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# A comparison of the impact of ‘seagrass-friendly’ boat mooring systems on *Posidonia australis*

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## ABSTRACT

Permanent boat moorings have contributed to the decline of seagrasses worldwide, prompting the development of ‘seagrass-friendly’ moorings. We contrasted seagrass cover and density (predominantly *Posidonia australis*) in the vicinity of three mooring types and nearby reference areas lacking moorings in Jervis Bay, Australia. We examined two types of ‘seagrass-friendly’ mooring and a conventional ‘swing’ mooring. ‘Swing’ moorings produced significant seagrass scour, denuding patches of ~9 m radius. Seagrass-friendly ‘cyclone’ moorings produced extensive denuded patches (average radius of ~18 m). Seagrass-friendly ‘screw’ moorings, conversely, had similar seagrass cover to nearby reference areas. Our findings reinforce previous work highlighting the negative effects of ‘swing’ and ‘cyclone’ moorings. In contrast, the previously unstudied ‘screw’ moorings were highly effective. We conclude that regular maintenance of moorings and the monitoring of surrounding seagrass are required to ensure that ‘seagrass-friendly’ moorings are operating effectively. This is important, as following damage *Posidonia* will take many decades to recover.

## 1. Introduction

Seagrass meadows are considered a pivotal marine habitat and provide important ecosystem services (Costanza et al., 1997). Seagrass meadows make significant contributions to coastal productivity worldwide (Orth et al., 1984) and their primary production ranks amongst the highest recorded for marine ecosystems (Hillman et al., 1989). They also support dis-proportionately high levels of biodiversity (Hemminga and Duarte, 2000) providing habitat, food and shelter to a diverse array of organisms (Beck et al., 2001). Seagrasses are particularly important in sustaining commercial and recreational fisheries (Heck et al., 2003; Gillanders, 2006) and it is likely that damage to seagrass will diminish stocks of important commercial and recreational fish, molluscs and crustaceans (Bell and Pollard, 1989; Butler and Jernakoff, 1999; McArthur and Boland, 2006). Seagrass meadows also support a large number of rare and threatened species, many of which relying on seagrass habitat for survival (Short et al., 2011).

Despite the importance of seagrass, it has been in significant decline worldwide and this appears to have accelerated over recent decades (Short and Wyllie-Echeverria, 1996; Waycott et al., 2009). One-third of the world’s seagrass species are in decline with 10 species having a high risk of extinction (Short et al., 2011). Between 1985 and 1995, approximately 1,200,000 ha of seagrass meadow have been lost globally (Short and Wyllie-Echeverria, 2000). In Australia, seagrass meadows have suffered extensive declines in several states in the past (Shepherd et al., 1989; Walker and McComb, 1992).

Seagrass loss has been attributed to a broad spectrum of anthropogenic and natural disturbances (Duarte, 2002) with direct mechanical damage one of the key anthropogenic disturbances (Short and Wyllie-Echeverria, 1996; Duarte, 2002; Ceccherelli et al., 2007; Waycott et al., 2009). Permanent boat moorings are one of the main causes of mechanical disturbance to seagrass, almost always producing scoured areas within seagrass meadows (Walker et al., 1989; Hastings et al., 1995; Montefalcone et al., 2008). These moorings are often highly concentrated across many of the world’s embayments, especially on densely inhabited coastlines, and so represent a large-scale press disturbance (Bender et al., 1984). These impacts will likely increase with the need for more vessel moorings worldwide (Duarte et al., 2008). This threat is heightened as both seagrasses and vessel anchorages favour locations with reduced water movement and wave-action, hence the siting of mooring locations is often in places where seagrass occurs. The

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state of New South Wales has recognised these declines and has sought to counteract seagrass loss with legislative protection under the *NSW Fisheries Management Act, 1994*. This legislation states that seagrass may not be cut, removed, damaged or destroyed except under the authority of a permit system which is strictly managed (NSW Department of Primary Industries, 2010). This kind of legislative protection has resulted in the need to develop ‘seagrass-friendly’ moorings and still provide mooring opportunities for the burgeoning recreational boating community.

Several ‘seagrass-friendly’ mooring systems have been developed worldwide. Nevertheless, to date, we are aware of just two published assessments of the effectiveness of purported ‘seagrass-friendly’ moorings, both of these on ‘cyclone’ moorings (Walker et al., 1989; Hastings et al., 1995). This is surprising as the ability of the mooring systems not to harm seagrass is central to their intended use and without an appropriate assessment it would seem that the claim of ‘seagrass-friendly’ moorings remains unsubstantiated.

To provide moorings for the growing numbers of vessels in Jervis Bay (Australia), the Jervis Bay Marine Park in conjunction with the Southern Rivers Catchment Management Authority trialled the use of ‘seagrass-friendly’ ‘screw’ moorings. Several private ‘screw’ moorings were also installed. All of these moorings were installed between January 2008 and July 2009 (Frances Clements, Jervis Bay Marine Park Permitting Officer, pers. comm.). Also present within the marine park were a series of ‘cyclone’ moorings that are also considered ‘seagrass-friendly’ (Walker et al., 1989); installed by private mooring owners. This study presents a quantitative assessment of the effectiveness of the newly designed and never previously assessed ‘seagrass-friendly’ ‘screw’ moorings and older ‘seagrass-friendly’ ‘cyclone’ moorings.

Specifically, we compared patterns of seagrass density and cover (*Posidonia australis*, *Halophila ovalis* and *Zostera* spp.) surrounding these ‘seagrass-friendly’ designs (Fig. 1) relative to conventional ‘swing’ moorings and reference areas lacking moorings. We tested the general prediction that both kinds of ‘seagrass-friendly’ moorings (‘screw’ and ‘cyclone’) would have greater densities and coverage of seagrass in their vicinity than the conventional ‘swing’ moorings. Reference areas were used in order to quantify the effectiveness of the moorings relative to the background conditions of the seagrass which can differ due to environmental conditions and past anthropogenic disturbance. This represents the first published study to examine the effect of ‘screw’ moorings on seagrass condition.

## 2. Materials and methods

### 2.1. Study area

Seagrass was sampled adjacent to three types of moorings and reference areas in Jervis Bay Marine Park. Jervis Bay is an open embayment of approximately 12,400 ha situated on the south eastern Australian coast. *P. australis* is the prevalent seagrass species in Jervis Bay with extensive meadows totalling 5.7 km$^2$ in depths of 2–10 m (West, 1990). These meadows constitute the largest continuous areas of this species along Australia’s south eastern coast (Meehan and West, 2000), and are considered some of the most pristine seagrass meadows on this coastline (West et al., 1989; Kirkman et al., 1995).

Callala Bay (35°00’S 150°43’E) and Bindijine Beach (35°03’S 150°46’E) (See Fig. 1 in Fyfe and Davis, 2007) possess permanent boat moorings and were selected as study areas. At the time of the

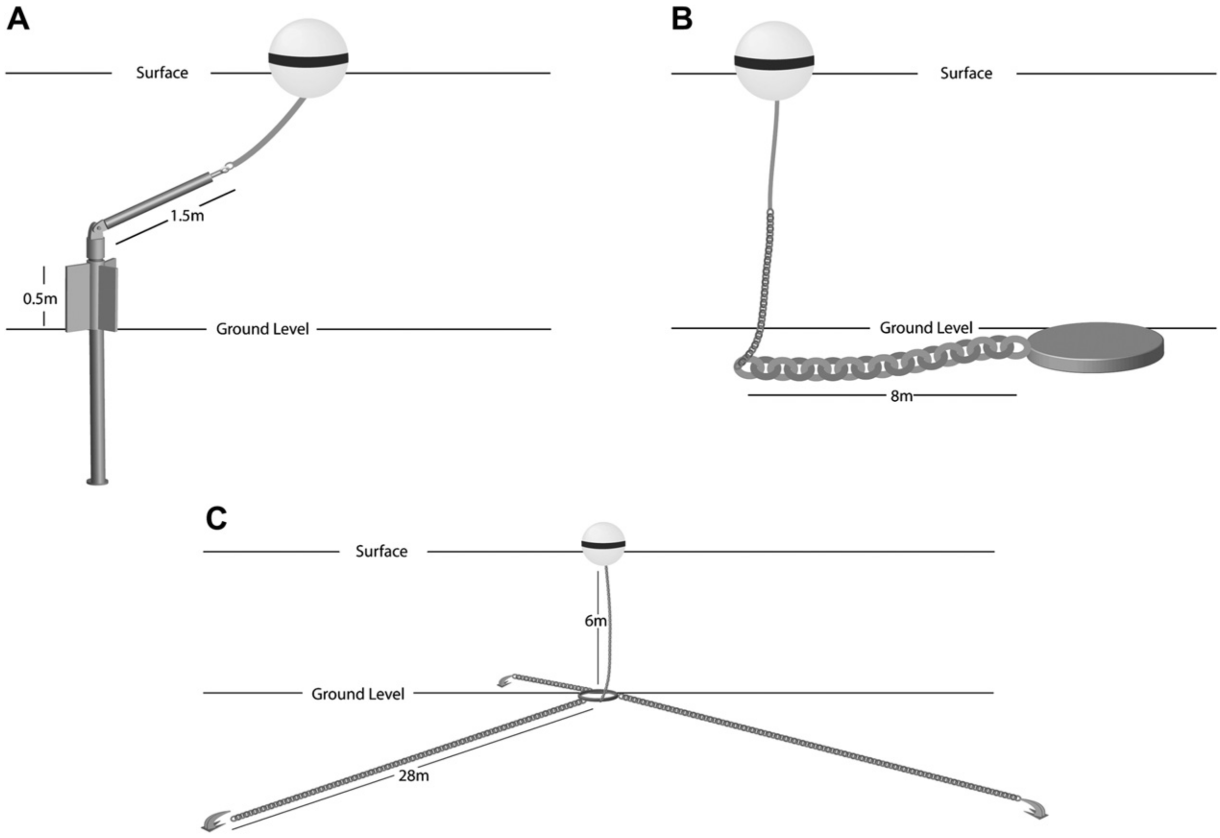

**Fig. 1.** Schematic representation of a typical (**A**) ‘screw’ mooring system, (**B**) ‘swing’ mooring system and (**C**) ‘cyclone’ mooring system.

study, Callala Bay had approximately 5 'screw' moorings, 5 'cyclone' moorings and 60 'swing' moorings (Frances Clements, Jervis Bay Marine Park pers. comm). Moorings have been present in Callala Bay for over 30 years and almost all of them are located in *P. australis* meadow, over a depth range of 3–6 m. Previous research has shown that the seagrass at Callala Bay has suffered substantial damage from boat moorings (Fig. 2A, Crawford, 2003). The level of damage done to the seagrass at Callala Bay presented a complex background over which to objectively assess the effects of permanent mooring systems. In contrast, Bindijine Beach had 3 'screw' moorings installed in June 2009 (Frances Clements, Jervis Bay Marine Park pers. comm.). This location has virtually no history of boat mooring (Crawford, 2003) and the seagrass meadow was relatively pristine.

### 2.2. Seagrass species

The seagrass species present in the meadows of Jervis Bay include *P. australis, H. ovalis and Zostera* spp. *P. australis* Hook.f. is a slow growing horizontal spreader with slow rhizome expansion and colonisation rates (Gobert et al., 2006). For this reason, *Posidonia* does not generally recover once disturbed (Clarke and Kirkman, 1989) or recovers very slowly (Meehan and West, 2000). *H. ovalis* (R.Br.) Hook. and the taxonomically difficult to separate *Zostera* spp. are pioneer species of smaller size and rapid growth rates (Birch and Birch, 1984; Marbá and Duarte, 1998). They have the ability to recolonise disturbed areas and may initiate a sequence of succession (Clarke and Kirkman, 1989; Duarte et al., 2006; Montefalcone et al., 2010). This implies that

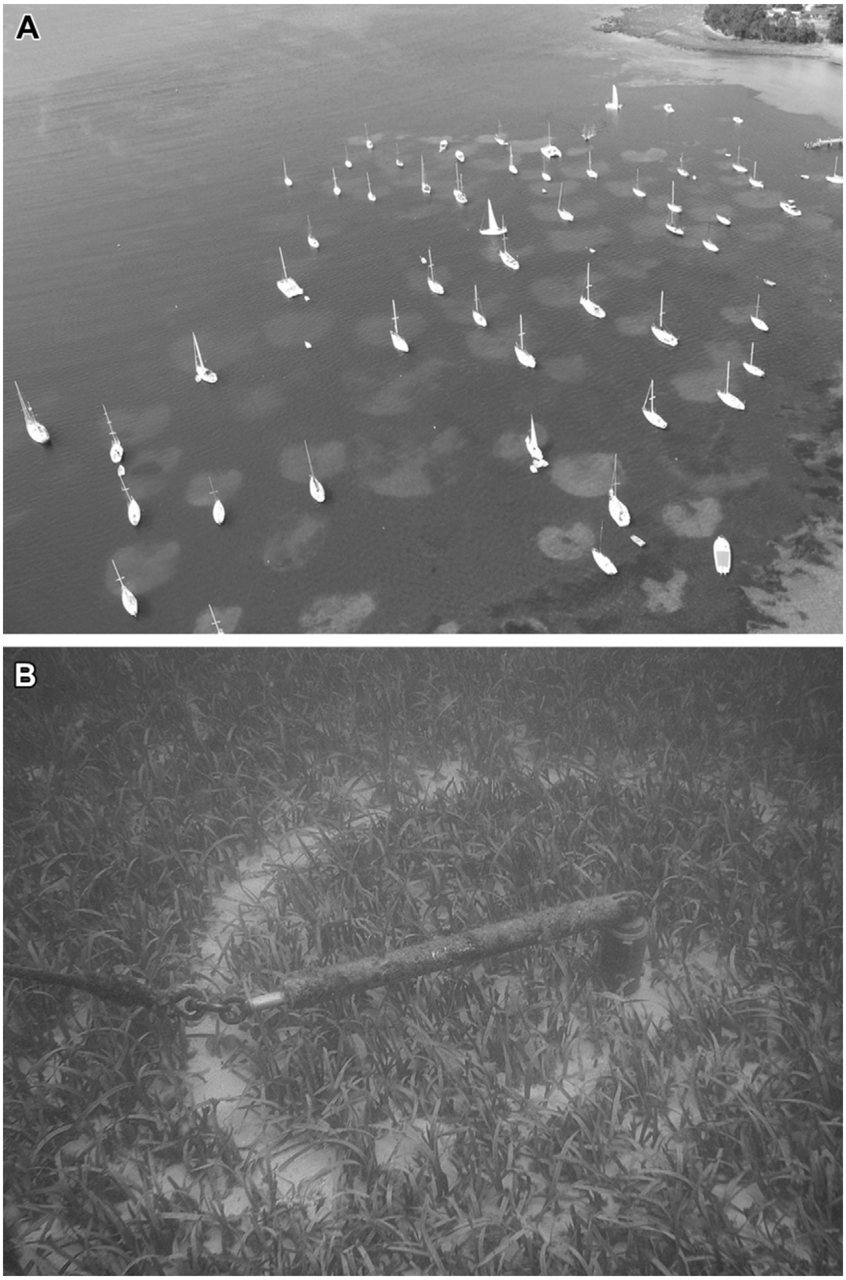

**Fig. 2.** (**A**) Aerial photograph of the mooring area at Callala Bay showing distinctive circular areas denuded of seagrass, (**B**) underwater photograph of the ring of bare seagrass observed around 'screw' moorings at Bindijine Beach.

following a disturbance generated by moorings, if the direct scouring impact is removed, the area is more likely to be recolonised by pioneer species than *P. australis*. We predicted greater densities and cover of these pioneer species in areas that had suffered previous scour.

### 2.3. Sampling method

We sampled seagrass density and cover surrounding each mooring type and in reference areas. This included a reference area, a 'screw' and a 'swing' mooring at two sites at Callala Bay; a reference area and a 'cyclone' mooring at three sites at Callala Bay; and a reference area and a 'screw' mooring at two sites at Bindijine Beach. Reference areas for each site were located at least 10 m from existing moorings over similar depths and conditions to the adjacent mooring(s). This reduced the spatial variation in seagrass density and cover with which we had to contend. At Callala Bay, the 'swing' and 'screw' moorings (3–5 m) were shallower than the 'cyclone' moorings (5–6 m). Hence, we tested the effectiveness of the two 'seagrass-friendly' mooring types separately and sampled separate sets of reference areas. At Bindijine Beach the 'screw' moorings were at a depth of 3 m.

Seagrass density was quantified within 0.25 $m^2$ quadrats (0.5 m × 0.5 m) at three distances (0–2 m, 3–5 m and 6–8 m) along 2 transect lines from the centre of each mooring or reference area. We sampled three distances to assess whether impacts diminish from the centre of each mooring. Two quadrats were placed haphazardly within 1 m of the transect line at each of the three distances. Hence, at each mooring, we examined 12 quadrats, 4 at each distance. Within each quadrat the number of *P. australis* shoots, consisting of one to several leaf-blades joined at the base, were counted by divers on SCUBA. Shoots with at least 50% of their leaf sheath located inside the quadrat were included. We sampled from the centre of each mooring; for the 'cyclone' mooring system this was identified as the mooring's central ring, which connects all 3 ground chains to a riser chain (Fig. 1).

Seagrass cover was also estimated using point counts along the same transect lines. We recorded the nature of the substratum (seagrass or sediment) at 10 cm intervals for 8 m along each transect. The occurrence of any component of seagrass, such as root, rhizome, stem, leaf sheath and leaf-blade under each point on the tape was recorded as seagrass cover. We distinguished among all seagrass species, counting them separately.

Additional information we recorded included the GPS coordinates of each mooring and reference area, the height of the base of each 'screw' mooring, length of the chain for 'swing' and 'cyclone' moorings, as well as the radius of the annuli of scoured seagrass surrounding each mooring. We characterised the extent of scoured seagrass as the area of substratum with <5% seagrass cover.

### 2.4. Statistical analyses

Analysis of variance (ANOVA) was used to test the stated hypotheses regarding the density and cover of seagrass species for each of the mooring comparisons. Three factors were analysed: treatment (mooring type) was a fixed orthogonal factor with three levels (reference, 'screw', 'swing') at Callala Bay, two levels (reference, 'cyclone') at Callala Bay and two levels (reference, 'screw') at Bindijine Beach; Site was a random orthogonal factor with three levels for the 'cyclone' moorings and two levels for the other comparisons; while distance was a fixed orthogonal factor with three levels (0–2 m, 3–5 m and 6–8 m).

The seagrass density values were expressed as percentages of the maximum seagrass density recorded at the reference area for each site ($n = 4$). A different maximum seagrass density value was used for each analysis, consisting of 'screw' and 'swing' moorings at Callala Bay, 'cyclone' moorings at Callala Bay and 'screw' moorings at Bindijine Beach. We standardised our density estimates in this way to account for differences in seagrass density across reference areas at different depths, and mooring histories.

We estimated the mean seagrass cover for each distance (0–2 m, 3–5 m and 6–8 m) and analysed these using the same design as the density measurements ($n = 2$). Variances were tested for homogeneity using Cochran's C-test and normality of the data were assessed visually as per Quinn and Keough (2002). In the case of heterogeneous data, the analyses were still performed since ANOVA is robust to heterogeneity with balanced experimental designs and large numbers of replicates (Underwood, 1997). We used Student–Newman–Keuls (SNK) tests for *a-posteriori* comparisons.

An estimate of the scoured area (blowout size) was made for each mooring. The mean ($n = 2$) radius of scoured seagrass at each mooring was plotted against the length of ground chain. We did not include the lighter riser chain of 'cyclone' moorings in these estimates as it was generally not in contact with the substratum.

## 3. Results

### 3.1. Conventional 'swing' moorings

We observed 'swing' moorings with large circular areas of scour at Callala Bay (Fig. 2A, Table 1, Appendix SNK: Reference > Swing). These moorings consistently lacked seagrass around them (Fig. 3). These impacts lessened with distance from the mooring anchor at

**Table 1**
Analyses of variance comparing 'seagrass-friendly' 'screw' and conventional 'swing' mooring systems at Callala Bay. Tr: treatment, Si: site, Di: distance. NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

| Source | A) Estimated shoot density | | | | B) *Posidonia* cover | | | | C) *H. ovalis* and *Zostera* spp. cover | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | df | MS | *F* | *P* | df | MS | *F* | *P* | df | MS | *F* | *P* |
| Tr | 2 | 21,048.47 | 3.12 | NS | 2 | 6477.08 | 2.27 | NS | 2 | 18.58 | 1.27 | NS |
| Si | 1 | 3956.61 | 14.53 | *** | 1 | 156.25 | 2.47 | NS | 1 | 17.51 | 28.86 | *** |
| Di | 2 | 807.29 | 1.10 | NS | 2 | 468.75 | 25.00 | * | 2 | 1.30 | 0.81 | NS |
| Tr × Si | 2 | 6753.57 | 24.81 | *** | 2 | 2852.08 | 45.13 | *** | 2 | 14.66 | 24.15 | *** |
| Tr × Di | 4 | 1260.68 | 0.83 | NS | 4 | 898.96 | 0.73 | NS | 4 | 0.74 | 0.84 | NS |
| Si × Di | 2 | 732.51 | 2.69 | NS | 2 | 18.75 | 0.30 | NS | 2 | 1.62 | 2.66 | NS |
| Tr × Si × Di | 4 | 1510.82 | 5.55 | *** | 4 | 1223.96 | 19.37 | *** | 4 | 0.87 | 1.44 | NS |
| Residual | 54 | 272.26 | | | 18 | 63.19 | | | 18 | 0.61 | | |
| Total | 71 | | | | 35 | | | | 35 | | | |
| Cochran's test | | $C = 0.2740$ (not significant) | | | | $C = 0.2747$ (not significant) | | | | $C = 0.3739$ (not significant) | | |
| Transformation | | None | | | | None | | | | Sqrt($X + 1$) | | |

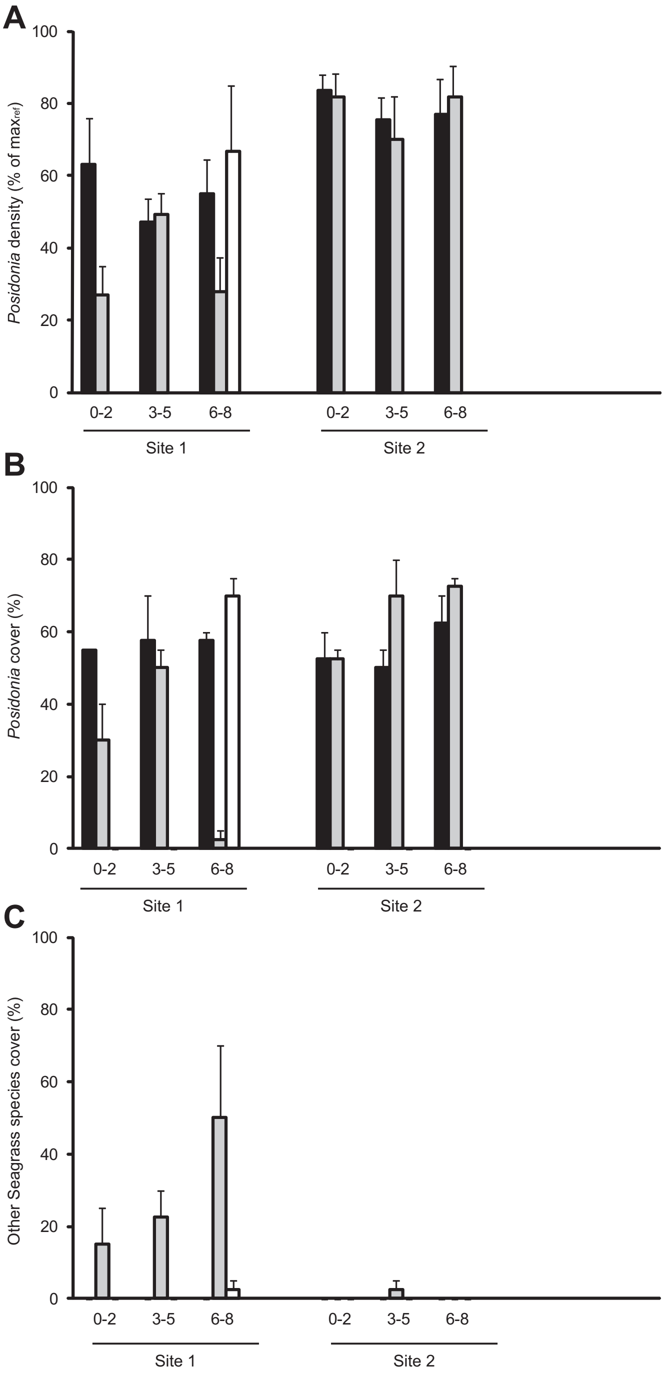

**Fig. 3.** Comparison of seagrass density and cover for 'screw' and 'swing' moorings with reference areas at Callala Bay. (**A**) mean (+SE) estimates of *Posidonia* density. These estimates were expressed as percentages of the maximum density recorded in the reference area for each site. Each bar represents a total of 4 quadrats; 2 quadrats of 0.25 m$^2$ for each of the two transect lines ($n$ = 4). (**B**) mean (+SE) percent cover of *Posidonia*. Each bar represents 20 points per distance for each of the 2 transect lines ($n$ = 2). (**C**) mean (+SE) percent cover of *Halophila ovalis* and *Zostera* spp. Each bar represents 20 points per distance for each of 2 transect lines ($n$ = 2). Distances (0–2, 3–5 and 6–8 m) are from the centre of each mooring. ■ Reference; ▨ 'Screw' mooring; ☐ 'Swing' mooring.

site 1; at 6–9 m we observed a seagrass density and cover similar to the reference area (Fig. 3A, B, Appendix site 1, 6–8 m, SNK: Reference = Swing). The presence of *Posidonia* at this distance at this site produced a significant higher order interaction (Tr × Si × Di).

### 3.2. Seagrass-friendly 'screw' moorings

Patterns of seagrass density and cover surrounding the 'screw' moorings at Callala Bay and Bindijine Beach were similar to that at the reference areas at these locations (Figs. 3 and 4). This was particularly clear at site 2 at Callala and both sites at Bindijine Beach. At site 2, where *Posidonia* was most abundant at Callala Bay, there was little difference between the seagrass density and cover of the reference area and the area surrounding the 'screw' mooring (Appendix site 2, SNK: Reference = Screw > Swing). In contrast, site 1 had a seagrass cover and density that were generally lower surrounding the 'screw' mooring than in the reference area (Appendix site 1, 0–2 m and 6–8 m, SNK: Reference > Screw). At Bindijine Beach, a location with virtually no history of mooring, the *Posidonia* density and cover around the 'screw' moorings was very similar to that at the reference areas (Table 2, Fig. 4A, B).

'Screw' moorings were not without impacts, however. We observed a small circular scar around most of the 'screw' moorings at Bindijine Beach (Fig. 2B) although we did not detect it in our data set (Fig. 4). This scoured area, approximately 10 cm in width, corresponded to the coupling of the mooring to the float line. Contact between the coupling and the substratum had created this small-

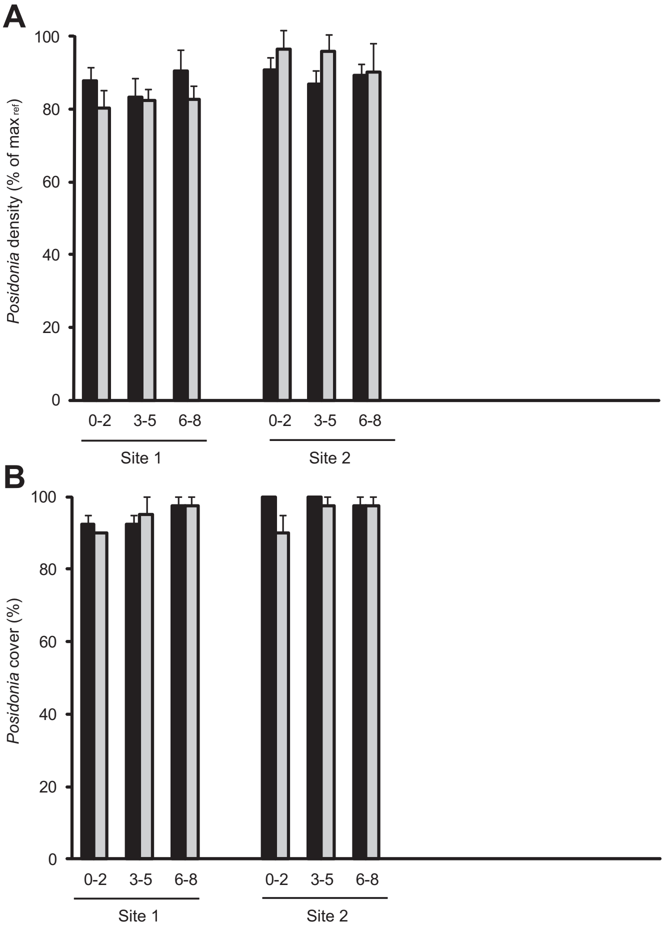

**Fig. 4.** Comparison of seagrass density and cover for 'screw' moorings with reference areas at Bindijine Beach. (**A**) mean (+SE) estimates of *Posidonia* density. These estimates were expressed as percentages of the maximum density recorded in the reference area for each site. Each bar represents a total of 4 quadrats; 2 quadrats of 0.25 m$^2$ for each of the two transect lines ($n$ = 4). (**B**) mean (+SE) percent cover of *Posidonia*. Each bar represents 20 points per distance for each of the 2 transect lines ($n$ = 2). Distances (0–2, 3–5 and 6–8 m) are from the centre of each mooring. ■ Reference; ▨ 'Screw' mooring.

**Table 2**

Analyses of variance comparing ‘seagrass-friendly’ ‘screw’ mooring systems at Bindijine Beach. Tr: treatment, Si: site, Di: distance. NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

| Source | A) Estimated shoot density | | | | B) *Posidonia* cover | | | |
|---|---|---|---|---|---|---|---|---|
| | df | MS | *F* | *P* | df | MS | *F* | *P* |
| Tr | 1 | 0.10 | 0.00 | NS | 1 | 26.04 | 1.00 | * |
| Si | 1 | 612.08 | 6.61 | * | 1 | 51.04 | 3.27 | NS |
| Di | 2 | 12.16 | 0.26 | NS | 2 | 40.63 | 3.00 | NS |
| Tr × Si | 1 | 338.92 | 3.66 | NS | 1 | 26.04 | 1.67 | NS |
| Tr × Di | 2 | 59.83 | 10.10 | NS | 2 | 26.04 | 3.57 | NS |
| Si × Di | 2 | 46.53 | 0.50 | NS | 2 | 13.54 | 0.87 | NS |
| Tr × Si × Di | 2 | 5.92 | 0.06 | NS | 2 | 7.29 | 0.47 | NS |
| Residual | 36 | 92.56 | | | 12 | 15.63 | | |
| Total | 47 | | | | 23 | | | |
| Cochran’s test | | $C = 0.2272$ (not significant) | | | | $C = 0.2667$ (not significant) | | |
| Transformation | | None | | | | None | | |

scale disturbance. Such small-scale effects were not observed at Callala Bay where the screw moorings sat higher above the substratum and did not make contact with it.

We also noted colonisation of pioneering seagrass *H. ovalis* and *Zostera* spp. observed around many of the ‘screw’ moorings as well as in some of the reference areas (Figs. 3C and 5C). These species were not observed surrounding moorings at Bindijine Beach, as the meadow was composed entirely of *P. australis*.

### 3.3. Seagrass-friendly ‘cyclone’ moorings

We observed large areas cleared of seagrass at all of the ‘cyclone’ moorings we sampled. These cleared areas were in the form a Y-shape, closely matching the layout of the mooring itself and generally extended to 18 m from the centre of each mooring (Fig. 6). As our transects were laid in random directions they did not always align with the areas of maximal scour and hence *Posidonia* was observed in some transects particularly with increasing distance from the centre of the ‘cyclone’ moorings (Fig. 5A, B). The presence of *Posidonia* produced a significant Treatment by Site interaction (Table 3). Nevertheless, seagrass cover and density was consistently lower around ‘cyclone’ moorings than nearby reference areas (Fig. 5A, B, Table 3, Appendix SNK: Reference > Cyclone).

### 3.4. Size of mooring impact

We observed a strong correlation between the length of the ground chain and the extent of the damage to seagrass as measured by the mean radius of the blowout around the moorings (Fig. 6, $r^2 = 0.73$, $P = 0.01$). The mean radius of the blowout area of conventional ‘swing’ moorings was ~9 m, while for ‘cyclone’ moorings it was ~18 m (Fig. 6).

## 4. Discussion

Dramatic impacts on seagrass were apparent around conventional ‘swing’ moorings with virtually no seagrass found within ~9 m of these moorings. Conversely, seagrass surrounding the ‘seagrass-friendly’ ‘screw’ moorings was similar to that of reference areas. In contrast, ‘seagrass-friendly’ ‘cyclone’ moorings had far greater impact on seagrass than that associated with the ‘swing’ moorings; scouring areas of almost double the size. ‘Screw’ moorings are indeed genuinely ‘seagrass-friendly’ at least over the first 12 months of their operation as we content that this is a crucial period in assessing the efficacy of mooring systems. In addition, *Posidonia* is highly sensitive to disturbances and responds quickly to physical damage (Ceccherelli et al., 2007).

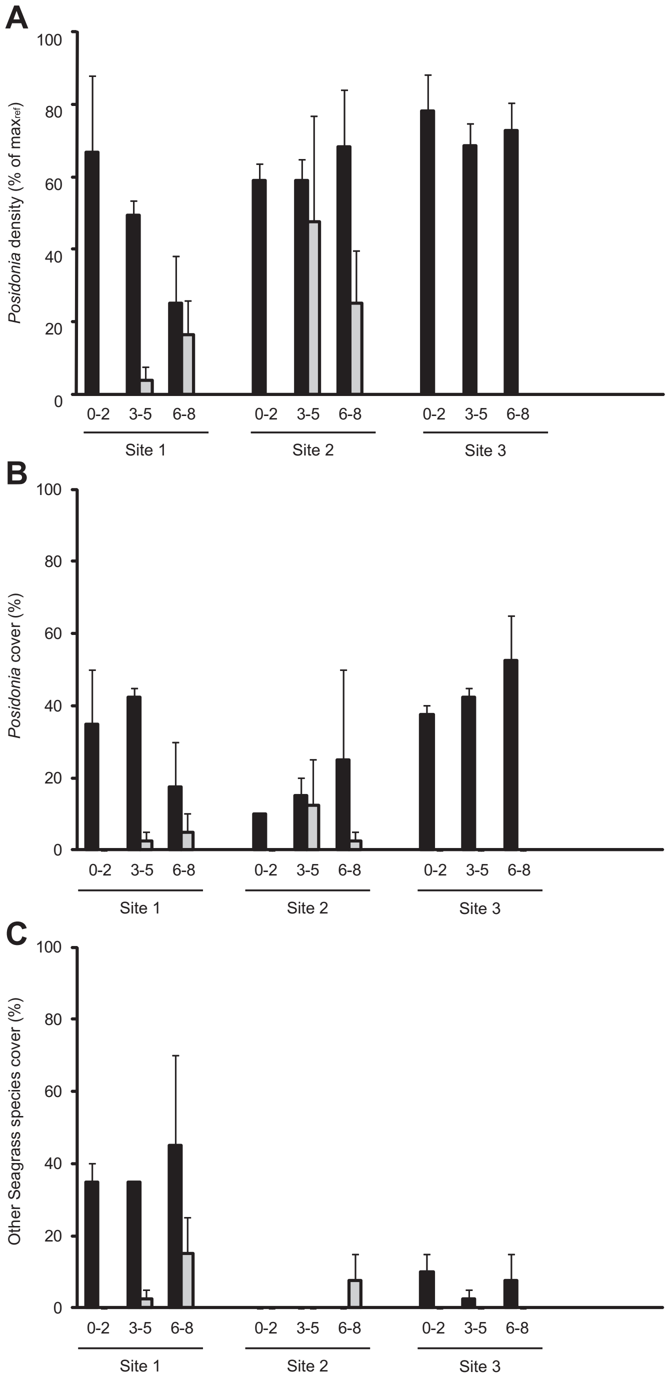

**Fig. 5.** Comparison of seagrass density and cover for ‘cyclone’ moorings with reference areas at Callala Bay. (**A**) mean (+SE) estimates of *Posidonia* density. These estimates were expressed as percentages of the maximum density recorded in the reference area for each site. Each bar represents a total of 4 quadrats; 2 quadrats of 0.25 $m^2$ for each of the two transect lines ($n = 4$). (**B**) mean (+SE) percent cover of *Posidonia*. Each bar represents 20 points per distance for each of 2 transect lines ($n = 2$). (**C**) mean (+SE) percentage cover of *Halophila ovalis* and *Zostera* spp. Each bar represents 20 points per distance for each of 2 transect lines ($n = 2$). Distances (0–2, 3–5 and 6–8 m) are from the centre of each mooring. ■ Reference; ▨ ‘Cyclone’ mooring.

Numerous studies report that cleared areas surrounding ‘swing’ moorings are generated by the continuous dragging of the mooring chains (Walker et al., 1989; Lenihan et al., 1990; Hastings et al., 1995; Creed and Amado Filho, 1999; Francour et al., 1999; Marbà et al., 2002; Crawford, 2003; Milazzo et al., 2004; Montefalcone et al., 2008). At Callala Bay, we estimate that the patch size of the

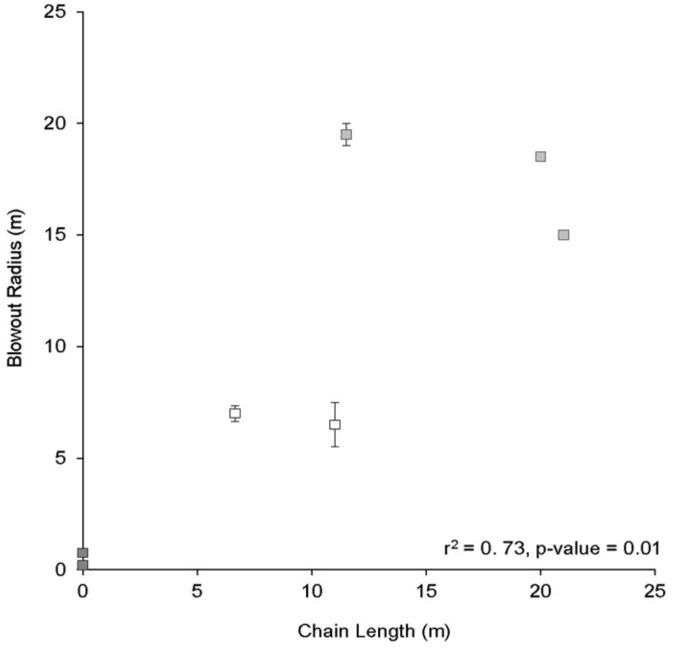

**Fig. 6.** Relationship between mooring chain length and the mean (±SE) radius of areas scoured of seagrass for 'swing' and 'cyclone' mooring systems at Callala Bay ($n = 2$). ■ 'Screw' mooring; □ 'Swing' mooring; ▨ 'Cyclone' mooring.

scoured seagrass was 254 m$^2$ per mooring (Fig. 2A) and there are ≈60 swing moorings at this location. This estimate of damage per mooring is similar to that reported by Walker et al. (1989) in Western Australia. Surprisingly, there are no quantitative reports of impacts of moorings from other parts of the world, although impacts have been alluded to, especially in the Mediterranean (e.g. Milazzo et al., 2004). Given the large number of moorings and their continued installation worldwide, their overall impacts are alarming. There is an immediate and explicit need to address this issue (Hastings et al., 1995; Smith et al., 1997).

The newly designed 'screw' moorings were highly successful in conserving seagrass, with seagrass density and cover generally indistinguishable from that observed in reference areas. The patchy nature of the seagrass at Callala Bay, stemming from previous mooring damage (Crawford, 2003), complicated the interpretation of present mooring impacts. It should be noted that small-scale damage was observed around 'screw' moorings at Bindijine Beach. This ring of damage (Fig. 2B) was not detected by our analysis due to its relatively small size; especially when compared to the large areas of scour around conventional 'swing' moorings. This small-scale effect highlights the need for regular inspection of these moorings to assess their performance and ensure that they do not malfunction and threaten seagrass.

Of major importance were the signs of seagrass recovery around some of the 'screw' moorings. *H. ovalis* and *Zostera* spp., which are considered pioneer species, colonised previously damaged areas either before or since the installation of the 'screw' moorings. Either way this indicates that 'screw' moorings allow recovery to take place, as observed in Shoal Bay and Pittwater (Gladstone, 2011a,b). This is important as the continued presence of the 'swing' moorings represent a press disturbance (*sensu* Bender et al., 1984) where the impact is on-going and recovery is halted by the frequent movement of the anchor chain. The removal of the 'swing' moorings and their replacement with effectively operating 'seagrass-friendly' moorings will enable seagrass recovery and lead to the restoration of original ecosystem function and services. In the case of *Posidonia*, recovery will be a very slow process and may take many decades (Meehan and West, 2000).

Although considered 'seagrass-friendly', we observed large areas devoid of seagrass at all of the 'cyclone' moorings we sampled. Scoured areas were in the form a Y-shape, matching the layout of the mooring for distances of 18 m from the centre of the mooring (Fig. 6). Although seagrass was apparent in some quadrats closer to the mooring anchors than this 18 m value (Fig. 3B), it should be remembered that these values were estimated from random transects which were not aligned with the areas of scoured seagrass. Hastings et al. (1995) also reported that 'cyclone' moorings generated greater seagrass loss than 'swing' moorings at Rottnest Island, Western Australia; often generating 'tri-circle' sand areas. That is, three 10 m diameter circular blowouts in a triangle formation. These blowouts were assumed to be caused by the dragging of the ground chains and were found to coalesce with neighbouring blowouts in shallow water, producing a greater impact than 'swing' moorings (Hastings et al., 1995). The three ground chains of 'cyclone' moorings are designed to be under tension and concealed within the substratum (Jeyco, 2010; Adrian Nute, Jervis Bay Commercial Marine, pers. comm.), this was not the case at any of the 'cyclone' moorings at Callala Bay.

An earlier assessment of the impact of permanent boat mooring systems at Rottnest Island revealed that 'cyclone' moorings were less damaging than 'swing' moorings (Walker et al., 1989) – only producing a relatively small area of damage (3 m$^2$). Possible explanations for the discrepancy between the results of Walker et al. (1989), our findings and those of Hastings et al. (1995) include time since the installation of the moorings or the level of maintenance they receive. We contend that these differences are due to

**Table 3**
Analyses of variance comparing 'seagrass-friendly' 'cyclone' mooring systems at Callala Bay. Tr: treatment, Si: site, Di: distance. NS, $P > 0.05$; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

| Source | A) Estimated shoot density | | | | B) *Posidonia* cover | | | | C) *H. ovalis* and *Zostera* spp. Cover | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | df | MS | *F* | *P* | df | MS | *F* | *P* | df | MS | *F* | *P* |
| Tr | 1 | 45,894.72 | 19.72 | * | 1 | 7225.00 | 9.10 | NS | 1 | 24.80 | 1.63 | NS |
| Si | 2 | 1615.09 | 3.17 | * | 2 | 381.25 | 2.45 | NS | 2 | 29.22 | 22.33 | *** |
| Di | 2 | 115.83 | 0.16 | NS | 2 | 89.58 | 0.91 | NS | 2 | 2.25 | 2.19 | NS |
| Tr × Si | 2 | 2327.20 | 4.57 | * | 2 | 793.75 | 5.10 | * | 2 | 15.24 | 11.65 | *** |
| Tr × Di | 2 | 1390.99 | 1.77 | NS | 2 | 2.08 | 0.01 | NS | 2 | 1.67 | 3.45 | NS |
| Si × Di | 4 | 734.90 | 1.44 | NS | 4 | 98.96 | 0.64 | NS | 4 | 1.03 | 0.78 | NS |
| Tr × Si × Di | 4 | 784.07 | 1.54 | NS | 4 | 186.46 | 1.20 | NS | 4 | 0.48 | 0.37 | NS |
| Residual | 54 | 509.70 | | | 18 | 155.56 | | | 18 | 1.31 | | |
| Total | 71 | | | | 35 | | | | 35 | | | |
| Cochran's test | | $C = 0.3686$ ($P < 0.01$) | | | | $C = 0.4464$ (not significant) | | | | $C = 0.3137$ (not significant) | | |
| Transformation | | None | | | | None | | | | Sqrt($X + 1$) | | |

reduced effectiveness of these moorings over time as tension in the mooring chains dissipates; reinforcing the need for on-going maintenance.

## 5. Conclusions and recommendations

'Screw' moorings were found to work effectively, while 'cyclone' moorings did greater damage to seagrass than conventional 'swing' moorings. We consider that a lack of regular inspection and maintenance has contributed to this damage. We therefore recommend that all 'seagrass-friendly' moorings receive annual maintenance checks and servicing to ensure their effectiveness. Such maintenance checks are especially important considering that failure of a mooring may do irreparable damage to *Posidonia* beds and contravene laws protecting seagrass (i.e. *NSW Fisheries Management Act, 1994*). Greater accountability of those responsible for those moorings may reduce the likelihood of future damage from faulty mooring systems.

Habitat fragmentation has the potential to dramatically impact ecosystem integrity (Wilcox and Murphy, 1985) and indeed, there have been demonstrated impacts of fragmentation in seagrass meadows (Hovel, 2003). Such impacts remain to be examined over the spatial scale of mooring damage that we have observed in temperate seagrass meadows. Although we observed small-scale scour with 'screw' moorings, we encourage their use and further improvements in their design and maintenance. In addition, we argue for assessments like ours on 'seagrass-friendly' moorings in other parts of the world and other types of systems (e.g. with different vessel sizes, different types of substrata, etc). 'Seagrass-friendly' systems are necessary in order to sustainably accommodate the global increase in demand for moorings in coastal embayments. As well, their installation may allow seagrass recovery in areas previously damaged by conventional moorings and the return of the ecosystem function and services in these habitats.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.marenvres.2012.10.010.

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