Impacts of docks on seagrass and effects of management practices to ameliorate these impacts

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Abstract

Seagrasses have high conservation and human-use values, but around the world they are being damaged by human activities. Compared to the larger spatial scale at which some human activities affect estuaries and their seagrasses (e.g. catchment disturbance, dredging, pollution, trawling), recreational boating and infrastructure of moorings and docks act at smaller scales. However, the cumulative effects contribute to stresses acting on seagrass beds. This study assessed the effects of docks on the native seagrass *Zostera muelleri* subsp. *capricorni* in an estuary in south-east Australia and of current management practices designed to reduce dock impacts on this seagrass. A field survey found that seagrass biomass was significantly reduced below docks, and the effects were not influenced by dock orientation. Management practices requiring the use of a mesh decking to provide greater light penetration reduced, but did not eliminate, the reduction in seagrass biomass caused by docks. A modified beyond BACI experiment provided evidence for a causal link between the installation of wooden or mesh docks and reductions in biomass of seagrass. The reduction in biomass was apparent 6 mo after dock installation, and by 26 mo seagrass biomass had declined by at least 90%. Faced with increasing coastal populations, increases in recreational use, and continued pressures from other human activities, alternative management practices that further minimize the effects of docks are needed.

Keywords: Before-After-Control-Impact (BACI); coastal zone management; environmental assessment; environmental management; sea grass; Australia, New South Wales, Lake Macquarie

1. Introduction

Seagrass beds are productive, shallow-water ecosystems that provide a habitat for a rich and unique faunal biodiversity including the juveniles of many species important for commercial and recreational fishing activities (Waycott *et al*., 2009; Unsworth and Cullen, 2010). Seagrass beds stabilize sediments and are likely to play an important role in the prevention of coastal erosion. Seagrasses are an important component of estuarine ecological processes due to their high primary productivity, roles in detrital pathways and nutrient cycles, and their export of nutrients and energy to other associated ecosystems (Poiner and Peterken, 1995; Gillanders, 2007). The faunal biodiversity of estuarine seagrass beds is greater than, and different from, nearby unvegetated habitats and seagrass beds therefore represent a substantial component of the overall habitat and species diversity of estuaries (Jenkins and Wheatley, 1998; Rotherham and West, 2002).

Australia has the greatest richness of seagrass species and the largest area of temperate seagrass beds in the world (Gillanders, 2007). Seagrasses within New South Wales (NSW), Australia, have declined in extent and condition as a result of increased turbidity, siltation, erosion from dredging, eutrophication, sea urchin grazing, and trawling (Brodie, 1995; Poiner and Peterken, 1995; Macdonald, 1996; NSW EPA, 2000; ASEC, 2001). The outcome of these pressures on seagrass within NSW was an average 50% loss of seagrass area in estuaries in the period of 1960s-early 1990s (Poiner and Peterken, 1995). Similar, and sometimes greater, losses of seagrass have occurred in other Australian states (Neverauskas, 1987; Preen *et al.*, 1995; Kendrick *et al.*, 2002; Campbell and McKenzie, 2004) and other countries (Delgado *et al*., 1999; Baden *et al*., 2003; Hauxwell *et al*., 2003; Waycott *et al*. 2009).

Although less dramatic than the losses due to human industry and ecosystem alteration, seagrasses are damaged by recreational activities such as boating (Dunton and Schonberg, 2002; Milazzo *et al*., 2004), bait collecting (Skilleter *et al*., 2006), food harvesting (Boese, 2002; Cabaço *et al*., 2005), trampling (Eckrich and Holmquist, 2000), and the infrastructure installed for recreation such as moorings (Hastings *et al*., 1995) and docks (Fyfe and Davis, 2007). Seagrasses in NSW estuaries are located in the shallow, nearshore environment and, extending out from the shore for distances of 10s to 100s of metres in shallow waters, they are potentially exposed to the impacts of dock construction and use. Current understanding of the impacts of docks on seagrass comes from a small number of studies. Seagrass shoot density was significantly reduced immediately below a dock in Jervis Bay (NSW, Australia), but no impact was detected 5 metres away from the dock (Fyfe and Davis, 2007). Two-thirds of docks in Nantucket Harbor and Waquoit Bay (Massachusetts, USA) had no seagrass (*Zostera marina*) below them (Burdick and Short, 1999). Seagrass (*Halodule wrightii*) biomass below docks in Perdido Bay (Alabama, USA) was 67-70% of the values recorded in areas without docks (Shafer, 1999).

Loss of seagrass below docks occurs as a direct result of shading and the indirect impacts of associated boating activities. *H. wrightii* were not present under docks where light levels were less than 14% surface irradiance (Shafer, 1999). The effect of shading was greatest between 1000 h and 1500 h, and seagrasses subject to additional shading during the morning and late afternoon due to dock height and orientation were particularly vulnerable to effects of shading (Shafer, 1999). Seagrass and sediment in the vicinity of docks are affected through boat propeller scarring (Shafer, 1999; Burdick and Short, 1999). A cumulative assessment of dock impacts in Waquoit Bay (Massachusetts, USA) found that docks shaded less than 1% of total seagrass area in the Bay. However, seagrass beds in the vicinity of docks were also affected by anchor damage and propeller scarring, and so the areal extent of impact was substantially greater than the area of seagrass directly shaded by docks (Burdick and Short, 1999).

There are large numbers of docks in some estuaries in NSW, including Lake Macquarie (760), Tuggerah Lakes (32), Brisbane Water (≈750), and Pittwater (≈675). Some of these estuaries have lengthy shorelines (e.g. 174 km in Lake Macquarie). However, docks are often concentrated in some areas, reaching densities of 60 docks per km, which is likely to lead to a localization of effects. The effects of docks on seagrass are covered by the NSW by the Fisheries Management Act and its associated Policy and Guidelines for Fish Habitat Conservation and Management (Fairfull, 2013), and implemented by local municipalities. The Policy and Guidelines exclude docks from beds of *Posidonia australis* seagrass (existing as endangered populations in several estuaries), provide guidelines on dock designs, and require a permit for construction of docks over other seagrasses. Construction permits are issued jointly by the NSW Department of Primary Industries (DPI), the Department of Lands, and the local municipality. Guidelines on dock designs include restrictions on the maximum length, minimum water depth, orientation (a north-south orientation is preferred but not mandated), height, and decking materials (e.g. the use of aluminium mesh or translucent PVC to allow greater light penetration). There is, however, no published information on the effects of docks on seagrasses in NSW to inform conservation planning (with the exception of Fyfe and Davis, 2007) or the effects of design options (such as alternative decking materials and orientation) in modifying the impacts of docks on seagrass.

The aims of this study were to quantify the effects of docks on seagrass and evaluate the effects of management options for minimizing their effects, including dock orientation and decking materials. The approaches taken included a series of spatially and temporally replicated mensurative experiments that compared seagrass biomass below wooden or mesh docks with control sites (no docks), and tested the effects of dock orientation on seagrass loss. In order to definitively identify docks as the cause of seagrass loss, a modified beyond BACI (Before-After-Control-Impact) experiment was done to quantify the changes in seagrass following the installation of wooden or mesh docks.

2. Materials and Methods

2.1 Study area

This study was undertaken in Lake Macquarie (Fig. 1) between 2006 and 2008. Lake Macquarie is a natural estuarine lagoon with an average depth of 5.7 m, covering an area of about 100 km^2 and surrounded by extensive residential and industrial development. Although seagrass cover has increased in some parts of the lake, the total extent of seagrass has declined since the 1960s (King and Hodgson, 1986). Seagrasses occurring in the shallow (max. depth 1 m) nearshore waters are *Zostera muelleri* subsp. c*apricorni, Halophila* spp., and *Ruppia megacarpa* (King and Holland, 1986). This study was restricted to an examination of the effects of docks on *Z. muelleri* subsp. *capricorni*. We use the term dock to mean small single wharves installed perpendicular to the shoreline on private property, and distinguish them from public wharves (that may be used mostly for public transport, shipping, commercial fishing operations) and marinas. This study focused on domestic docks (i.e. adjoining privately owned land), which have design constraints imposed by the current policy and guidelines and the local municipality (Lake Macquarie City Council, LMCC). At the time of this study LMCC Development Control Plan 1 Section 3.1.1 (Development Adjoining the Lake and Waterways Zone) required the width of domestic docks to be 900-1200 mm, the height to be 600-750 mm above mean high water mark, and the deck to be constructed from 150 mm x 35 mm hardwood or aluminium mesh (dimensions not specified). Although the gaps between hardwood deck planks, and the dimensions of the openings in the aluminium mesh are not specified, the Plan requires the deck to provide natural light penetration when the dock is situated over seagrass. The locations of all domestic docks were obtained from the LMCC and confirmed by personal visits as part of site selections. Docks were pre-selected to minimize inter-dock variation in dimensions, so their width varied from 900 to 1100 mm and their height above the water varied from 600 to 700 mm. Spring tide range in Lake Macquarie at the study sites is ~120 mm (Nielsen and Gordon 2008).

2.2 Effects of wooden docks and dock orientation

The null hypotheses that seagrass biomass below wooden docks would not differ from beds without docks, and that dock orientation (i.e. north-south vs east-west) would not affect seagrass biomass, were tested. Samples of *Z. muelleri* subsp. *capricorni* plants were collected by inserting a 10 cm diameter PVC corer into the sediment to a depth of 10 cm. The corer was withdrawn and the sample washed through a 1 mm sieve to remove adhering sediment. Seagrass samples were returned to the lab and oven-dried at 70^{o}C until a constant weight was achieved (this usually required 48-72 hr). The final dry weight of the seagrass sample was used as an estimate of seagrass biomass (whole plant). The values for seagrass biomass reported hereafter represent dry weight biomass 0.008 m^{-2}. Five replicate cores were collected following the results of an earlier pilot study (authors' unpublished data) that found that this amount of replication provided mean values with an acceptable sampling precision (standard error/mean) of 0.15 (Andrew and Mapstone, 1987).

Sampling was done by laying a tape measure (hereafter called the 'transect') immediately below and along the centreline of a dock and inserting the PVC corer at randomly selected distances (based on a table of random numbers) along the tape measure. Sampling began at least 3 m from the low tide mark on the shore and replicate samples were separated by at least 1.5 m to prevent disturbance during collection of adjacent samples. In seagrass beds without jetties the transects were laid and samples collected using an identical protocol.

A four-factor design was used to test the hypotheses, based on the following model: Treatment (2 levels (dock, no dock), fixed, orthogonal); Orientation (2 levels (north-south, east-west), fixed, orthogonal); Site (3 levels, random, nested in Treatment x Orientation); and Transect (3 levels, random, nested in Site (Treatment x Orientation)). There were n=5 replicate samples per Transect. Three sites of each combination of Treatment and Orientation were randomly selected from amongst the available docks. Replicate sites were at least 1 km apart. Within each site 3 docks or non-dock areas were selected. The orientation of all docks was determined during site visits. The large number of docks in Lake Macquarie meant that it was possible to select docks that were within $\pm 10^{o}$ of north-south or east-west. Sampling occurred in January-February 2006.

2.3 Effects of wooden and mesh docks

The null hypotheses that seagrass biomass below wooden and mesh docks would not differ, and that seagrass biomass below both types of docks would not differ from seagrass beds without docks, were tested. Preliminary site visits in May 2006 revealed there were insufficient mesh docks to include site as a potential source of variation. Seven mesh docks and 7 wooden docks of the same orientation, length and height on the western side of Lake Macquarie were selected for the comparison. All docks were within the range of allowable width and height specified by LMCC. Gaps between wooden decking planks were 10-12 mm. The decking of all mesh docks was identical and consisted of aluminium expanded mesh, with diamond-shaped openings of length 95 mm, maximum width 32 mm, and mesh thickness 7 mm. Reference transects were positioned in seagrass beds in the same orientation as the dock transects and at least 500 m from the nearest dock. Sampling occurred in June 2006, September 2006, and December 2006. Transects were placed in the same position on each sampling occasion, the positions of samples recorded, and subsequent positions selected to ensure that samples were at least 1.5 m from previous samples.

A three-factor design was used to test the null hypotheses, based on the following model: Time (3 levels (June 2006, September 2006, December 2006), random, orthogonal); Treatment (3 levels (mesh dock, wooden dock, controls i.e. no dock), fixed orthogonal); and Transect (7 levels, random, nested in each level of Treatment). There were n=5 replicate samples per Transect.

2.4 Effects of installation of wooden and mesh docks: BACI test

Although the aforementioned mensurative field experiments provided evidence for an association between docks and seagrass loss (see Results), they do not demonstrate conclusively that docks caused the loss of seagrass. Therefore, a modified beyond BACI field experiment (Underwood, 1992; Glasby 1997) was used to test whether installation of wooden and mesh docks led to loss of seagrass. The design is 'modified' because only a single example of each dock type was available for testing, and each was compared with multiple controls. The mesh and wooden docks were installed in May and June 2006 respectively. Sampling associated with the new mesh dock was done 1 week before installation (hereafter called the 'before' sample) and at 6 mo ('after 1') and 26 mo ('after 2') following installation. Sampling associated with the new wooden dock was done 3 mo before installation ('before') and again at 7 mo ('after 1') and 26 mo ('after 2') following installation. The different time periods of the 'before' sample for the two dock types occurred because the installation of the new mesh dock became known to the authors only 1 wk prior to its installation. The effects of dock installation were quantified by comparing the biomass of *Z. muelleri* subsp. *capricorni* along transects below each new dock with the biomass of *Z. muelleri* subsp. *capricorni* along 6 control transects in each of 3 control sites. Control sites were located from 250 m to 5 km away from the new docks. The selection of multiple control sites, and multiple transects within each control site, addresses the need for impacts to be assessed by accounting for the range in natural variation in seagrass growth that is likely to be occurring (Underwood, 1992). The control transects were the same length and depth as the transects under the new docks.

The null hypothesis that seagrass biomass would not decline after installation of wooden and mesh docks was tested. The model consisted of the following factors: Before vs After (fixed); Dock vs Control (fixed); Sites (random and nested in (Dock vs Control) with n=1 site in Dock and n=3 sites in Control; and Transects (random and nested in Site (Dock vs Control) with n=1 transect in the Impact site and n=6 transects in the Control sites. There were n=5 replicate samples per transect. As only a single before sample was obtained, separate analyses were done for each dock type for the comparison of before with after 1, and before with after 2. In this asymmetrical design, an effect of dock installation is demonstrated by a significant Before vs After x Dock vs Control interaction and post-hoc pairwise tests that demonstrate significant loss of seagrass below docks, but not control transects, from Before to After.

All hypotheses were tested with permutational multivariate analysis of variance (PERMANOVA) (Anderson 2001). Univariate asymmetrical PERMANOVAs (Terlizzi *et al*., 2005; Anderson *et al*., 2008) were used to compare changes in seagrass biomass from before to after dock installation in transects below new docks and in control transects. Prior to PERMANOVA the raw data were checked for homogeneity of variances and, where necessary, transformed to eliminate heterogeneity. The resemblance measure was Euclidean distance and the analyses were done with PERMANOVA+ for PRIMER software (PRIMER-E Ltd).

3. Results

3.1 Effects of wooden docks and dock orientation

The biomass of seagrass below docks was significantly less than the biomass of seagrass in beds without docks, regardless of their orientation (Table 1, Fig. 2). The average seagrass biomass below docks (3.3±0.85 g) was 25.8% of the average biomass in beds without docks (12.8±1.45 g). The absence of a significant result for Site (Table 1) shows that this difference was spatially consistent throughout Lake Macquarie. The significant result for Transects (Site(Treatment x Orientation)) occurred because there was significant variation in average seagrass biomass among some, but not all, transects in most sites.

3.2 Comparison of wooden and mesh docks

The Ti x Tr interaction occurred because seagrass biomass below mesh docks and in the control sites changed through time but it did not change below wooden docks. The three treatments differed significantly in their seagrass biomass at each sampling time (Table 2, Figure 3). The average seagrass biomass below wooden docks was 5.2%, 16.9% and 20.9% of the average seagrass biomass in control transects at the three times. The average seagrass biomass below mesh docks was 41.5%, 49.7% and 46.7% of the average seagrass biomass in control transects at the three times. Therefore the null hypothesis that seagrass biomass below wooden and mesh docks would not differ is rejected, and the null hypothesis that seagrass biomass below both types of docks would not differ from seagrass beds without docks is rejected.

The significant Time x Transect(Treatment) interaction occurred because there was inconsistent temporal variation among transects in the three treatments. Average seagrass biomass varied significantly among some transects (not shown in graph) below wooden docks at all sampling times. Seagrass biomass did not vary significantly among mesh docks at any time, whereas it varied among some control transects at some (but not all) times.

3.3 Effects of dock installation

Seagrass biomass below the wooden dock was not significantly reduced 6 mo after installation, relative to the changes that occurred at transects in the control sites, as shown by the absence of a significant (Before vs After) x (Dock vs Controls) interaction (Table 3a, Figure 4a). Average seagrass biomass declined significantly in the transect below the new wooden dock but also to varying degrees in many of the transects in each of the control sites, as shown by the significant (Before v After) x Transect (Site(Dock vs Control) interaction. It is worth noting that the greatest decline in biomass from Before to After 1 occurred at the dock transect (even though the difference was not significant). Seagrass biomass also varied significantly among the control sites, in a consistent manner among times.

Twenty-six months after installation, the biomass of seagrass below the wooden dock was significantly less than controls, and this temporal decline was greater than the reduction that occurred in the control transects (as shown by the significant (Before vs After) x (Dock vs Control) interaction) (Table 3b). Seagrass biomass below the wooden dock declined significantly from before to after 2 (t=7.29, P=0.009) and seagrass biomass in the controls was not significantly different in the after 2 sample (t=15.20, P=0.10) (Figure 4a). Seagrass biomass declined by 96% under the new wooden dock between the before and after 2 samples. There was also significant variation in seagrass biomass among transects in the control sites, and significant variation among the control sites, although this variation was less than the temporal changes below the dock.

Between the before and after 1 sampling associated with the new mesh dock there were significant, but inconsistent, changes in seagrass biomass that were unrelated to the dock installation (Table 4a, Figure 4b). The significant (Before vs After) x Transect (Site(Dock vs Control)) interaction occurred because seagrass biomass changed in the transect below the new mesh dock, in some transects in two control sites, and in all transects in one control site. Average seagrass biomass also varied significantly among the three control sites.

The (Before vs After) x (Dock vs Control) interaction term for the test of before and after 2 samples was marginally significant (P=0.05) (Table 4b, Figure 4b). Pairwise tests showed that seagrass biomass changed significantly below the mesh dock between the before and after 2 samples (t=4.12, P=0.008) and did not change in the controls over the same time period (t=12.05, P=0.10). Seagrass biomass below the new mesh dock declined by 90% between the before and after 2 samples, compared to 72% decline in the controls. Seagrass biomass varied significantly among transects in two of the three control sites, and among the control sites (Table 4b).

4. Discussion

4.1 Effects of existing wooden docks

Seagrass was present below all wooden docks examined, however, the average seagrass biomass below docks was 25.8% of the average biomass in beds without docks. This loss of seagrass biomass is considerably larger than values reported in Perdido Bay (Alabama USA) (67-70% of the values recorded in areas without docks; Shafter 1999). However, Burdick and Short (1999) reported that seagrass was absent below two-thirds of the docks examined in two estuaries in Massachusetts (USA).

The distribution, abundance and growth of seagrasses are influenced by a range of physical environmental influences and biological processes. Biological processes influencing the survival of seagrass beds include the distribution of other seagrass plants, productivity of epiphytic algae, grazing and burrowing activity of invertebrates

(Edgar 2001), and algal blooms (Beal and Schmit, 2000). Physical factors influencing seagrass include sediment composition, salinity, nutrients, water depth, turbidity, wave exposure and light (Hillman *et al.*, 1995; Abal and Dennison, 1996; Vermaat *et al.*, 1996; Longstaff and Dennison, 1999; Moore and Wetzel, 2000). Control areas used in this study were selected to be as similar as possible to areas with docks to minimize the potential for other factors to contribute to differences in seagrass biomass. Seagrass below docks in Lake Macquarie was compared with control areas of similar depth and exposure and there is no evidence that the study areas differed in water quality or sediment composition (WBM, 1997).

An examination of the impacts of dock shading on the seagrass *Halodule wrightii* in Alabama (USA) quantified the amount of light reduction due to dock shading (Shafer, 1999). The amount of light *H. wrightii* received was critical to seagrass survival: seagrass was not present under docks where light levels were less than 14% surface irradiance. The effect of shading was greatest between 1000 h and 1500 h, and seagrasses subject to additional shading during the morning and late afternoon due to dock height and orientation were particularly vulnerable to effects of shading (Shafer, 1999). The minimum light level below docks needed to support seagrass (i.e. allow for 50% of normal production) has been estimated to be 30% of available light (Burdick and Short, 1999).

Shading seagrass species by experimentally manipulating light levels or exposure to high water turbidity leads to reduced production or death of seagrass plants and seedlings. These impacts are reflected at the habitat scale as reduced density, shoot length, biomass and leaf cover (Gordon *et al.*, 1994; Fitzpatrick and Kirkman, 1995; Grice *et al.*, 1996; Longstaff and Dennison, 1999; Wood and Lavery, 2000; Bintz and Nixon, 2001). Therefore, shading caused by docks is the most likely explanation for the declines in seagrass biomass observed below docks. There is, however, a need for studies to quantify the declines in light levels below wooden and mesh docks (and other potentially suitable decking materials) and to correlate this with seagrass abundance below docks and with features of individual docks (e.g. height, width, water depth). Such studies would be a first step towards determining the threshold for significant shading effects on seagrass and the interactive effects of dock design on this threshold.

Seagrass biomass varied among transects in sites with docks of both orientations and in sites without docks. Variation among transects in sites with docks may have occurred because of variation in the age of docks and therefore the duration of shading of seagrass beds. The observed variation in seagrass biomass among transects and among replicates within transects in seagrass beds without docks is not unusual. Spatial variation (at similar scales used in this study) in seagrass features (biomass, leaf length, shoot density) has been reported in other estuaries in south-east Australia (Bell and Westoby, 1986; Edgar *et al*., 1994; Fyfe and Davis, 2007).

4.2 Effects of dock orientation

There was no effect of the orientation of docks on seagrass biomass: seagrass was consistently reduced below wooden docks with north-south or east-west orientations. This result contrasts with the only other study of dock orientation (Burdick and Short 1999) that reported significantly less seagrass below east-west docks than north-south docks. The authors explained that the difference between dock orientations reflected the daily movement of the sun from east to west causing the centres of east-west docks to be shaded for most of the day whereas the centres of north-south docks were shaded only in the middle of the day (Burdick and Short, 1999). The authors therefore recommended that, to minimize impacts on seagrass, docks should be oriented within 10^0 of the north-south axis. The difference in results between the present study and the study of Burdick and Short (1999) may be attributed to differences in dock widths. The docks studied in Lake Macquarie were 900-1100 mm wide. Docks studied by Burdick and Short (1999) were 0.7 to 6.9 m wide and 12 of the

21 docks exceeded 1.5 m width. The absence of an effect of dock orientation in Lake Macquarie may reflect the generally narrower width and the change in the angle of the sun throughout the year. At a latitude of 32^0S (the approximate position of the study area) in June the sun's altitude will be approximately 33^0 above the northern horizon and in December its altitude will be approximately 80^0 (source: http://wwwphys.murdoch.edu.au/rise/reslab/resfiles/sun/text.html, accessed June 14, 2007). Therefore there would not be many months per year that the area immediately below docks may be shaded for a large part of the day. Additional studies comparing the effects of a range of dock widths and orientations on light availability and seagrass growth may provide more information on the acceptable limits of dock dimensions.

4.3 Comparison of wooden and mesh docks

The use of an aluminium mesh decking reduced the effects of docks on seagrass. Biomass of seagrass below mesh docks was always greater than below wooden docks, although biomass below both dock types was always less than undisturbed seagrass. Although light was not measured in this study, it is likely that the mechanism responsible for the reduced effects of aluminium mesh docks is greater light penetration through the deck compared to wooden docks. The effects of wooden and mesh docks were not compared in another study (Fyfe and Davis, 2007); however, it found a significant effect of a single mesh dock on seagrass (73% decline in shoot density). Other studies evaluating the effectiveness of alternative materials to increase light penetration through docks, such as glass prisms (Steinmetz et al. 2004) and grating (Fresh et al. 2006), also found no measurable benefits.

The comparison of wooden and mesh docks and the assessment of the impacts of dock installation revealed changes in seagrass biomass through time. Although we used a destructive method of sampling seagrass, we attempted to eliminate potentially negative effects of sampling at one time on the plants collected subsequently by ensuring the latter were not collected within the vicinity of previous collections (i.e. within 1.5 m). The inconsistency among treatments in the direction (i.e. increase or decrease) and magnitude of temporal variation in seagrass biomass suggests this risk was minimised by our sampling approach. Temporal variation in seagrass biomass occurred under existing mesh docks as well in seagrass beds with no docks. The major feature of this temporal variation was an autumn-winter decline in seagrass biomass, which was apparent as a decline after March-June 2006. Similar winter die-back of *Z. muelleri* subsp. *capricorni* has been reported in Port Hacking (Kirkman *et al*., 1982) and Botany Bay (Larkum *et al*., 1984) and for *Z. muelleri* subsp. *muelleri* in Port Phillip Bay, Victoria (Kerr and Strother, 1990) and for *Heterozostera tasmanica* in Westernport Bay, Victoria (Bulthuis and Woelkerling, 1983; Edgar *et al*., 1994). Shoot growth rates of *Z. muelleri* subsp. *capricorni* are also lowest in winter (King and Holland, 1986). The temporal variation in *Z. muelleri* subsp. *capricorni* reported for Lake Macquarie in this study therefore appears to represent a natural phenomenon typical of this species and other related species.

The lack of temporal variation in *Z. muelleri* subsp. *capricorni* biomass below wooden docks is intriguing. Seasonal declines in *Z. muelleri* subsp. *muelleri* biomass are associated with changes in solar radiation and day length (Kerr and Strother, 1989). The majority of the seasonal change in total plant biomass in *Z. muelleri* subsp. *capricorni* and *Z. muelleri* subsp. *muelleri* is accounted for by changes in leaf biomass (Kirkman *et al*., 1982; Larkum *et al*., 1984; Kerr and Strother, 1990). The lack of seasonal variation in seagrass biomass below wooden docks could be due to the absence of a strong seasonal variation in light levels, or the amount of light penetrating below docks may not be sufficient for a significant increase in growth. This explanation is supported by other studies (Shafer, 1999) that have found a greater relative reduction in shoot density than total plant biomass under docks.

A modified beyond BACI experiment confirmed the results of the field surveys and provided evidence that the installation of docks caused a significant decline in seagrass biomass. Although only single examples of each dock type were available for study, the comparison of both dock types with multiple control sites provided a meaningful test of the effects of dock construction. Simultaneous testing of multiple examples of dock construction will improve the generality of this finding. Seagrass biomass below the wooden and mesh docks declined by similar amounts, 96% and 90% respectively, 26 months after dock installation. The experimental design employed in this study cannot distinguish between potential impacts of the installation process (e.g. seagrass destruction resulting from the insertion of pilings into the sediment as the support for the decking) and the combined effects of the installation process and shading from the dock decking. It was not possible to include a control for the installation process (i.e. pilings without decking) therefore the results of this study refer to the combined effects of installation and shading.

The declines in biomass below the new docks were detectable over and above a general decline in seagrass biomass that occurred in all the control sites over the same time period (Figure 4). Similar dramatic declines in seagrass under new docks and in control sites were also reported in the only other study to assess the impacts of dock construction (Beal and Schmit, 2000). The declines were due to natural processes (i.e. algal bloom) that affected control and treatment sites equally. However, by 33 weeks after construction the cover of seagrass was less under the new docks than control sites.

5. Conclusion

Infrastructure, such as docks, associated with recreational usage of estuaries in south-east Australia is an issue for the long-term conservation of seagrasses. Although the total 'footprint' of ecological effects of docks in estuaries is small relative to other disturbances, they contribute to the total impact of human uses of estuaries. The effects of docks on seagrass were not influenced by the orientation of the docks used in this study, and their effects were reduced when aluminium mesh decking was used in place of wooden decking. Field observations of the effects of docks on seagrass were supported by a modified BACI field experiment involving the installation of wooden-deck and aluminium mesh-deck docks. Alternative controls, such as limits to the total numbers of docks and the use of other construction materials, may have additional conservation benefits.

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Table 1. Summary of results of four-factor PERMANOVA testing for differences in biomass of *Zostera muelleri* subsp. *capricorni* between seagrass beds with and without wooden docks (Treatment) of north-south and east-west orientations (Orientation) in different sites (Sites), and at multiple docks or transects in each site (untransformed data, variances homogeneous, Cochran's C=0.12, P>0.05) (n=9999 permutations of residuals under a reduced model).

Source of variation	df	MS	Pseudo-*F*	*P*(perm)
Treatment: T	1	3912	29.81	0.002
Orientation: O	1	379.90	2.90	0.13
T x O	1	1.55	0.01	0.90
Site(T x O): Si(T x O)	8	131.21	1.48	0.19
Transect(Si(T x O))	24	88.96	5.81	0.0001
Res	144	15.31		

Table 2. Summary of results of three-factor PERMANOVA testing for differences in biomass of *Zostera muelleri* subsp. *capricorni* at three times (Time) between wooden docks, mesh docks and control seagrass beds without docks (Treatment) and among multiple examples of each Treatment level (Transects). Analyses done on Ln(X+1.5) transformed data (Cochran's C=0.07, P>0.05) and n=9999 permutations of residuals under a reduced model.

Source of variation	df	MS	Pseudo-*F*	*P*(perm)
Time: Ti	2	1.58	22.86	0.0001
Treatment: Tr	2	9.67	12.06	0.0001
Transects(Tr)	18	0.08	1.13	0.38
Ti x Tr	4	0.73	10.54	0.0001
Ti x Transect(Tr)	36	0.07	2.33	0.0002
Res	252	0.03		

Table 3. Summary of asymmetrical PERMANOVA results testing for a change in biomass of *Zostera muelleri* subsp. *capricorni* from (a) before to 7 mo after, and (b) from before to 26 mo after installation of a wooden dock. The change occurring below the newly installed dock was compared with changes among n=6 transects in each of n=3 control sites (n=9999 permutations of residuals under a reduced model).

(a) Before to 7 mo after installation (Ln(X+0.1) transformed data, Cochran's *C*=0.11, *P*>0.05)

Source of variation	df	MS	Pseudo-*F*	*P*(perm)
Before v After: B v A	1	12.36	38.62	0.002
Dock v Control: D v C	1	0.50	0.44	0.54
Site(D v C): Si(D v C)	2	3.92	10.29	0.002
(B v A) x (D v C)	1	1.12	3.50	0.07
Transect(Site(D v C)): Tr(Si(D v C))	15	0.38	1.96	0.02
(B v A) x Si(D v C)	2	0.07	0.18	0.83
(B v A) x Tr(Si(D v C)	15	0.39	1.99	0.02
Res	152	0.19		

(b) Before to 26 mo after installation (Ln(X+0.1) transformed data, Cochran's *C*=0.07, *P*>0.05)

Source of variation	df	MS	Pseudo-*F*	*P*(perm)
Before v After: B v A	1	35.17	141.08	0.001
Dock v Control: D v C	1	2.34	1.64	0.18
Site(D v C): Si(D v C)	2	4.97	10.31	0.002
(B v A) x (D v C)	1	3.53	14.15	0.007
Transect(Site(D v C)): Tr(Si(D v C))	15	0.48	3.22	0.0002
(B v A) x Si(D v C)	2	0.34	1.49	0.26
(B v A) x Tr(Si(D v C)	15	0.23	1.51	0.11
Res	152	0.15		

Table 4. Summary of asymmetrical PERMANOVA results testing for a change in biomass of *Zostera muelleri* subsp. *capricorni* from (a) before to 6 mo after, and (b) from before to 26 mo after installation of a mesh dock. The change occurring below the newly installed dock was compared with changes among n=6 transects in each of n=3 control sites (n=9999 permutations of residuals under a reduced model).

(a) Before to 6 mo after installation (Ln(X+0.1) transformed data, Cochran's C=0.10, P>0.05)

Source of variation	df	MS	Pseudo-*F*	*P*(perm)
Before v After: B v A	1	12.25	22.14	0.002
Dock v Control: D v C	1	3.42	1.81	0.15
Site(D v C): Si(D v C)	2	7.91	27.06	0.0001
(B v A) x (D v C)	1	1.82	3.29	0.09
Transect(Site(D v C)): Tr(Si(D v C))	15	0.29	2.01	0.02
(B v A) x Si(D v C)	2	0.48	0.83	0.46
(B v A) x Tr(Si(D v C)	15	0.57	3.94	0.0001
Res	152	0.15		

(b) Before to 26 mo after installation (Ln(X+0.1) transformed data, Cochran's C=0.08, P>0.05)

Source of variation	df	MS	Pseudo-*F*	*P*(perm)
Before v After: B v A	1	21.90	77.16	0.002
Dock v Control: D v C	1	2.61	1.15	0.24
Site(D v C): Si(D v C)	2	8.54	14.10	0.0004
(B v A) x (D v C)	1	1.24	4.38	0.05
Transect(Site(D v C)): Tr(Si(D v C))	15	0.61	3.45	0.0001
(B v A) x Si(D v C)	2	0.42	1.67	0.22
(B v A) x Tr(Si(D v C)	15	0.25	1.42	0.15
Res	152	0.18		

FIGURE CAPTIONS

Fig. 1. Locations of study sites in Lake Macquarie used to assess *Zostera muelleri* subsp. *capricorni* for ● effects of dock orientation (each symbol represents 3 docks or 3 seagrass beds without docks), ○ comparison of wooden vs mesh dock study (each symbol represents a single dock or single transect in a sesagrass bed without transects), and for BACI study on effects of installation of wooden dock (☆) and mesh dock (★).

Fig. 2. Biomass of *Zostera muelleri* subsp. *capricorni* in Lake Macquarie in each of 3 sites with no docks (east-west (EW) and north-south (NS) orientations) and 3 sites with wooden docks (EW and NS orientations). Values shown are mean+standard error of 3 transects in each site (n=5 replicate samples per transect).

Fig. 3. Biomass of *Zostera muelleri* subsp. *capricorni* seagrass below wooden docks, below mesh docks and in seagrass beds with no docks (i.e. controls). Values shown are mean+standard error from 7 transects in each treatment at each time (n=5 replicate samples per transect).

Fig. 4. Changes in biomass of *Zostera muelleri* subsp. *capricorni* seagrass from before to after installation of (a) wooden dock and (b) mesh dock in transects below each dock and in control site (C1-C3). Values shown are mean+SE based on 1 transect below each dock (n=5) and the mean of six transect-level means in each site at each time.

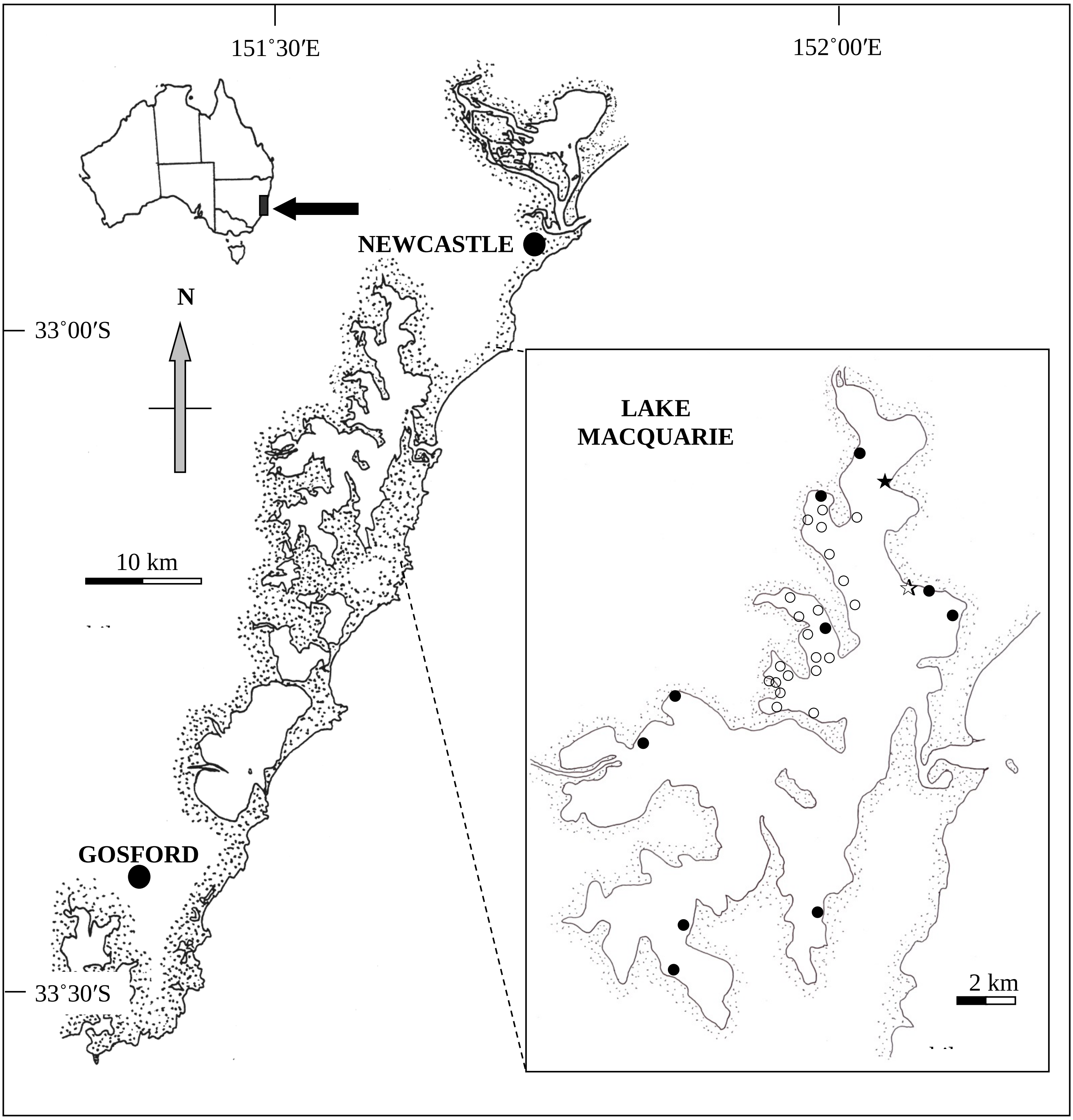
151˚30′E
152˚00′E
NEWCASTLE
N
33˚00′S
10 km
LAKE
MACQUARIE
GOSFORD
33˚30′S
2 km

Fig. 1.

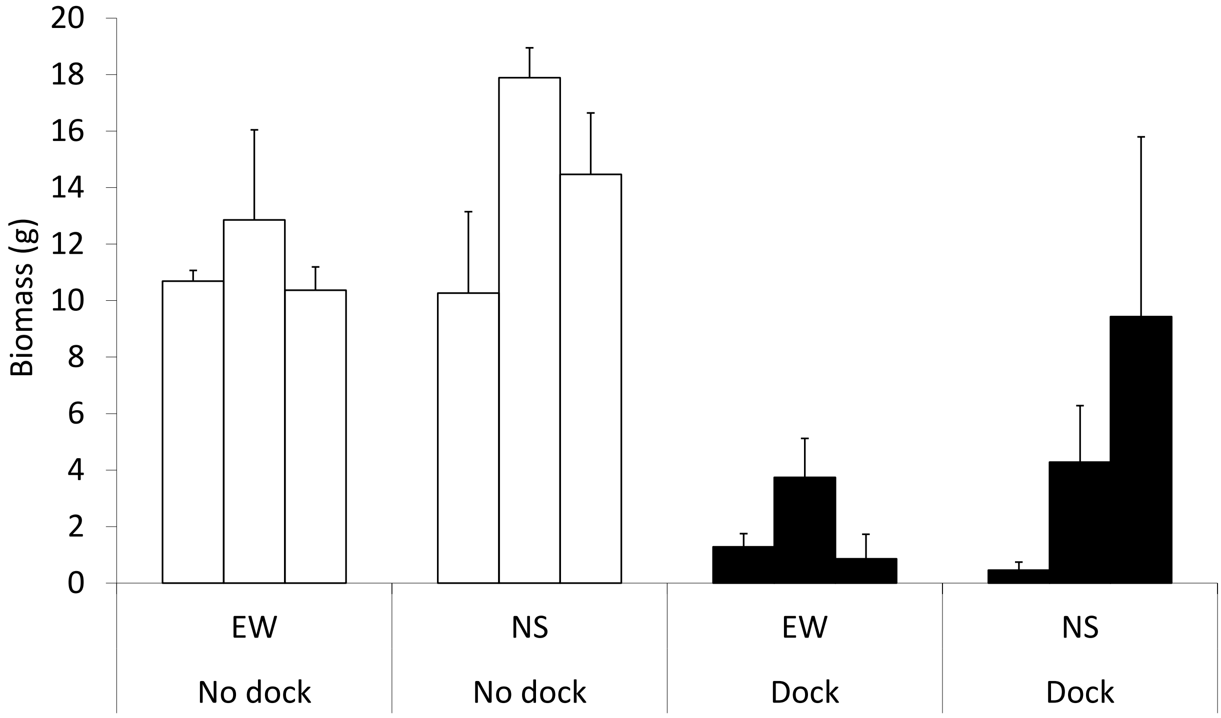
Biomass (g)
20
18
16
14
12
10
8
6
4
2
0
EW
No dock
NS
No dock
EW
Dock
NS
Dock

Fig. 2.

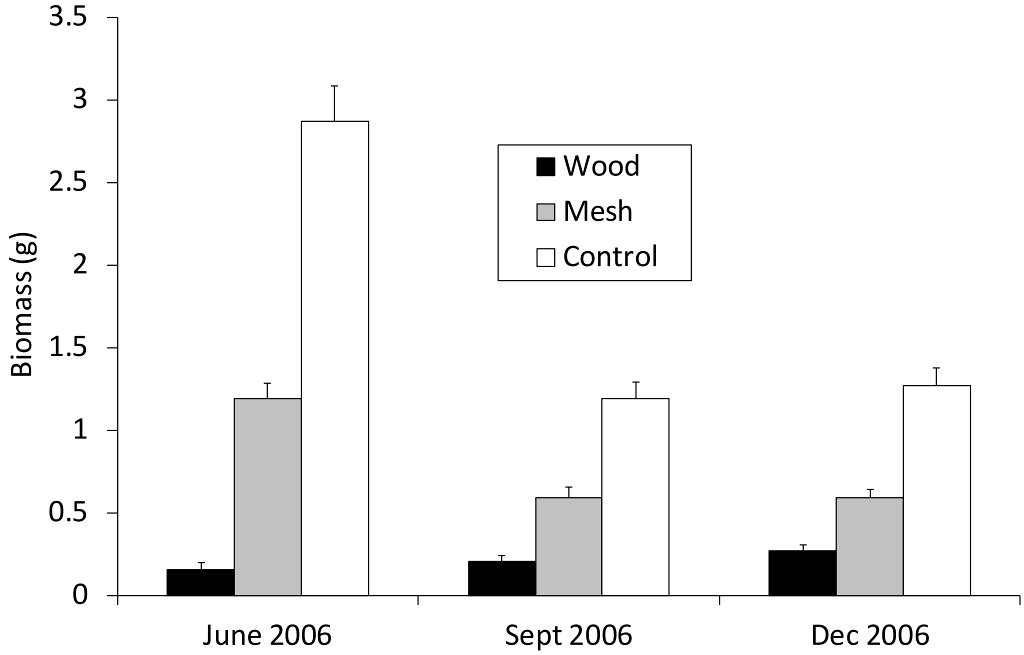
3.5
3
2.5
2
1.5
1
0.5
0
Biomass (g)
Wood
Mesh
Control
June 2006
Sept 2006
Dec 2006

Fig. 3.

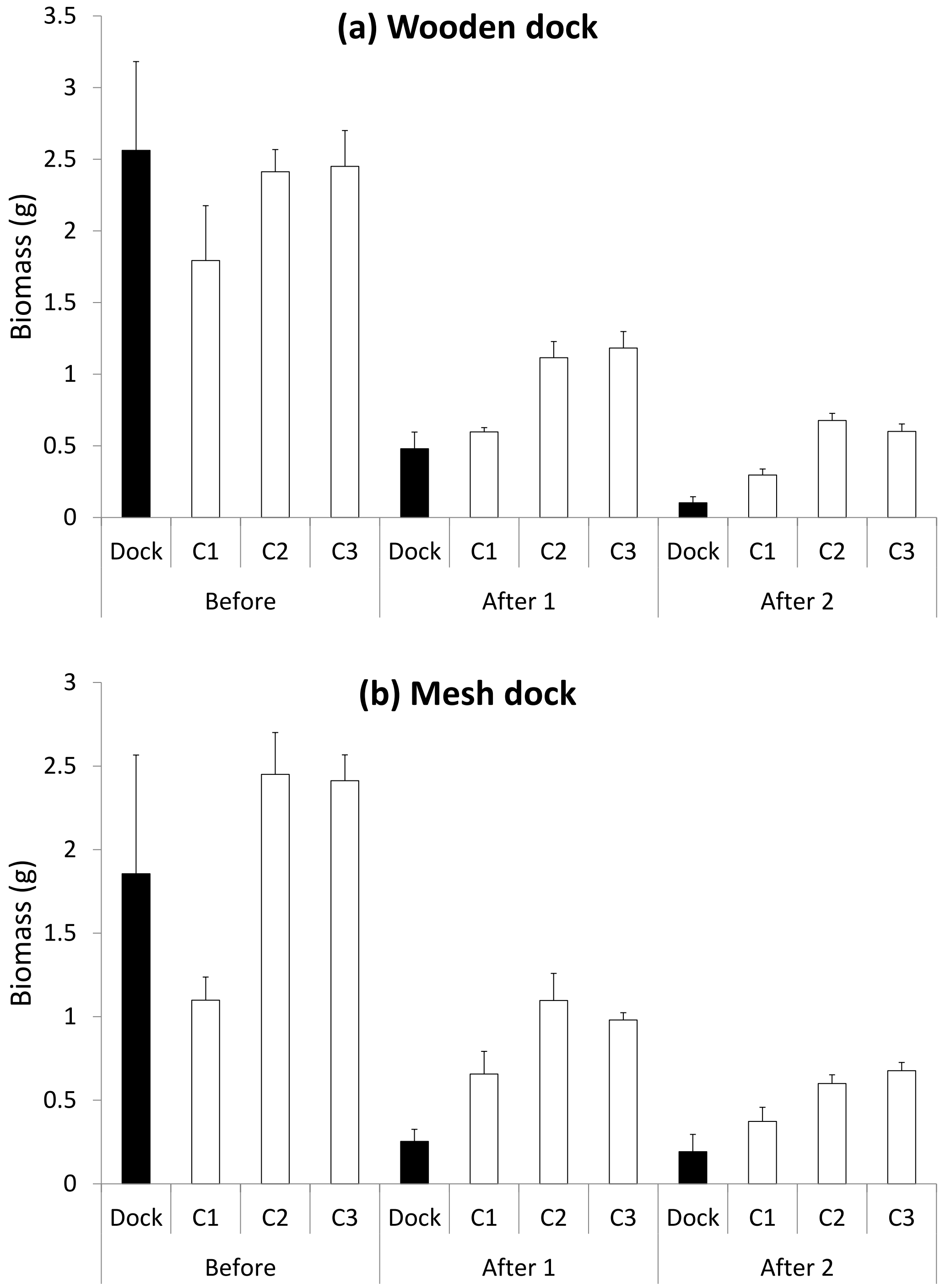
(a) Wooden dock
Biomass (g)
3.5
3
2.5
2
1.5
1
0.5
0
Dock
C1
C2
C3
Dock
C1
C2
C3
Dock
C1
C2
C3
Before
After 1
After 2
(b) Mesh dock
Biomass (g)
3
2.5
2
1.5
1
0.5
0
Dock
C1
C2
C3
Dock
C1
C2
C3
Dock
C1
C2
C3
Before
After 1
After 2

Fig. 4.