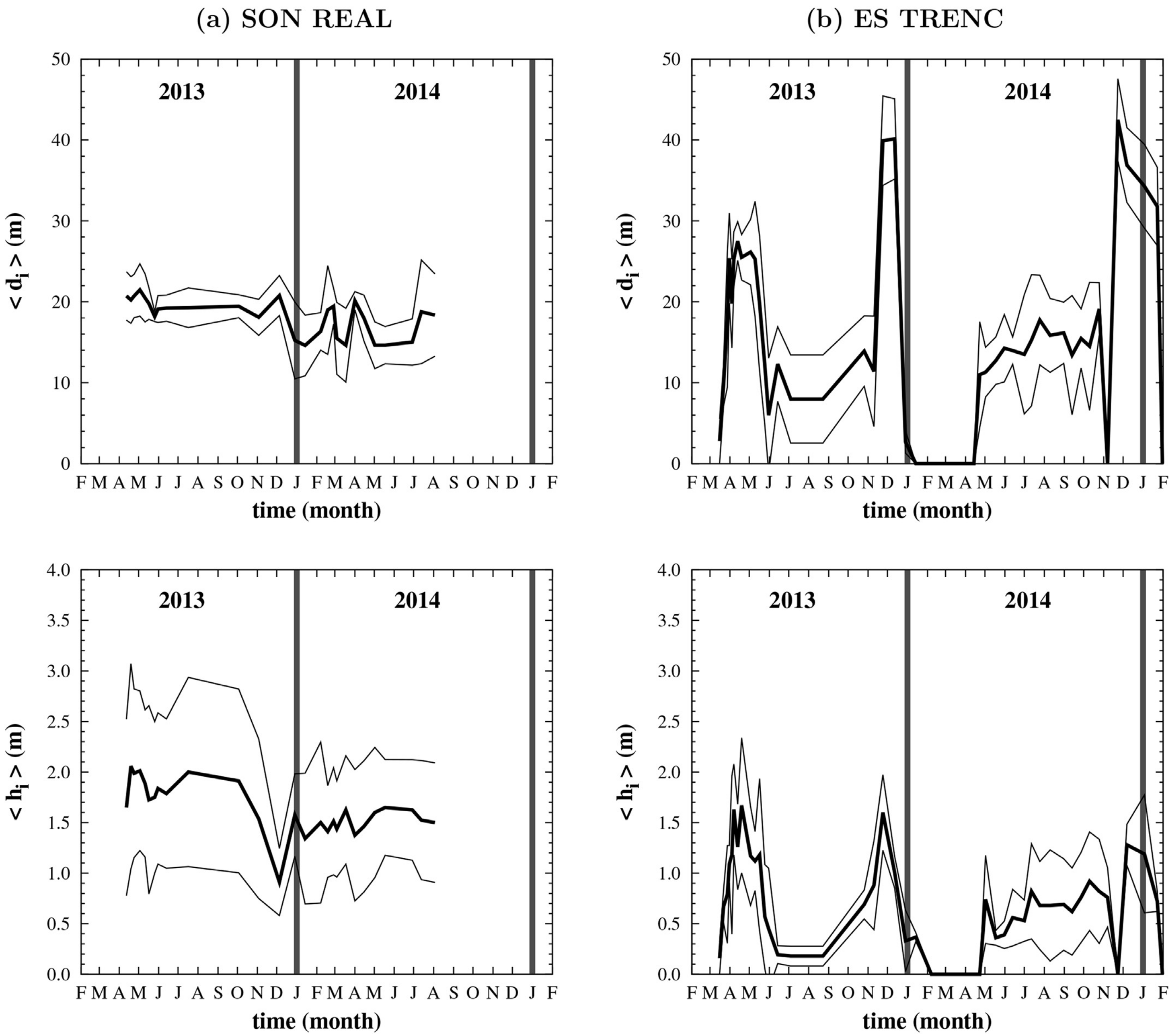

Fig. 3. Measurements of the beach-cast dimensions taken in the two selected beaches (Son Real in the left panel and Es Trenc in the right panel) averaged over the 5 horizontal lines (see definitions in Fig. 2) for: (a) and (b) horizontal extension and (c) and (d) vertical extension. The mean values are in thick lines whereas the standard deviations are shown in thinner lines.

m coastline^{-1}) and spring (about 13 m^3 m coastline^{-1}, 550 kg DW m coastline^{-1}). However, the spring peak was only observed in 2013 and it was weaker and persisted for longer (about 2 months) than those in autumn. During summer of both years, beach-cast volume at Es Trenc showed steady-state conditions, although the volume was zero in 2013 and 4 m^3 m coastline^{-1} (representing 150 kg DW m coastline^{-1}) in 2014.

The organic carbon and total nitrogen concentrations in seagrass litter were similar on both beaches. Conversely, the beach-cast on Son Real had about twice the concentration of carbonates compared to Es Trenc (Table 1). The amount of THAA per dry weight varied between 24 and 36 mmol THAA g DW^{-1}, with values significantly higher at Es Trenc than at Son Real (Table 1). Individual AA mol% composition revealed that the most abundant amino acid was consistently Gly, displaying values of 24.5 ± 1.1% (number of observations N = 6) at Es Trenc and 25.6 ± 1.3% (N = 6) at Son Real (Table 1), followed by Asx, Leu, Ala, and Val, with all values ranging between 11 and 12% in both sample sets. On the contrary Met, Ile and Phe were the most depleted, with values averaging 0.5%, 5% and 6%, respectively. The Degradation Index (DI) ranged between −0.05 and 1.8 and tended to be higher at Es Trenc than at Son Real (Table 1). Considering the whole dataset, Mol % of Gly significantly and inversely correlated with DI (N = 12; $R^2 = 0.4$, $P < 0.05$), whereas mol % of Phe and % of carbonates significantly and positively correlated with DI (N = 12; $R^2 = 0.5$, $P < 0.01$, and N = 12; $R^2 = 0.4$, $P < 0.05$, respectively).

The computed wind rose for Sa Pobla (Fig. 5a) showed a similar wind pattern for 2013 and 2014 with prevailing winds from south and southwest (about 50% of the days of the year) with weak mean wind speeds (2 m s^{-1}). Due to the orientation of Son Real, the wave heights from south and southwest are low and infrequent (Fig. 6a). However, the strongest mean winds (averaged wind speed of

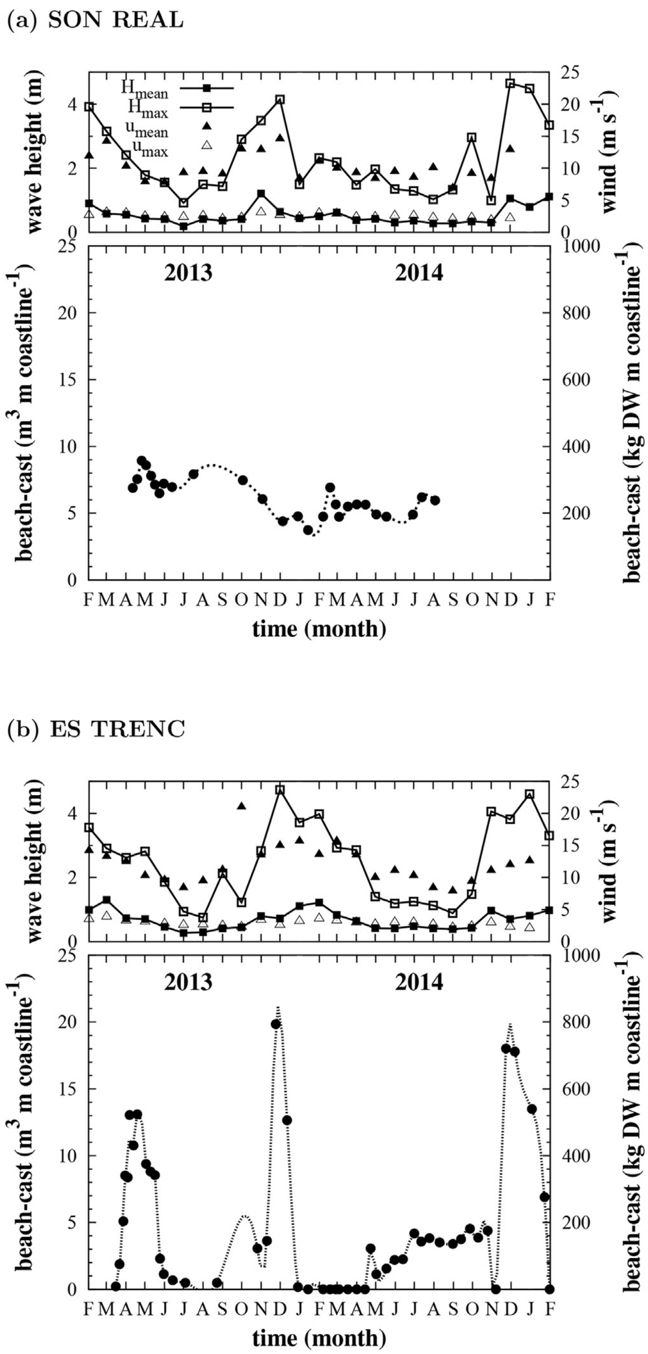

Fig. 4. Temporal evolution of the estimated beach-cast volume (in m^3 m coastline^{-1} and kg DW m coastline^{-1}) for the two studied beaches: (a) Son Real and (b) Es Trenc (see locations in Fig. 1). Observations are marked with points and their corresponding polynomial fits are in dotted lines. In the upper part of both panels there are the temporal evolutions of the monthly mean and maximum wave heights (H_{mean} and H_{max}, respectively, in m) extracted from the closest SIMAR-44 points to the studied beaches (see locations in Fig. 1). The monthly mean and maximum wind speed (u_{mean} and u_{max}, in m s^{-1}) observed in the closest AEMET surface weather station are also included.

4 m s^{-1}, Fig. 5a) were from north. The 10 m-diameter island (Fig. 1b) in front Son Real beach protects it against these northerly waves. The analysis of winds and waves in this beach (Figs. 5a and 6a), together with its topographical features (Fig. 1b) clearly showed its sheltered feature and that the dynamics of the seagrass beach-cast was not linked to wave heights. However, the decrease of the deposit during autumn 2013 might be related to a period of strong winds and, therefore, high mean and maximum waves (top panel in Fig. 4a).

A similar analysis was performed for the observations in Ses Salines (Fig. 5b). The most frequent winds were from northeast and west with mean wind speeds of 2 and 5 m s^{-1}, respectively. The same pattern was found when the wind rose was computed for the period 2008–2014 (Fig. 5b). Waves are also linked to the prevailing winds at Es Trenc, and the most frequent and highest waves are from southwest (Fig. 6b). Thus, due to its orientation, Es Trenc could be considered as an exposed beach and the peaks in the amount of seagrass beach-cast could be attributed to periods of strong winds generating high mean and maximum waves (top panel in Fig. 4b).

The annual wind rose for Es Trenc (Fig. 5b) computed for each season (Figure A in the appendix) showed that during autumn (2013 and 2014) and spring 2013 westerly winds exceeding 6 m s^{-1} were more frequent than in other seasons. Therefore, in autumn and spring the aeolian transport of seagrass litter from the beach to the backshore was enhanced. During summer (Figure A) the prevailing winds were less intense than in the other seasons and the aeolian transport of seagrass beach-cast was zero. The increase of seagrass beach-cast was mainly related to the strong westerly winds (Fig. 7), particularly in spring 2013.

The mass of seagrass litter arriving to the shore at Son Real was 309 kg DW m coastline^{-1} yr^{-1}, one quarter of that arriving at Es Trenc (Fig. 8, Table 2). The amount of seagrass litter decomposed annually on the beaches of Son Real and Es Trenc was similar (Fig. 8). However, the fate of beach-cast to decomposition represented 1.3% of beach-cast annual inputs at Son Real whereas this percentage decreased down to 0.4% at Es Trenc (Fig. 8). The annual export of beach-cast biomass at Son Real (334 kg DW m coastline^{-1} yr^{-1}) exceeded by 29 kg DW m coastline^{-1} yr^{-1} annual seagrass litter input, and thus it was subsidised by seagrass litter accreted on this beach in previous years. The net annual balance of seagrass beach-cast at Es Trenc equalled zero (Fig. 8b). At Es Trenc, 70% of seagrass litter annually arriving on the beach was exported towards the fore dune system whereas 30% returned to the sea. Conversely, only half of the amount of seagrass litter annually washed on Son Real beach was annually exported towards the fore dune (Fig. 8b).

4. Discussion

The prevailing winds at Sa Pobla (from south and southwest, Fig. 5a) can be related to large-scale (synoptical) winds or to the organization at a basin/island scale of the flow at lower levels (land-breeze, Cuxart et al., 2007 or sea-breeze generated in other basins, Cuxart et al., 2014). The strongest northerly winds were probably related to the Mistral (a strong channelled north-westerly wind in the Gulf of Lion, Guenard et al., 2005). Waves in the western Mediterranean are typically generated by the presence of these local winds (Lionello and Sanna, 2005). Similar results are found when the winds and waves are analysed at Ses Salines (Figs. 5b and 6b). The most frequent winds there were from northeast and west that according to the orientation of the Campos basin they can be related to large-scale or to locally-generated winds (land and sea breeze).

There is a good correspondence between the peaks in the amount of seagrass beach-cast at Es Trenc reported during autumn (2013 and 2014) and spring 2013 and the westerly winds exceeding 6 m s^{-1}, the critical wind speed for aeolian transport (Nordstrom et al., 2007). These conditions only were reported about 10% of the days but the wind speed was sufficiently strong to enhance the transport (Fig. 7). The corresponding wind-generated waves can erode the seagrass beach-cast but the litter often remains near the shore and it can be transported back to the beach by the waves (Roig and Martín, 2005). During the decrease of the size of the

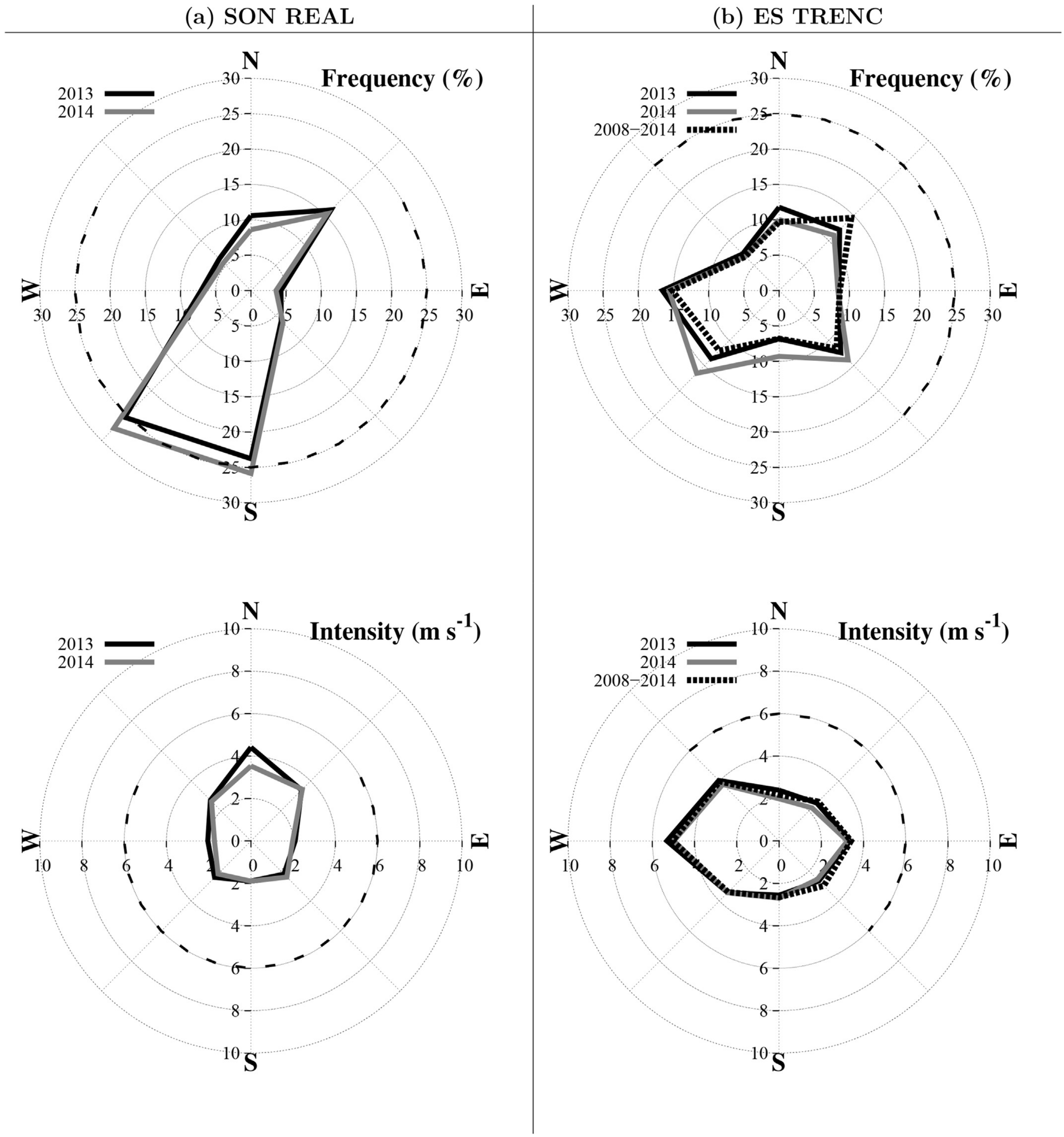

Fig. 5. Annual wind rose computed from the observed 10 min wind (speed and direction) in (a) Sa Pobla and (b) Ses Salines (see locations in Fig. 1) for the studied years 2013 and 2014. In Ses Salines the wind rose during the period 2008–2014 is also included. In the top panel there is the wind frequency (in %) and in the bottom the averaged wind speed for each direction (in m s^{-1}). The dashed black line shows the orientation of the beach.

seagrass beach-cast deposit, westerly winds were the most frequent, contributing to the net transport from the beach to the dunes. However, prevailing winds of other directions occurred and these contributed to the redistribution of seagrass litter among the different transects of the beach (Fig. 2) or enhanced the transport back to the sea (north-easterly winds).

Our results demonstrate that seagrass beach-cast deposits on Mallorca beaches rank amongst the largest reported worldwide (Table 2). This is probably due to beach morphology (sheltered or exposed beaches, Mateo, 2010) as well as to the slow decomposition rate and large size of *P. oceanica* debris (e.g. Romero et al., 1992). In addition, the large accumulations of seagrass beach-cast in Mallorca beaches reflect the large areal extent of *P. oceanica* meadows around the Balearic Islands, estimated at 633 km^2 (Álvarez et al., 2015; see Fig. 1a for the island of Mallorca). The few estimates available in the literature on seagrass beach-cast deposits

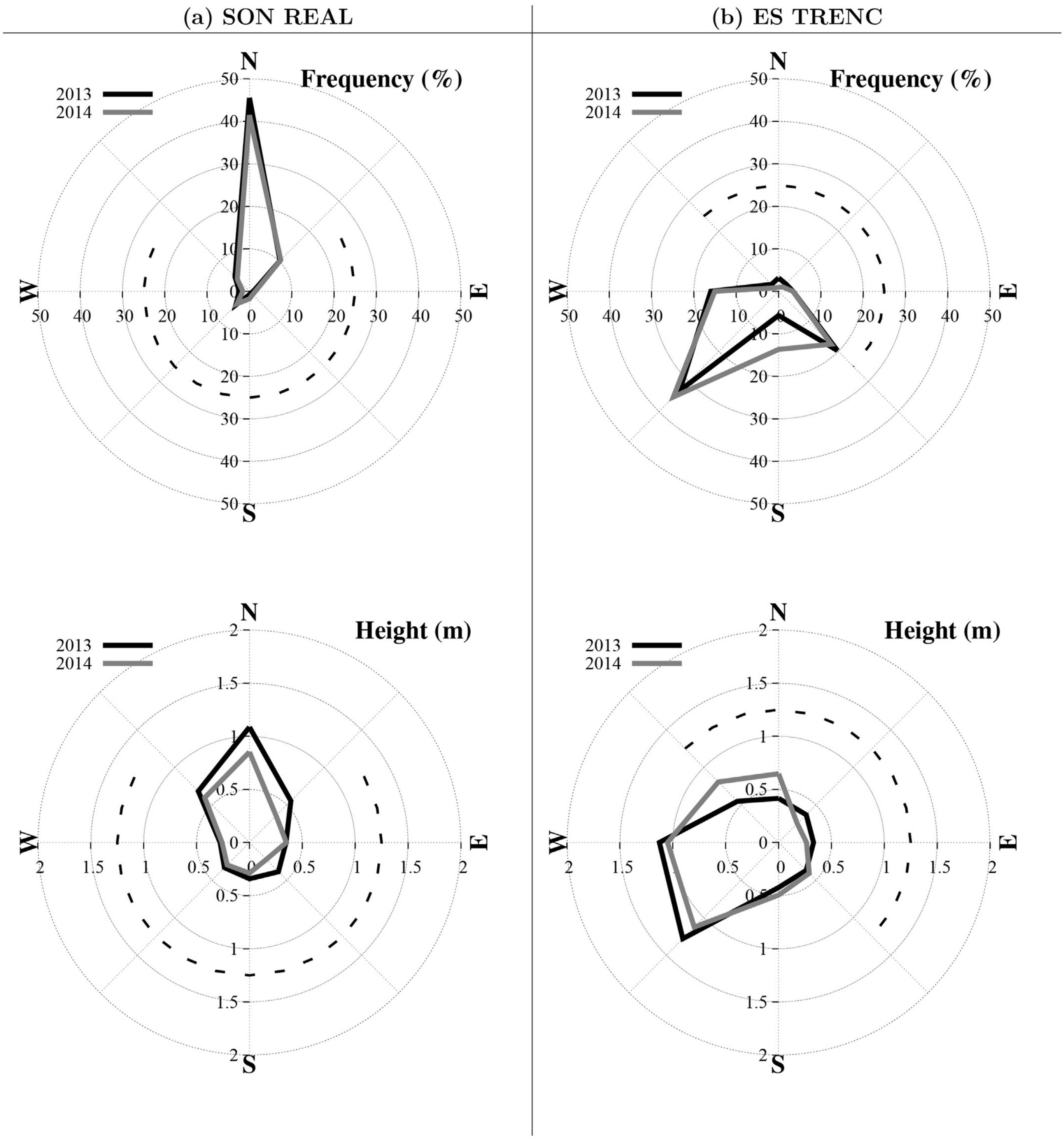

Fig. 6. The same as Fig. 5 but for the mean wave heights extracted from the closest SIMAR-44 points to the studied beaches (see locations in Fig. 1). In the top panel there are the frequency (in %) of the waves for each direction and in the bottom panel the averaged wave height (in m) for each direction. The dashed black line shows the orientation of the beach.

show that *P. oceanica* and *Amphibolis antarctica* may have the largest deposits, suggesting that the size of the deposits might be constrained by seagrass species.

We found that the size of *P. oceanica* beach-cast deposits can exhibit wide seasonal fluctuations and that the magnitude and dynamics of the deposit can be largely constrained by weather conditions (i.e. intensity of prevailing winds and waves) and coastal morphological features. Indeed, the island in front of the beach and the backshore pine forest at Son Real protects the beach from the wave action and the strongest and prevailing winds. This limits the transport of seagrass litter from the sea to the beach, resulting in a nearly constant amount of seagrass beach-cast during the two study years. Our results show that protected beaches are able to accumulate large amounts of seagrass litter that can persist over time, in agreement with findings by De Falco et al. (2008) on Sardinia Island. By contrast, Es Trenc is more exposed to the environment conditions; the periods with larger seagrass beach-cast deposits in this beach are linked to the highest wave heights and stronger winds, in both cases from the southwest direction.

The phenology of *P. oceanica* drives the seasonal fluctuations of seagrass beach-cast deposits. The rapid increase of the beach-cast volume between November and December at Es Trenc occurs when *P. oceanica* renews and sheds most of its leaves (Romero et al., 1992). During this period, a large amount of shed seagrass leaves in the seabed are available for transportation to the shore. Part of the shed leaf material, however, remains in the seabed until next spring if favourable wind and wave conditions transport it towards the beach, as observed at Es Trenc in 2013 and in Sardinia (De Falco et al., 2008; Simeone et al., 2013). Inspecting the period 1970–2014, the wave patterns observed in 2013 were also reported in 1975, 1978, 1981, 1988, 2001 and 2008. This indicates that the spring peak in Es Trenc is not a common feature of this beach although it is reported for several years for the last 44 years (1970–2014) without exhibiting a clear frequency. The leaf litter deposited on the beach in spring contains smaller plant fragments than in fall because they have been travelling along the seabed for a longer time (Beltran et al., 2016; personal data; Simeone et al., 2013). Therefore, the critical wind speed to trigger aeolian transport (from the beach to backshore or to the sea) would be lower in spring than in the fall.

Amino acids, a critical substrate for microbial growth (Keil et al., 2000), were examined in the form of THAA and derived parameters. Although the organic carbon content in seagrass litter was similar in both beaches, the significantly higher value of THAA content at Es Trenc suggests the presence of a fresher organic matter pool compared to the Son Real deposit. Accordingly, there was a tendency for lower DI values and higher molar percentage of glycine at Son Real. As the accumulation of glycine is associated with diagenetically altered organic matter (Dauwe et al., 1999; Calleja et al., 2013; Fernandes et al., 2014), these results reveal a higher degradation or decomposition stage in Son Real deposits, indicative of older material, than in Es Trenc deposits. The DI values measured in this study fell within the range and were occasionally higher than those previously observed for coastal and margin sediments (−0.5 to 1.5, Dauwe et al., 1999; Fernandes et al., 2014) that are important sites of organic matter burial and degradation, and indicates that *P. oceanica* beach deposits at both study sites were undergoing microbial degradation. The DI trends and percentage of glycine isolated from the seagrass beach-cast deposits appear to be a potential tool to evaluate its lability and degradation stage.

The most energetic waves and storms can erode the seagrass beach-cast (Gómez-Pujol et al., 2013) but these events are both related to the wind and wave intensity. Under these conditions, the seagrass litter remains in the nearshore and it can be transported

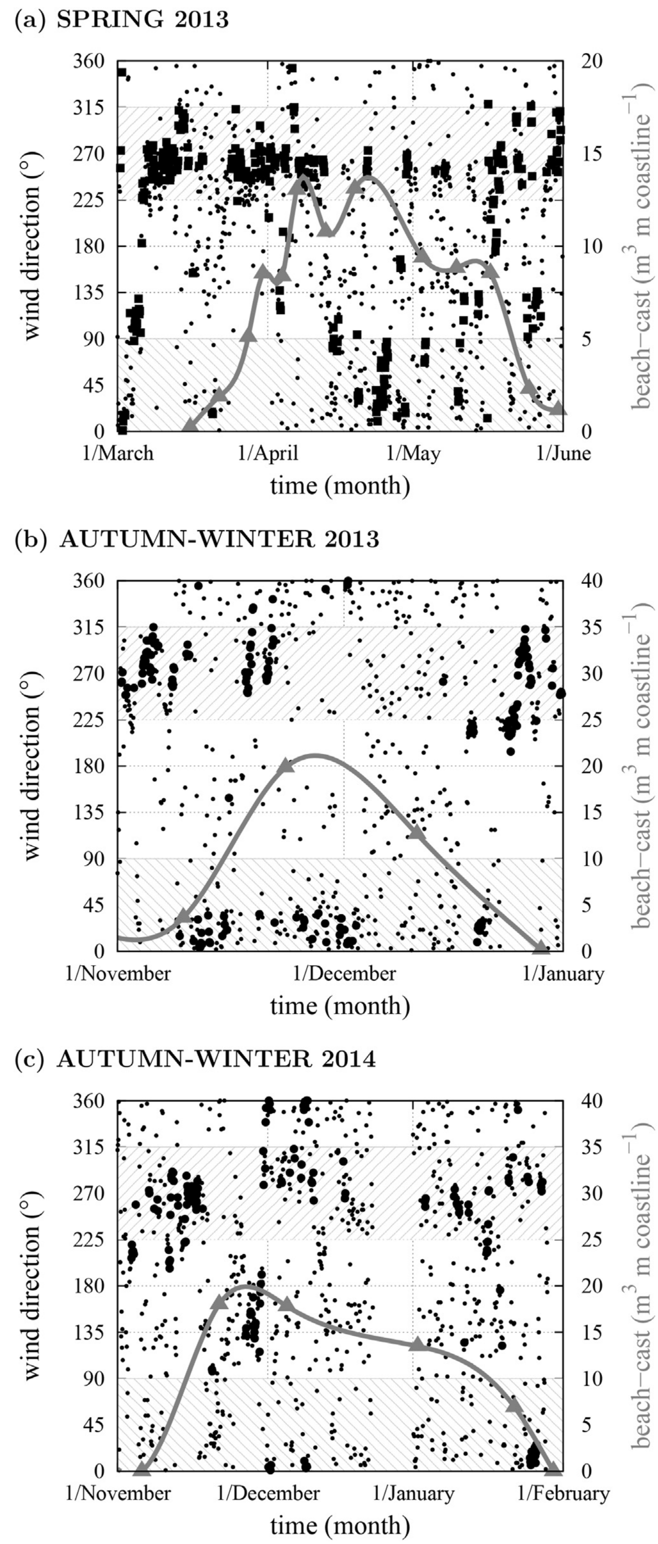

Fig. 7. Observed wind direction in Ses Salines during (a) spring 2013 and autumn-winter (b) 2013 and (c) 2014 maximum values of the seagrass beach-cast (seen in Fig. 4b). Larger points indicate winds stronger than 6 m s^{-1} and the shaded areas indicate the wind direction from land to sea (0-90°) and from sea to land (225-315°). The grey line and triangles represent the beach-cast volume (following the Y-axis on the right), extracted from Fig. 4.

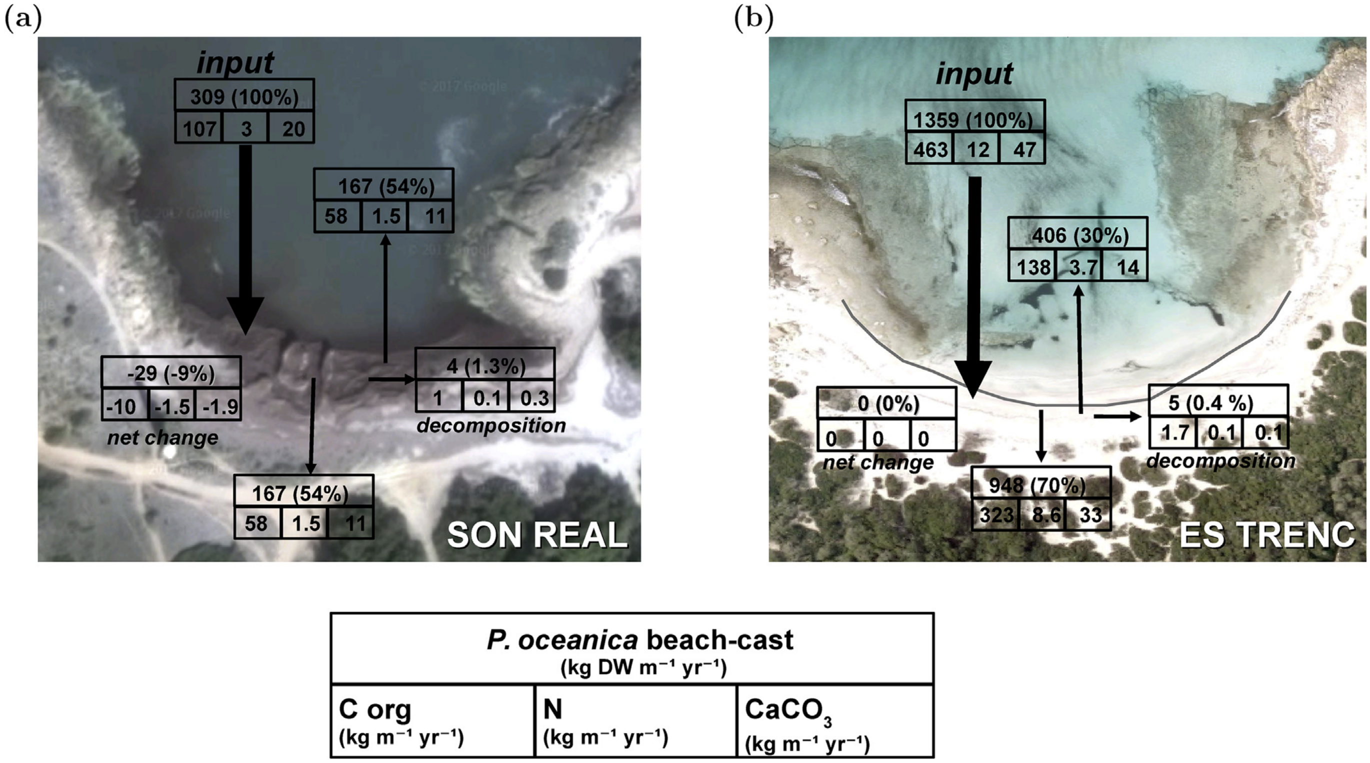

Fig. 8. Schematic representation of the mass transport of seagrass beach-cast on the shoreline in (a) Son Real and (b) Es Trenc together with the corresponding aerial pictures (google earth). The units of the numbers are indicated in the boxes and the percentages are referred to the input of seagrass beach-cast. The grey line at Es Trenc indicates the coastline.

Table 2
Size of seagrass beach-cast deposits and annual amounts of seagrass litter washed on shore reported worldwide, including our findings.

number of beaches	site	type of seagrass	m^3 m coastline^{-1}	kg DW m coastline^{-1}	kg DW yr^{-1} m coastline^{-1}	reference
4	Corsica & Sardinia (Italy)	*Posidonia oceanica*	1.3–15.3			Chessa et al. (2000)
44	Sardinia (Italy)	*Posidonia oceanica*	0.4–4.2	37–390		De Falco et al. (2008)
116	Sardinia (Italy)	*Posidonia oceanica*	0.8–2.9			Simeone and De Falco (2013)
3	Sardinia (Italy)	*Posidonia oceanica*	0.4–12.5			Simeone and De Falco (2012)
1	Tabarca (Spain)	*Posidonia oceanica*		18–500		Mateo et al. (2003)
6	Tarragona (Spain)	*Cymodocea nodosa*		4.9	3–15	Mateo (2010)
2	Gran Canaria (Spain)	*Cymodocea nodosa*		0–7		Portillo (2014)
3	Mombasa (Kenya)	*Thalassodendron ciliatum, Syringodium isoetifolium*		10	0.7	Ochieng and Erftemeijer (1999)
1	Bosttman (Germany)	*Zostera marina*		0–3	0.4*	Hammann and Zimmer (2014)
10	Barkley Sound (BC, Canada)	*Zostera marina, Phyllospadix* spp		0–3.5	140**	Orr et al. (2005)
1	Oakajee (Western Australia)	*Posidonia sinuosa, Amphibolis antartica*	0–2			Wells (2002)
1	Perth (Western Australia)	species not indicated			900–1800	Kirkman and Kendrick (1997), Orr et al. (2005)
1	Son Real (Mallorca)	*Posidonia oceanica*	4–9	200–350	309	current study
1	ES Trenc (Mallorca)	*Posidonia oceanica*	0–18.5	0–800	1359	current study

back to the beach by waves (Roig and Martín, 2005). This effect is indirectly included in the wind analysis (highest waves are linked to strongest winds). Nevertheless, storms are not frequent in the Balearic Islands, except for winter and autumn (Romero et al., 1999), and instantaneous rain, which could enhance erosion, is not large. This suggests that storm effects should be considered when assessing instantaneous mass balance of seagrass beach cast (Gómez-Pujol et al., 2013) but not when it is computed on time series with observation frequency is 15 days as in our study.

The results of our study reveal that the high productivity of *P. oceanica* meadows could subsidize the functioning of adjacent terrestrial systems. Considering the nitrogen contained in the beach-cast exported to the dune system and the length of the beach, *P. oceanica* meadows deliver 0.26 Mg N yr^{-1} and 1.81 Mg N yr^{-1} to the adjacent dunes at Son Real and Es Trenc, respectively. The nitrogen supplied by *P. oceanica* to the dune system could contribute to fulfil the nutrient requirements of dune vegetation. Indeed, stable isotope analysis conducted on camephytes, geophytes, and C3 perennial grasses growing on the coastal dune systems of Menorca (Balearic Island, Western Mediterranean) revealed that beach-cast *P. oceanica* material was a relevant source of nitrogen for the vegetation of Mediterranean foredunes (Cardona and García, 2008). Similarly, a recent experimental study demonstrated that dune plants sowed in soil enriched with *P. oceanica* beach-cast grow faster and have higher N tissue concentrations than those growing in non-enriched soils (Del Vecchio et al., 2013). Moreover, part of *P. oceanica* beach-cast nitrogen - together with substantial amounts of organic carbon and labile amino acid molecules - exported to the dune system could subsidize the dune food webs (Heck et al., 2008).

Our mass balance of beach-cast also reveals that *P. oceanica* is an important source of calcium carbonate, and thus sand, for the beach and/or the dune system. Annually, *P. oceanica* delivers a total of 2.2 Mg Ca CO_3 yr^{-1} (13 kg m^{-1} yr^{-1}) and 7 Mg Ca CO_3 yr^{-1} (33 kg m^{-1} yr^{-1}) that remains on land (beach and dunes) at Son Real and Es Trenc, respectively. The amount of calcium carbonate annually supplied by *P. oceanica* beach-cast in the studied beaches ranks within the low range of the amounts of sand artificially delivered during beach restoration programs in the Balearic Islands in order to fulfil tourism demands since 1977 which later intensified in the 1990's (Barón et al., 2008). Our results demonstrate that the provision of sand by *P. oceanica* meadows to the beaches of the Balearic Islands is large. The role of *P. oceanica* meadows as a sand source in the Balearic Islands is particularly relevant since this region is characterized by permeable carbonate margins where fluvial inputs are lacking and sedimentary particles are of biogenic origin (Canals and Ballesteros, 1997). In addition to supplying sand to the adjacent beaches, *P. oceanica* beach-cast deposits also physically prevent beach erosion by absorbing sea wave energy during storms.

In summary, our results demonstrate that seagrass beach-cast deposits are highly dynamic, and the combined inspection of the estimated beach-cast volume and the weather conditions identifies that aeolian transport is an important mechanism driving beach-cast dynamics. However, if the natural environment (vegetation, geomorphology) of the nearby surroundings protects the beach from weather conditions, the amount of beach-cast is nearly stationary for any of the observed wind speeds and directions. The presented methodology to analyze the seagrass beach-cast dynamics can be easily applied to other beaches in Mallorca or at other sites. Atmospheric observations, together with the observations of the dimensions of the seagrass beach-cast allow for the understanding of physical mechanisms involved in the transport of seagrass beach-cast from the sea to the coast and from the coast back to the sea or further inland, depending on the environmental conditions. Our study demonstrates that *P. oceanica* meadows supply significant amounts of materials, including nutrients, carbon and sand to adjacent emerged systems such as beaches and dunes. Only a small fraction of *P. oceanica* litter decomposes on the beach itself although beach-cast decomposition is larger on protected beaches, with nearly stationary beach-cast deposits, than exposed beaches. This finding is also supported by the results of THAA, derived parameters, and DI values. Therefore, conservation of this key Mediterranean marine ecosystem is vital to support the functioning of the entire coastal zone.

Author contribution

Authorship should be restricted to those who have contributed substantially to the work in one or more of the following categories:

- MAJ, RB, AT, MLLC and NM Designed study
- MAJ, RB, AT, MLLC, ADH and NM Performed research
- MAJ, MLLC and NM Analyzed data
- MAJ, AT, MLLC and NM Wrote the paper

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Appendix

In order to further analyze the role of the wind on the seasonal dynamics of beach-cast deposits, we computed a wind rose for the periods when the largest changes in the amount of beach-cast were detected at Es Trenc (Fig. 4b). Those periods are November-December (autumn), March-May (spring) and June-August (summer). During autumn (Figure Aa), the prevailing winds were from west and southwest, consistent with the direction of the waves with mean heights of about 1 m (ranging between 0.2 and 5 m, data not shown). These findings agree with those previously reported by Gómez-Pujol et al. (2013). According to the beach orientation, winds enhance the transport of seagrass leaves from the seabed towards the seashore. In addition, these winds were stronger than those from other directions for any year within the period 2008–2014. During November-December, westerly winds exceed 6 m s^{-1}, the critical wind speed for aeolian transport (Nordstrom et al., 2007), 7% of the period (i.e. 4.3 days, Figure Aa). These strong south and westerly winds are also responsible for transport of seagrass litter from the beach to the backshore, whereas the north and northeasterly winds transport seagrass beach-cast back to the sea at Es Trenc.

The wind rose computed for spring (Figure Ab) showed that the prevailing winds in 2013 were from southwest and west, with 10% of the time of the period with wind speeds larger than 6 m s^{-1} (Fig. 7b). Due to the orientation and exposure of the Es Trenc, west and southwest winds are responsible of the transport of the seagrass litter from the seabed towards the beach. However, the prevailing winds in 2014 were weaker than in 2013 and from northeast and the southern sector. As a result, the transport of leaves from the seabed to the seashore was reduced in 2014 and a distinct peak in the amount of beach-cast was not observed (Fig. 4b). Inspecting the wave features from the closest WANA point (not shown), 50% of the waves in 2013 were from west and southwest with mean heights of 1 m whereas this percentage declined to 40% in 2014 and the mean wave height was 0.5 m.

During summer (Figure Ac) the prevailing winds were from northeast and southwest, corresponding to the land-breeze and sea-breeze directions. The waves were mainly from southeast but much lower (on average less than 1 m, not shown) in comparison to the other seasons. On average, these winds were weak and the net transport of seagrass beach-cast in summer time was zero. However, at shorter temporal scales transport from/to the sea/land can take place, as it is reported in Gómez-Pujol et al. (2013), but it was not captured by our bi-monthly observations. Southeastern winds were also frequent and slightly more intense than the breeze winds but they did not significantly contribute to the beach-cast transport due to the beach orientation (Fig. 1c and Ac).

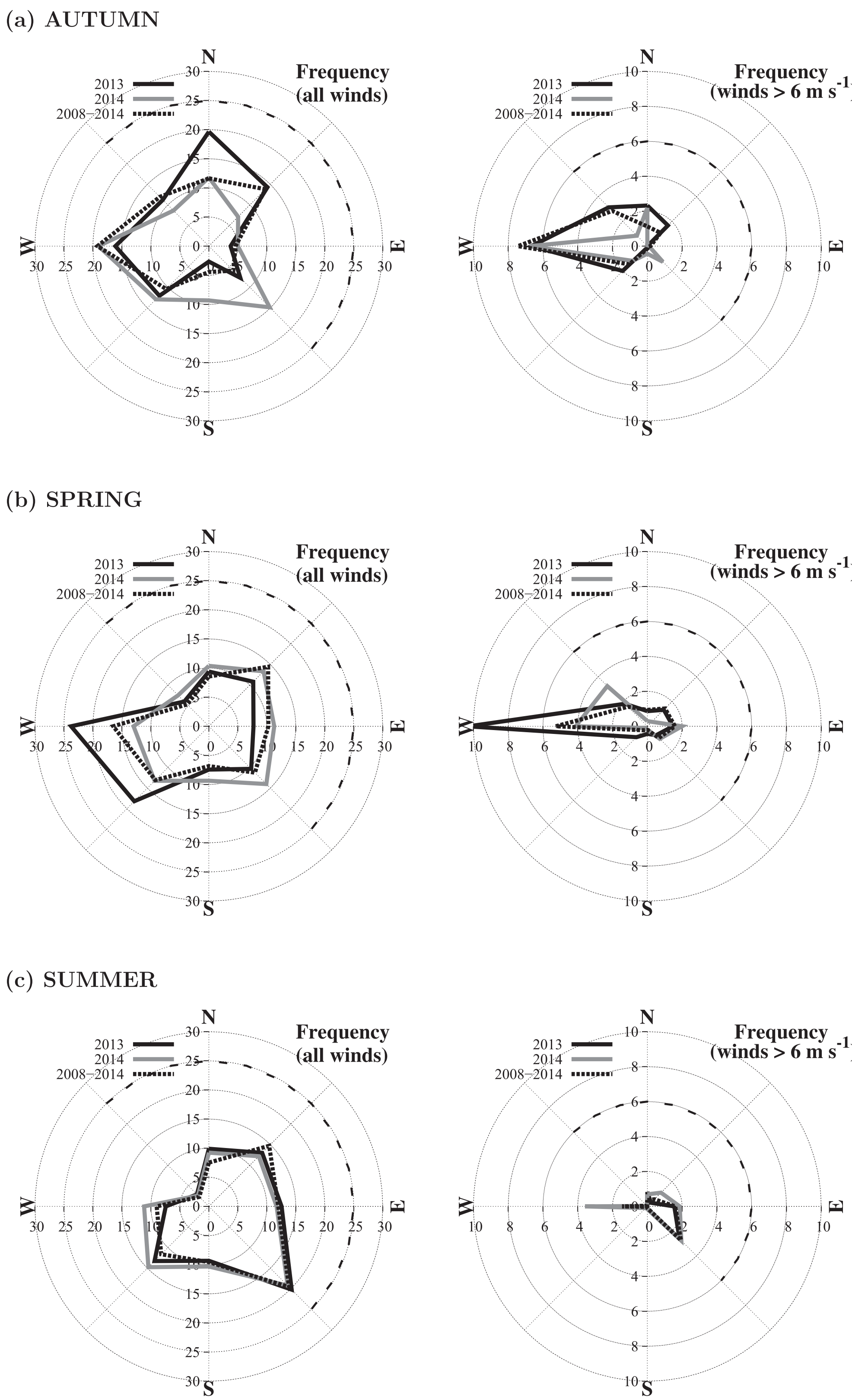

Figure A. Comparison of the wind rose for 2013, 2014 and 2008–2014 in Ses Salines for some selected months: (a) autumn (November and December), (b) spring (March, April and May) and (c) summer (June, July and August). On the left all observed wind speeds are taken whereas on the right only those larger than 6 m s^{-1}. The dashed black line shows the orientation of the beach.

References

Almar, R., Coco, G., Bryan, K.R., Huntley, D.A., Short, A.D., Senechal, L., 2008. Video observation of beach cusps morphodynamics. Mar. Geol. 254, 216–223.

Álvarez, E., Grau, A.M., Marbà, N., Carreras, D., 2015. Islas Baleares. Atlas de praderas marinas de España. In: Ruiz, J.M., Guillén, J.E., Otero, M.M., Ramos, A. (Eds.), IEO/IEL/UICN, pp. 179–220.

Barón, A., Orozco, F., Reviriego, B., Pozo, M., Alomar, G., Mir, M., 2008. Análisis detallado de presiones en aguas costeras de las Islas Baleares. Gov. Balearic Isl. http://www.caib.es/sacmicrofront/contenido.do?mkey=M0808011112185729323%26lang%2dCA%26cont%3d38397.

Bethoux, J.P., Copin-Montégut, G., 1986. Biological fixation of atmospheric nitrogen in the Mediterranean Sea. Limnol. Oceanogr. 31, 1353–1358.

Boudouresque, C.F., Meinesz, A., 1982. Découverte de l'herbier de Posidonie, 4, Hyères, Cahier Parc National de Port-Cros, p. 79.

Calleja, M.Ll, Batista, F., Peacock, M., Kudela, R., McCarthy, M.D., 2013. Changes in compound specific δ^{15}N amino acid signatures and D/L ratios in marine dissolved organic matter induced by heterotrophic bacterial reworking. Mar. Chem. 149, 32–44.

Canals, M., Ballesteros, E., 1997. Production of carbonate particles by phytobenthic communities on the Mallorca-Menorca shelf, northwestern Mediterranean Sea. Deep-Sea Res. II 44, 611–629.

Cardona, L., García, M., 2008. Beach-cast seagrass material fertilizes the foredune vegetation of Mediterranean coastal dunes. Acta Oecol. 34, 97–103.

Cavaleri, L., 2005. The wind and wave atlas of the Mediterranean Sea - the calibration phase. Adv. Geosciences 2, 255–257.

Chessa, L.A., Fustier, V., Fernandez, C., Mura, F., Pais, A., Pergent, G., Serra, S., Vitale, L., 2000. Contribution to the knowledge of 'banquettes' of *Posidonia oceanica* (L.) Delile in Sardinia island. In: Pergent, G., Pergent-Martini, C., Buia, M.C., Gambi, M.C. (Eds.), Proceedings 4th International Seagrass Biology Workshop, vol. 2. Biologia Marina Mediterranea, Corsica France, pp. 35–38.

Colombini, I., Chelazzi, L., 2003. Influence of marine allochthonous input of sandy beaches communities. Oceanogr. Mar. Biol. Annu. Rev. 41, 115–159.

Coupland, G.T., Duarte, C.M., Walter, D.I., 2007. High metabolic rates in beach-cast communities. Ecosystems 10, 1341–1350.

Cuxart, J., Jiménez, M.A., Telišman-Prtenjak, M., Grisogono, B., 2014. Study of a sea-breeze case through momentum, temperature and turbulence balances. J. Appl. Meteorology Climatol. 53, 2589–2609.

Cuxart, J., Jiménez, M.A., Martínez, D., 2007. Nocturnal meso-beta basin and katabatic flows on a midlatitude island. Mon. Weather Rev. 135, 918–932.

Dauwe, B., Middelburg, J.J., 1998. Amino acids and hexosamines as indicators of organic matter degradation state in North Sea sediments. Limnol. Oceanogr. 43 (5), 782–798.

Dauwe, B., Middelburg, J.J., Herman, P.M.J., Heip, C.H.R., 1999. Linking diagenetic alteration of amino acids and bulk organic matter reactivity. Limnol. Oceanogr. 44 (7), 1809–1814.

De Falco, G., Simeone, S., Baroli, M., 2008. Management of beach-cast *Posidonia oceanica* seagrass on the island of Sardinia (Italy, western mediterranean). J. Coast. Res. 69–75, 24–4A.

Del Vecchio, S., Marbà, N., Acosta, A., Vignolo, C., Traveset, A., 2013. Effects of *Posidonia oceanica* beach-cast on germination, growth and nutrient uptake of coastal dune plants. PLoS One 8 (7), e70607.

Duarte, C.M., 1990. Seagrass nutrient content. Mar. Ecol. Prog. Ser. 67, 201–207.

Duarte, C.M., Middelburg, J.J., Caraco, C., 2005. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2, 1–8.

Duarte, C.M., Chiscano, C.L., 1999. Seagrass biomass and production: a reassessment. Aquat. Bot. 65 (1–4), 159–174.

Fernandes, L., Garg, A., Dnyandev, V.B., 2014. Amino acid biogeochemistry and bacterial contribution to sediment organic matter along the western margin of the Bay of Bengal. Deep Sea Res. Part I Oceanogr. Res. Pap. 83, 81–92.

Gómez-Pujol, L., Orfila, A., Álvarez-Ellacuría, A., Terrados, J., Tintoré, J., 2013. *Posidonia oceanica* beach-caster litter in Mediterranean beaches: a coastal video-monitoring study. J. Coast. Res. 65 (2), 1768–1773.

Gómez-Pujol, L., Orfila, A., Cañellas, B., Alvarez-Ellacuria, A., Méndez, F.J., Medina, R., Tintoré, J., 2007. Morphodinamic classification of sandy beaches in low energetic marine environment. Mar. Geol. 242, 235–246.

Guénard, V., Drobinski, P., Caccia, J.-L., Campistron, B., Bénech, B., 2005. An observational study of the mesoscale mistral dynamics. Boundary-Layer Meteorol. 115, 263–288.

Günther, H., Hasselmann, S., Janssen, P.A.E.M., 1992. The WAM Model Cycle 4. Report number 4, Deutsches Klimareschenzentrum (available from Deutsches Klimareschenzentrum Bundesstr 55 D-20146, Hamburg, Germany), p. 102.

Hammann, S., Zimmer, M., 2014. Wind-driven dynamics of beach-cast wrack in a tide-free system. Open J. Mar. Sci. 4, 68–79.

Heck Jr., K.L., Carruthers, T.J.B., Duarte, C.M., Hughes, A.R., Kendrick, G.A., Orth, R.J., Williams, S.W., 2008. Trophic transfers from seagrass meadows subsidize diverse marine and terrestrial consumers. Ecosystems 11, 1198–1210.

Hemminga, M.A., Nieuwenhuize, J., 1991. Transport, deposition and in situ decay of seagrasses in a tropical mudflat area (Banc d'Arguin, Mauritania). Neth. J. Sea Res. 27 (2), 183–190.

Hemminga, M.A., Nieuwenhuize, J., 1990. Seagrass wrack-induced dune formation on a tropical coast (Banc d'Arguin, Mauritania). Estuar. Coast. Shelf Sci. 31, 499–502.

Holmer, M., Duarte, C.M., Marbà, N., 2003. Sulfur cycling and seagrass (*Posidonia oceanica*) status in carbonate sediments. Biogeochemistry 66, 223–239.

Jeudy de Grissac, A., 1984. Effets des herbiers a *Posidonia oceanica* sur la dynamique marine et la sédimentologie littorale. In: Boudouresque, C.F., Jeudy de Grissac, A., Oliver, J. (Eds.), International Workshop on Posidonia Oceanica Meadows, vol. 1. GIS Posidonie Publ. Fr, pp. 437–443.

Keil, R., Tsamakis, E., Hedges, J., 2000. Early diagnosis of particulate amino acids in marine systems. In: Goodfriend, G.A., Collins, M.J., Fogel, M.L., Macko, A.A., Wehmiller, J.F. (Eds.), Perspectives in Amino Acids and Protein Geochemistry. Oxford University Press.

Kirkman, H., Kendrick, G.A., 1997. Ecological significance and commercial harvesting of drifting and beach-cast macro-algae and seagrasses in Australia: a review. J. Appl. Phycol. 9, 311–326.

Lavery, P.S., McMahon, K., Weyers, J., Boyce, M.C., Oldham, C.E., 2013. Release of dissolved organic carbon from seagrass wrack and its implications for trophic connectivity. Mar. Ecol. Ser. 494, 121–133.

Lionello, P., Sanna, A., 2005. Mediterranean wave climate variability and its link with NO and the Indian Monsoon. Clim. Dyn. 25, 611–623.

Mateo, M.A., 2010. Beach-cast *Cymodocea nodosa* along the shore of a semienclosed bay: sampling and elements to assess its ecological implications. J. Coast. Res. 26 (2), 283–291.

Mateo, M.A., Cebrián, J., Dunton, K., Mutchler, T., 2006. Carbon flux in seagrass ecosystems. In: Larkum, A.W.D., Orth, R.J., Duarte, C.M. (Eds.), Biology, Ecology and Conservation. Springer, The Netherlands, pp. 157–191. Seagrasses:

Mateo, M.A., Sánchez-Lizaso, J.-L., Romero, J., 2003. *Posidonia oceanica* "banquettes": a preliminary assessment of the relevance for meadow carbon and nutrients balance. Estuar. Coast. Shelf Sci. 56, 85–90.

McCarthy, M.D., Benner, R., Lee, C., Fogel, M.L., 2007. Amino acid isotopic fractionation patterns as indicators of heterotrophy in plankton, particulate, and dissolved organic matter. Geochimica Cosmochimica Acta 71, 4727–4744.

Navascués, B., et al., 2013. Long-term verification of HIRLAM and ECMWF forecasts over southern Europe: history and perspectives of numerical weather prediction at AEMET. Atmosheric Res. 125–126, 20–33.

Nieto, M.A., Garau, B., Balle, S., Simarro, G., Zarruk, G.A., Ortiz, O., Tintoré, J., Álvarez-Ellacuría, A., Gómez-Pujol, L., Orfila, A., 2010. An open source, low cost video-based coastal monitoring system. Earth Surfarce Process. Landforms 35, 1712–1719.

Nordstrom, K.F., Jackson, N.L., Korotky, K.H., 2011. Aeolian sediment transport across beach wrack. J. Coast. Res. 59, 211–217.

Nordstrom, K.F., Jackson, N.L., Hartman, J.M., Wong, M., 2007. Aeolian sediment transport on a human-altered foredune. Earth Surf. Process. Landforms 32, 102–115.

Ochieng, C.A., Erftemeijer, P.L.A., 1999. Accumulation of seagrass beach-cast along the Kenyan coast: a quantitative assessment. Aquat. Bot. 65, 221–238.

Orr, M., Zimmer, M., Jelinski, D.E., Mews, M., 2005. Wrack deposition on different beach types: spatial and temporal variation on the pattern of subsidy. Ecology 86 (6), 1496–1507.

Portillo, E., 2014. Relation between the type of wave exposure and seagrass losses (*Cymodocea nodosa*) in the south of Gran Canaria (Canary Islands-Spain). Oceanol. Hydrobiological Stud. 43, 29–40.

Ray, G.C., Hayden, P., 1992. Coastal zone ecotones. In: Hansen, A.J., di Castri, F. (Eds.), Landscape Boundaries: Consequences of Biotic Diversity and Ecological Flows. Springer, New York, pp. 403–420.

Roig, F.X., Rodriguez-Perea, A., Martin-Prieto, J.A., Pons, G.X., 2009. Soft management of beach-dune systems as a tool for their sustainability. J. Coast. Res. 56, 1284–1288.

Roig, F.X., Martín, J.A., 2005. Effects of retreat of vegetable berms of *Posidonia oceanica* on beaches of the Balearic Islands: consequences of the touristic pressure. Investig. Geográficas, Bol. Investig. Geográficas 57, 40–52. UNAM, ISSN 0188-4611.

Romero, R., Ramis, C., Guijarro, J.A., 1999. Daily rainfall patterns in the Spanish Mediterranean area: an objective classification. Int. J. Climatol. 19, 95–112.

Romero, J., Pergent, G., Pergent-Martini, C., Mateo, M.A., Regnier, C., 1992. The dentritic compartment in a *Posidonia oceanica* Meadow: litter features, decomposition rates, and mineral stocks. Mar. Ecol. 13, 69–83.

Silfer, J.A., Engel, M.H., Macko, S.A., Jumeau, E.J., 1991. Stable carbon isotope analysis of amino acid enantiomers by conventional isotope ratio mass spectrometry and combined gas chromatography/isotope ratio mass spectrometry. Anal. Chem. 63, 370–374.

Simeone, S., De Falco, G., 2013. *Posidonia oceanica* banquette removal: sedimentological, geomorphological and ecological implications. J. Coast. Res. 65, 1045–1050.

Simeone, S., De Falco, G., 2012. Morphology and composition of beach-cast *Posidonia oceanica* litter on beaches with different exposures. Geomorphology 151–152, 224–233.

Simeone, S., De Muro, S., De Falco, G., 2013. Seagrass berm deposition on a Mediterranean embayed beach. Estuar. Coast. Shelf Sci. 135, 171–181.

Vacchi, M., De Falco, G., Montefalcone, M., Morri, C., Ferrari, M., Bianchi, C.N., 2016. Biogeomorphology of the Mediterranean *Posidonia oceanica* seagrass meadows. Earth Surf. Process. Landforms 42 (1), 42–54.

Wells, F.E., 2002. Seasonality of beachwrack at Oakajee in the mid-west region of Western Australia. Rec. West. Aust. Mus. 21, 269–275.