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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