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Long-term responses of sandy beach crustaceans to the effects of coastal armouring after the 2010 Maule earthquake in South Central Chile

Iván F. Rodil [a,b,c,*], Eduardo Jaramillo [d], Emilio Acuña [d], Mario Manzano [e], Carlos Velasquez [e]

[a] Interdisciplinary Centre of Marine and Environmental Research (CIIMAR/CIMAR), University of Porto, Porto, Portugal
[b] Tvärminne Zoological Station, University of Helsinki, Hanko, Finland
[c] Baltic Sea Centre, Stockholm, University, Stockholm, Sweden
[d] Instituto de Ciencias de la Tierra, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile
[e] Escuela de Graduados, Facultad de Ciencias, Universidad Austral de Chile, Valdivia, Chile

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ABSTRACT

Earthquakes and tsunamis are large physical disturbances frequently striking the coast of Chile with dramatic effects on intertidal habitats. Armouring structures built as societal responses to beach erosion and shoreline retreat are also responsible of coastal squeeze and habitat loss. The ecological implications of interactions between coastal armouring and earthquakes have recently started to be studied for beach ecosystems. How long interactive impacts persist is still unclear because monitoring after disturbance generally extends for a few months. During five years after the Maule earthquake (South Central Chile, February 27th 2010) we monitored the variability in population abundances of the most common crustacean inhabitants of different beach zones (i.e. upper, medium, and lower intertidal) at two armoured (one concrete seawall and one rocky revetment) and one unarmoured sites along the sandy beach of Llico. Beach morphology changed after the earthquake-mediated uplift, restoring upper- and mid-shore armoured levels that were rapidly colonized by typical crustacean species. However, post-earthquake increasing human activities affected the colonization process of sandy beach crustaceans in front of the seawall. Lower-shore crab *Emerita analoga* was the less affected by armouring structures, and it was the only crustacean species present at the three sites before and after the earthquake. This study shows that field sampling carried out promptly after major disturbances, and monitoring of the affected sites long after the disturbance is gone are effective approaches to increase the knowledge on the interactive effects of large-scale natural phenomena and artificial defences on beach ecology.

1. Introduction

Sandy beaches are natural dynamic ecosystems that are becoming increasingly disturbed around the world by intensive human direct use, coastal development and erosive evolution (Defeo et al., 2009; Dugan et al., 2010). Beaches are also threatened by intense and transformative major disturbances, such as sea level rise, large storms, beach nourishment (e.g. Hughes et al., 2009; Lucrezi et al., 2010; Peterson et al., 2014; Witmer and Roelke, 2014), and in some regions by mega-earthquakes/tsunamis (e.g. Jaramillo, 2012; Lomovasky et al., 2011; Mascarenhas and Jayakumar, 2008; Seike et al., 2013; Urabe et al., 2013). The most common response to coastal erosion, shoreline retreat, extreme storms and/or tsunamis is to build coastal defences (Nordstrom, 2000). Paradoxically, armouring accelerates beach erosion, leading to decreases in beach width and intertidal habitat constraining upper-shore communities to such a narrow width that regular inhabitants of these zones are no longer able to establish, resulting in loss of biodiversity (Dugan et al., 2008; Jaramillo et al., 2012a, 2012b; Lucrezi et al., 2010; Rodil et al., 2015).

Sandy beaches located on seismically active areas, such as the coast in South Central Chile, are periodically affected by coseismic coastal deformation and tsunamis, due to large subduction earthquakes (Ruegg et al., 2009). On February 27th 2010, the Maule earthquake (Mw 8.8) hit Chile along the central-southern coast (ca. 33–38°S) resulting in coastal coseismic uplift of up to 2.0 m at several locations in Península de Arauco (ca. 37°S) (Vargas et al., 2011). Coastal ecosystems were strongly affected by the devastating action of the coastal uplift, as well as by the associated tsunami, with consequences for intertidal communities suddenly exposed to drastic changes such as air exposure (Castilla et al., 2010; Jaramillo et al., 2012a, 2012b; Ortega et al., 2014). The coastal uplift associated with the earthquake caused an increase of the total sandy beach width in some locations that resulted in a significant expansion of the upper and mid-intertidal habitats

* Corresponding author at: Tvärminne Zoological Station, University of Helsinki, Hanko, Finland.
E-mail addresses: ifrodil@gmail.com, ivan.rodil@helsinki.fi (I.F. Rodil).

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potentially available for colonization by macrofauna (Jaramillo et al., 2012a, 2012b).

Physical disturbance is a key factor in structuring infaunal communities and its effect upon beach ecological communities depends on the nature, intensity and frequency of such disturbance (e.g. Defeo et al., 2009; Hughes et al., 2009; Jaramillo et al., 2012a). Previous studies that have focused on the effects of large disturbances have reported a wide range of responses of the resident beach biota (e.g. Jaramillo et al., 2012a, 2012b; Leewis et al., 2012; Lucrezi et al., 2010; Schlacher et al., 2012). This is partly due to the haphazard nature of such events, but mainly because there is often no pre-disturbance community data available, making difficult to assess the effects of such a disturbance (Hughes et al., 2009). Furthermore, the ecological responses of macrofauna to an extreme disturbance event will depend on a suite of factors, including previous conditions of the impacted sites and surrounding areas, features of the biota, seasonality, and the characteristics of the disturbance itself (Hughes et al., 2009; Jaramillo et al., 2012a; Peterson et al., 2014).

The ecological implications of interactions between coastal armouring and major earthquakes have recently started to be studied for beach ecosystems (e.g. Jaramillo et al., 2012a, 2012b; Rodil et al., 2015). For instance, the effects of coastal uplift and armouring in earthquake-affected beaches from Península de Arauco (Chile) included restoration of upper and mid-intertidal habitats seaward of armouring structures followed by rapid colonization of mobile crustaceans typical of these zones, such as talitrid sand hoppers formerly excluded by constraints imposed by the coastal defences (Jaramillo et al., 2012a, 2012b). Simultaneously, the uplift of rocky subtidal substrate generated by the Maule earthquake eliminated low intertidal habitat for ecologically important beach species such as the crustacean anomuran *Emerita analoga* (Jaramillo et al., 2012a, 2012b; Veas et al., 2013). However, monitoring beyond a few months after the disturbance is rarely performed, so little is known of long-term effects (e.g. >3 years) to beach ecosystems (see Leewis et al., 2012; Peterson et al., 2014). Therefore, most of the studies on beach ecological responses to large disturbances show difficulties in separating natural fluctuations in macrofauna diversity from disturbance induced effects. Consequently, there is a little understanding of how beach fauna recovers after an extreme disturbance (Hughes et al., 2009; Peterson et al., 2014).

The use of armoured defences in coastal areas is expected to increase in the near future in response to a combination of expanding human populations, increasing subsidence and beach erosion, periodical occurrence of catastrophic events and global sea level rise (e.g. Dugan et al., 2008; Nordstrom, 2014; Ruegg et al., 2009). The Chilean coast experiences recurrent large subduction earthquakes (Moreno et al., 2010; Vargas et al., 2011) and major coastal development with accompanying armouring structures (Jaramillo, 2012). Since armoured beaches are thought to be more vulnerable to disturbances than natural unarmoured beaches (Castelle et al., 2008; Dugan et al., 2008; Lucrezi et al., 2010) the potential exists for stronger negative ecological effects of coastal armouring and earthquakes. In this research, we examined the long-term responses of beach crustaceans (representing the highest percentage of beach macrofauna) to the combined effects of armouring and the emergence of a new upper-shore habitat following the Maule earthquake at the sandy beach of Llico (Península de Arauco, Chile). The typical beach macroinfaunal zones were sampled a few weeks prior to the earthquake in front of two armouring sites and one adjacent unarmoured site. After the earthquake, we surveyed repeatedly, from 2010 to 2015, the crustacean community at the same sites to measure changes in beach habitat (i.e. beach face slope and intertidal width) and biota caused by the earthquake-mediated coastal uplift. Specifically, we wanted to examine the direct effect of the coseismic uplift on the population abundances of the main beach macrofaunal species, and whether shore-armouring influence the long-term responses of those species to a large earthquake event.

2. Material and methods

2.1. Location, sites and sampling design

This study was conducted at the sandy beach of Llico (37°11′38″ S, 73°33′44″ W), on the northern coast of Península de Arauco in South Central Chile (Fig. 1). Tidal range was close to 1.0 m (i.e. microtidal). Continental uplift at this location during the Maule earthquake was approximately 2.0 m (Moreno et al., 2010; Vargas et al., 2011). The coastal uplift associated with the earthquake at Llico caused a large increase of the total beach width up to 12.5 times (Jaramillo et al., 2012b). The study area included two sites located in front of armoured sections of the beach located on the western and eastern sides of a jetty (Figs. 1–2). The site located west of the jetty is in front of a concrete seawall while that located on the eastern side is in front of a rocky revetment (Figs. 1–2). The armouring structures were located low enough on the beach profile to interact with waves during high tides (Fig. 2). The third study site was an unarmoured section of the beach located nearly 350 m east of the armoured sites (Figs. 1–2). In terms of the morphodynamic beach state (sensu Short and Wright, 1983), before the earthquake, the sites in front of the revetment and the seawall were close to a reflective state (i.e. narrow beaches having coarse sands and steep slopes), while the beach site was close to an intermediate state (i.e. wider beaches having fine to medium sand with gentle slopes). After the earthquake, the three sites were close to an intermediate sate.

We started surveying the intertidal zones at the three beach sites in late January 2010. We sampled invertebrate crustaceans (i.e. the most abundant macrofauna in this beach) retained on a 1 mm sieve (Schlacher et al., 2008) setting up four replicated shore-normal transects 5 m apart from each other, extending from the upper intertidal to the low tide level of sites located in front of the seawall, the rocky revetment and in the unarmoured beach site. Along these transects we sampled each of the three typical beach faunal zones dominated by crustaceans along sandy beaches of South Central Chile (McLachlan and Jaramillo, 1995): i) the upper zone occupied primarily by the talitrid amphipod *Orchestoidea tuberculata* Nicolet, 1849, usually extending from the toe of the dunes to a limit located around the drift line or high tide level, ii) the mid zone occupied by two cirolanid isopod species, *Excirolana braziliensis* Richardson 1912 and *Excirolana hirsuticauda* Menzies, 1962, extending from the drift line to the effluent line, and iii) the lower zone occupied primarily by the anomuran crab *E. analoga* (Stimpson, 1857), extending from the effluent line to the lowest tide level. Five core samples of sediments were collected at each of the three faunal zones with a metal cylinder (10 cm in diameter) to a depth of 30 cm at equally spaced levels across the zone, for a total sampling area of 0.04 m^2 per zone on each transect. The five core samples from each zone and transect were pooled and sieved through a 1 mm sieve and the collected organisms were stored in 10% formalin in sea water until laboratory sorting. Following the Maule earthquake on the 27th of February 2010, intertidal surveys as described above were repeated at each of the three sites during seventeen more sampling dates in 2010 (April, July and September), 2011 (January, March, August and November), 2012 (February, May, August and October), 2013 (February, July and December), 2014 (July and November), and 2015 (January). To ensure temporal independence of samples, the position of the first transect was randomly determined within each site on each sampling date, with the other three transects laid out at fixed five m distances away.

Beach width was measured as the distance in metres, between the landward boundary of the beach defined by the toe of foredune or armouring structures and the low tide level during spring tides. The beach face slope was measured at each of the four transects of each site using the method of Emery (Emery, 1961). Beach face slope was expressed as 1/x, where x was the distance in metres at which a height difference of 1 m between two consecutive intertidal levels is reached.