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Estimating losses of *Posidonia australis* due to boat moorings in Lake Macquarie, Port Stephens and Wallis Lake

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Non-technical summary

Estimating losses of *Posidonia australis* due to boat moorings in Lake Macquarie, Port Stephens and Wallis Lake

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Objectives

- Develop a technique for accurately estimating losses of seagrasses due to boat moorings.
- Use recent aerial imagery to estimate the areal extent of mooring scars in *Posidonia australis* beds in the Hunter region.
- Raise awareness about the values of estuarine habitats.

Key words

Seagrass, boat, swing mooring, impact, habitat, estuary

Summary

Seagrasses create valuable estuarine habitats that play numerous ecological roles, including stabilising sediments, acting as carbon stores, regulating nutrients, and providing food and shelter for fishes, invertebrates and algae. The ability of seagrasses to recover from disturbances varies among species, with species of *Zostera* recovering relatively quickly whereas species of *Posidonia* are particularly slow to recover from damage. Consequently, *Posidonia* may experience decadal declines in abundance due to natural or anthropogenic disturbances.

In NSW, six estuarine populations of the seagrass *Posidonia australis* have been listed under the *Fisheries Management Act* 1994 as endangered, one of which (Lake Macquarie) is in the Hunter region. In addition, *P. australis* meadows in the Manning-Hawkesbury bioregion were listed on 7 May 2015 as threatened ecological communities in the endangered category under the Commonwealth's *Environment Protection and Biodiversity Conservation Act* 1999. *P. australis* is known to occur in 17 estuaries in NSW (between Wallis Lake and Twofold Bay) and in each it is subjected to boating-related disturbances, particularly from traditional block and chain boat moorings. Roads and Maritime Services (RMS) administers and manages over 19,000 moorings currently in use across NSW, most of which are in designated mooring areas. The most common moorings are block and chain swing moorings, so named because they have traditionally consisted of a heavy weight (a block) that sits on the seabed, to which a length of heavy chain is attached. When a vessel is attached to the mooring, wind and currents cause the

vessel to swing around the mooring and the chain scours the seabed, which removes any large organisms and results in a visible “scar” in the seagrass meadow.

This project quantified the loss of *P. australis* due to moorings in the three Hunter estuaries where this seagrass grows, namely Lake Macquarie, Port Stephens and Wallis Lake. We also estimated mooring damage to the smaller, faster growing seagrass *Zostera capricorni*, but only in Lake Macquarie. Given the natural patchiness of *Z. capricorni* and how variable its distribution and abundance can be over time, estimates of damage are likely to be far less reliable than those for *P. australis*. Moreover, it was not possible to accurately estimate damage caused by moorings to fragmented beds of *Z. capricorni*. Losses of seagrass due to moorings were estimated relative to the latest seagrass maps for each estuary, namely 2014 for Lake Macquarie and Port Stephens and 2011 for Wallis Lake. We did not distinguish between different densities of seagrass in this study and acknowledge that the total biomass of seagrass lost per mooring will differ greatly depending on the density of the seagrass bed in which the mooring is located.

Of the 2,602 moorings in Lake Macquarie, 122 (5%) were outside RMS-designated mooring areas. The percentage was similar in Port Stephens (8% of the 846 moorings), while in Wallis Lake 77% of the 103 moorings were outside RMS-designated mooring areas. Most of these “out of area” moorings were positioned on non-vegetated sediment, but some were impacting *P. australis* (4 in Lake Macquarie, 12 in Port Stephens, 0 in Wallis Lake) or *Z. capricorni* (30 in Lake Macquarie, 9 in Port Stephens, and 13 in Wallis Lake).

We demonstrated that the amount of damage a mooring creates to seagrass (measured as scar area) increases with depth and is typically greater in beds of *P. australis* than *Z. capricorni*. There was, however, considerable variability among scar areas for any given depth, which may reflect differences in the materials used to construct the mooring, boat sizes, and physical attributes of the mooring site (which influence exposure to wind and waves and hence movement of boats on the mooring).

Mean scar sizes in *P. australis* differed among estuaries, being larger in Port Stephens ($305 \pm 45 \text{ m}^2$ averaged over all depths) than in Lake Macquarie ($167 \pm 12 \text{ m}^2$ averaged over all depths). There were roughly similar numbers of moorings impacting *P. australis* in Lake Macquarie (210) and Port Stephens (179), but just one impacting *P. australis* in Wallis Lake. Of the moorings impacting seagrass, the vast majority in Port Stephens (70%) were impacting *P. australis* whereas the percentages were less in Lake Macquarie (33%) and Wallis Lake (3%).

The total loss of *P. australis* due to moorings was estimated as 76,467 m^2 in Lake Macquarie, 19,844 m^2 in Port Stephens and 320 m^2 in Wallis Lake (the latter from just one mooring). This was an underestimate for Port Stephens because a lack of detailed bathymetric data meant we could not accurately estimate total losses amongst fragmented seagrass beds. Most of the *P. australis* was lost from water < 3.5 m deep where the seagrass formed (or, in the absence of moorings, could have formed) contiguous beds. If all seagrasses are considered together, the loss in Lake Macquarie increases to 114,875 m^2 (no estimates for other seagrasses in Port Stephens or Wallis Lake). The large seagrass loss in Lake Macquarie was due in part to the large number of ‘residual’ mooring scars, that is, scars that were not directly related to any currently-assigned moorings. These residual scars may have been a result of old moorings that

have been removed or the repositioning of current moorings, but this cannot be verified without access to historical mooring data.

NSW DPI policy generally does not support proposals to install new, replace or relocate existing moorings in *P. australis* seagrass and other seagrass beds greater than 5m². But in situations where the harm of seagrass is permitted, adequate compensation measures are required. Monetary habitat compensation is calculated on a minimum 2:1 basis for seagrasses, which equates to a cost of \$112/m². Using this monetary value, the average environmental cost of a new block and chain mooring in seagrass in Hunter estuaries would be \$18,368 (based on a mean scar area of 164 m² across all habitats, depths and estuaries). This value could be up to \$79,072 for a mooring in *P. australis* in Port Stephens (largest mapped scar area of 706 m²). Effective environmentally friendly mooring (which have little physical contact with the seabed) cause minimal damage to seagrasses and can allow recolonization of seagrass (primarily *Halophila* spp. and *Z. capricorni*) in old scars. The cost of an effective environmentally friendly mooring (~\$3,500 purchase price plus annual maintenance costs) is considerably less than the cost of damage to seagrass based solely on monetary values for habitat compensation.

Based on the findings of this and other studies, it would be prudent to continue to implement strategies to minimise mooring-related damage to seagrass beds, particularly those dominated by *P. australis*. Such strategies could include (1) ensuring that block and chain moorings are not (accidentally or otherwise) deployed in seagrass beds, which requires accurate positioning of moorings and the utilisation of the latest available maps of seagrass beds; (2) ensuring that existing block and chain moorings are not moved within seagrass beds either by contractors during maintenance, or due to inadequate weight for the size of a vessel or exposure of the mooring site. This would require minimum standards for moorings and accurate co-ordinates for the position of the blocks; (3) relocating existing block and chain moorings out of seagrass beds wherever possible; (4) where moorings must be in seagrass beds, ensuring that they be environmentally friendly swing moorings that do not scour the seabed; (5) phasing out of the lawful use of traditional block and chain moorings in other sensitive aquatic habitats; and (6) creating the appropriate regulatory and market environment to reduce (or subsidise) the purchase and ongoing cost of environmentally friendly moorings and increase the demand for their use.

Introduction

Estuaries throughout the world are a focus for a range of human activities and infrastructure. Estuaries also support numerous ecologically important habitats which are very different from those on the open coast. The sheltered and relatively shallow nature of estuaries creates conditions suitable for the growth of many seagrass species and also makes them ideal for the housing of boats. The substantial interaction between human activities and estuarine habitats makes environmental impacts likely, unless appropriate management initiatives are implemented diligently.

Seagrass beds often support a rich variety of animals and algae, and act as sources of food (mainly indirectly via epiphytes and detritus) and shelter for numerous species (Beck et al. 2001). Seagrasses also stabilise sediments, act as carbon stores and regulate nutrients within estuaries (Duarte 2002, Orth et al. 2006). The ability of seagrasses to recover from disturbances varies among species, with species of *Halophila* being able to recolonise areas moderately quickly, followed by species of *Halodule* and *Zostera* (Orth et al. 2006). The long-lived genus *Posidonia* (represented in NSW by a single species, *P. australis*) is the most likely to be damaged in the long term because damaged plants are slow to recover (Clarke & Kirkman, 1989; Kuo & Kirkman, 1996; Meehan & West, 2000) and recolonisation of denuded areas by seedlings is rare (Meehan & West, 2000; Meehan & West 2004). As such, *Posidonia* may experience decadal declines in abundance due to natural or anthropogenic disturbances (Kirkman, 1985; Larkum & West, 1990; Kendrick et al., 2002).

For the reasons outlined above, all seagrass species in NSW are protected under the *Fisheries Management Act 1994*. In addition, *P. australis*, has been recognised to have been so impacted by humans over the last century that populations of it have been officially listed as endangered in six estuaries (Lake Macquarie, Brisbane Water, Pittwater, Port Jackson, Botany Bay and Port Hacking) under this Act. Furthermore, *P. australis* meadows in the Manning-Hawkesbury bioregion were listed on 7 May 2015 as threatened ecological communities in the endangered category under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*.

In total, *P. australis* occurs in 17 estuaries in NSW between Wallis Lake and Twofold Bay and in each it is subjected to boating-related disturbances, particularly from block and chain moorings. Because *P. australis* has a restricted potential distribution in NSW and is slow to recover from physical disturbances, it is crucial to minimise direct human impacts if further declines of the species are to be prevented. In the Hunter region, *P. australis* occurs in three estuaries, namely Lake Macquarie, Port Stephens and Wallis Lake.

NSW Roads and Maritime Services (RMS) has the responsibility for administering and managing moorings in NSW. There are 26,646 available or occupied moorings in NSW, which are grouped into one of four categories, namely commercial, private, courtesy or emergency (Transport NSW, 2014). The vast majority (76%) of these moorings are designated as private mooring leases (PMLs) and of these, swing moorings are the most common mooring system (86% of all PMLs) which are typically used for vessels ranging between 5 – 10 m in length (Transport NSW, 2014). Moorings are located in designated mooring areas scattered throughout NSW estuaries. Caps have been placed on the number of moorings that can be placed in mooring areas. These caps were determined by RMS with consideration of factors

such as water depth, navigational requirements and seagrass distribution (Transport NSW, 2014).

Swing moorings are also called block and chain moorings because they have traditionally consisted of a heavy weight, such as a concrete block, sitting on the seabed with a length of heavy chain attached. A rope connects the chain to a float (mooring buoy) on the surface of the water. When a vessel is attached to the mooring, wind and currents cause the vessel to swing around the mooring and the chain scours the seabed (Walker et al. 1989). Not surprisingly, this generally results in the loss of any obvious biota that was growing within the radius of the chain around the mooring block. The biota most commonly affected includes seagrasses, algae and invertebrates living either on or in the sediments (Herbert et al. 2009). The damage to seagrass can be either complete removal or a decrease in density in close proximity to the mooring (La Manna et al. 2015).

It has been estimated from aerial photos that approximately 13% of the seagrass in one area off Rottnest Island (Western Australia) was lost to boat moorings between 1981–1992 (Hastings et al. 1995). It is likely that these losses occurred relatively quickly after the installation of the moorings, rather than gradually over the 10 year period (noting that photos from just two dates, Oct 1981 and May 1992, were analysed). The damage caused by moorings in NSW was highlighted recently by West (2011) who concluded that a “thorough inventory of damaged sites and the development of a management strategy to resolve the problem, such as the use of seagrass friendly moorings, are urgently required”. A first attempt at quantifying the damage of moorings in Lake Macquarie estimated that 60,000 m² (6 hectares) had been lost (Wright et al. 2013). In Jervis Bay, Demers et al. (2013) demonstrated that the damage to seagrass (*Posidonia australis*) by traditional swing moorings was significantly greater than that caused by environmentally friendly moorings that did not have a heavy chain which could scour seagrasses.

The aim of this project was to quantify the loss of *P. australis* in boat mooring areas (measured as scar areas) in the three Hunter estuaries where *P. australis* occurs. For Lake Macquarie, we also estimated losses of *Zostera muelleri* ssp. *capricorni* (hereafter *Z. capricorni*), although this was not the main focus of the study. Given that seagrasses and boat moorings occur over a range of depths we also chose to examine the relationship between mooring damage and, depth and seagrass species.

Methods

Study locations

Three estuaries were included in this study, namely Lake Macquarie, Port Stephens and Wallis Lake. Estimates of mooring damage to *P. australis* were calculated for the entire distribution of this seagrass in each estuary. Losses of *Z. capricorni* due to moorings were also estimated but only for contiguous beds in Lake Macquarie.

Mooring data

The number of moorings in the three estuaries was determined using mooring location data provided by RMS. These data were composed of two layers; a point file showing the mooring locations dated May 2013 and a polygon layer showing the designated mooring areas.

Mapping seagrass extent

Lake Macquarie

Seagrass extent was mapped as part of a project for Lake Macquarie City Council in 2012. This mapping was carried out using high resolution imagery captured by AAM Pty Ltd. Seagrass habitat was mapped using the Object Based Image Analysis (OBIA) software, Definiens eCognition™. Seagrass polygons were identified using image segmentation and a combination of image band ratios and depth data thresholds. Preliminary identified seagrass areas were exported as shapefiles and used for field validation. The field validation data were then used to update the mapped data to create the final map.

A closer assessment of the 2012 seagrass maps indicated that the amount of *P. australis* mapped in the Belmont Bay area was over-represented. To rectify this, and to obtain a better estimate of the overall mooring damage, the images for this section of the lake were modified using Adobe® Photoshop® to enhance the separation of the seagrass from the background substrate (Figure 1.). These modified images were then remapped using the same OBIA methods and validated using field data collected on 15th December 2014.



Figure 1. Comparison of original and enhanced images for the updated mapping of *P. australis* in Belmont Bay, Lake Macquarie.

Port Stephens

For the purposes of this study, Port Stephens did not incorporate either the Myall or Karuah rivers. The 2004 map of all seagrasses throughout all of Port Stephens was used to estimate the number of moorings that were likely to be impacting different species of seagrasses. A new seagrass map was created for all areas where moorings were impacting *P. australis* using the latest available aerial imagery from Nearmap (9th August 2014) with a resolution of 0.29m. Seagrasses were mapped using OBIA techniques and the preliminary map was validated in the field using underwater video deployed from a boat from Nov–Dec 2014.

Wallis Lake

The seagrasses in Wallis Lake were originally mapped in 2002 and partially remapped in 2011. Given that only one mooring in Wallis Lake was close enough to be impacting *P. australis* (i.e. within 7 m, see below), it was decided that new mapping of the seagrass was not warranted. The extent of mooring damage was directly mapped from the most recent aerial imagery captured in May 2010 and validated in the field on 20th January 2015.

Moorings distribution relative to seagrasses

The distribution of moorings to the mapped seagrass was determined by overlaying the mooring point layer over the most recent entire-estuary seagrass map for each estuary, namely 2012 mapping for Lake Macquarie, 2004 for Port Stephens and 2002 for Wallis Lake. Any mooring that was within the outer boundaries of a seagrass bed (i.e. over seagrass or over a scar within the seagrass bed), or within 7 m of the seagrass beds was considered to be impacting the seagrass. This 7 m radius was a conservative estimate of scar size in *P. australis* meadows, the average size across Lake Macquarie and Port Stephens being 7.75 m (see Results).

We also investigated how many moorings were outside the RMS-designated mooring areas. To do this, we assumed that the spatial error of mooring positions could be up to 10 m (standard GPS error). Thus we conducted a spatial search of all moorings in or within 10 m of a RMS-designated mooring area.

Quantifying the amount of mooring damage

Losses of *P. australis* due to moorings were estimated relative to the latest seagrass maps for each estuary, namely 2014 for Lake Macquarie and Port Stephens and 2011 for Wallis Lake. Losses of *Z. capricorni* in Lake Macquarie were relative to a 2012 map. As outlined below, areal estimates of mooring damage were mapped using different methods for contiguous versus fragmented beds of seagrass, which involved using depth data to identify the likely deep edge of contiguous seagrass. Due a lack of detailed bathymetry data for Port Stephens, estimates of seagrass loss were not possible in all fragmented beds, meaning that the overall estimate of seagrass loss due to moorings was more conservative than in Lake Macquarie. Depth data were also used to investigate relationships between mooring scar size and depth, but again this was less accurate in Port Stephens due to the coarser bathymetry data compared to Lake Macquarie. Finally, we assessed two simplified methods for estimating mooring damage. The first was a method for estimating scar areas using a simple area calculation (rather than mapping the scar) and the second was a method for estimating total seagrass loss within an estuary. These simplified methods are also outlined below.

Mapped estimates of mooring damage

Lake Macquarie

Moorings scars were identified in *P. australis* and *Z. capricorni* meadows and locations of assumed scars were verified by association with known mooring locations in the RMS mooring layer and visual interpretation of the recent aerial imagery (i.e. either a boat or mooring buoy being visible close to a scar). Scars that were not clearly associated with any current moorings, but were nearby, amongst contiguous seagrass beds, roughly circular or arc-shaped and > 20 m² were assumed to have been created by swing moorings.

Within contiguous beds of seagrass, scars were delineated via onscreen editing in ArcGIS and the areas were calculated. In some locations, typically on the deeper edge of beds of *P. australis*, moorings were situated within fragmented beds of seagrass. *P. australis* beds can be naturally fragmented, thus, we needed to distinguish natural fragmentation from fragmentation caused by current or historical moorings (hereafter termed “ostensibly contiguous” beds). To do this, we selected *P. australis* beds that were outside RMS-designated mooring areas, apparently unmodified by physical human disturbances and extending over as large a depth range as possible. We then determined the depth at which the beds of *P. australis* changed from being contiguous to fragmented by measuring the depth of the interface between contiguous and fragmented *P. australis* at 100 random points along two sections (over a distance of 2.5 km; Figure 4). Depths were obtained from a high resolution bathymetry spatial layer provided by OEH. The mean depth of this fragmented/contiguous interface was then plotted as depth contour in mooring areas and all bare areas shallower than this depth contour (i.e. ostensibly contiguous beds) were assumed to have been created by either current or historical moorings. This area was then calculated as the area of *P. australis* lost due to moorings in ostensibly contiguous beds.

P. australis beds deeper than the fragmented/contiguous depth contour were deemed to be naturally fragmented (Figure 5). It was not possible to accurately delineate individual scar areas for moorings in the naturally fragmented beds. We, therefore, used a linear relationship between scar area and depth to estimate (a) the predicted scar area ($P_{\text{scar area}}$) for a mooring at any given depth and then estimated (b) percentage of this area that should be naturally covered by seagrass in a fragmented bed (%Frag). These two steps are outlined in the paragraphs below.

To establish the scar area vs depth relationship, we used only mooring scars in contiguous beds of seagrass that had clearly defined boundaries. We haphazardly selected mapped scars (62 amongst *P. australis* and 44 amongst *Z. capricorni*) and compared each area to its depth using linear regression. Depth data were derived from a bathymetric model with depths measured to the nearest millimetre (provided by OEH).

To estimate %Frag, four 50 x 50 m replicate quadrats were drawn in ArcMap over mapped areas of naturally fragmented seagrass (i.e. non-mooring areas) and, in each, the percentage cover of seagrass was calculated. Percentage covers were averaged over all quadrats. For each mooring in deeper naturally-fragmented *P. australis* beds, the predicted seagrass area (P_{seagrass}) in the absence of any mooring damage was calculated as $P_{\text{seagrass}} = \%Frag \times P_{\text{scar area}}$.

The area of seagrass loss per mooring could then be calculated as the difference between the predicted seagrass area and how much seagrass was actually mapped within the predicted scar

area, i.e. $P_{\text{scar area}}$ – mapped seagrass within $P_{\text{scar area}}$. In order to depict the predicted scar area in ArcMap, we assumed that the scar was circular (Figure 5B). This assumption was valid given that there was a very strong relationship between mapped scar area and estimated scar area (using two dimensions and the area of a circle, see results, Fig. 7). If $P_{\text{scar area}}$ for a mooring was less than the actual mapped seagrass, then it was assumed that there had been no loss of seagrass, i.e. the value for that mooring was set to zero rather than left as a negative number (which would have implied that the mooring had added seagrass).

Seagrass loss due to moorings in *Z. capricorni* habitat was estimated only for contiguous beds in Lake Macquarie. The great spatial variability in lower depth range of *Z. capricorni* throughout Hunter estuaries meant that it was difficult to calculate an average depth for fragmented *Z. capricorni* beds and so this was not attempted.

Port Stephens

Seagrass loss in Port Stephens was estimated as for Lake Macquarie, but only for *P. australis*. Moreover, ostensibly contiguous beds were not reconstructed for Port Stephens due to a lack of information about the depth distribution of naturally-fragmented beds of *P. australis* (i.e. it was not possible to find many *P. australis* beds that we could be sure were naturally fragmented). As such, losses of seagrass were underestimated relative to those in Lake Macquarie.

Where moorings were amongst fragmented seagrass, we used the method described above to estimate *P. australis* losses for particular depth ranges. The scar area vs depth relationship was investigated using coarse depth data derived from broad depth contours (0-2 m, 2-5 m) provided by RMS. The areas of 15 randomly selected scars in Port Stephens were compared to their depths using linear regression. To estimate %Frag, percentage cover of fragmented seagrass was estimated from the average of four 25 x 25 m quadrats.

Simplified methods for estimating mooring damage

We examined the accuracy of estimating scar area using a method that would be far quicker and simpler than creating a digitised map of the entire seagrass bed. This simplified method assumed scars were roughly circular, thus area was calculated using the formula $(\pi/4) \times D^2$. The size of each scar was measured in two dimensions (N-S and E-W) average diameter (D) calculated. This was done for *P. australis* and *Z. capricorni* habitats at a range of depths. These simplified scar area estimates were then compared to the actual mapped estimates for the same scars using linear regression.

Although we were able to obtain good aerial imagery for mapping mooring scars for this study, such imagery is not always available due to the great variability in estuarine water clarity and the fact that most imagery is not captured specifically for mapping in-water objects. Moreover, detailed mapping of seagrass beds from such high resolution imagery is time consuming and costly. Thus we investigated the usefulness of an alternative and greatly simplified method of estimating the amount of mooring damage which was not reliant on recent aerial imagery and high resolution seagrass maps. This alternative method utilised existing seagrass maps that lacked detail on the fragmentation of the beds. The method involved a simple calculation of the number of moorings (based on the RMS spatial layer) that potentially impacted seagrass, multiplied by the average size of a swing mooring scar for a particular depth. To determine which moorings impacted seagrass, we generated a circular buffer around each mooring point

(using the scar size vs depth relationship described in above) and overlaid this layer over the original mapped seagrass. In the fragmented beds, we reconstructed the seagrass loss using the estimate of natural percentage cover. The simplified loss estimates were calculated only for *P. australis* in Lake Macquarie.

Results

Moorings distribution relative to seagrasses

Based on the 2013 RMS mooring data provided to us, there are approximately 19,000 currently occupied moorings in NSW (of the 26,646 theoretically available; Transport NSW 2014) within 580 designated mooring areas covering a total area of 65.08 km². There are 167 RMS-designated mooring areas in the three estuaries examined in this study, covering a total area of 5.77 km² (Table 1). There are 3,551 moorings in the three estuaries with 2,602 in Lake Macquarie, 846 in Port Stephens and 103 in Wallis Lake (Table 2). In Lake Macquarie and Port Stephens 5 – 8% of moorings were outside designated mooring areas, whereas in Wallis Lake the majority of moorings (77%) were outside designated mooring areas (Table 2).

Any mooring that was within 7 m of seagrass was considered to be impacting on the seagrass. This 7 m radius was a conservative estimate of scar size in *P. australis*, the average size across Lake Macquarie and Port Stephens being 7.75 m (see below). The total number of moorings likely to be impacting seagrass in Lake Macquarie was 635, compared to 255 in Port Stephens and 24 in Wallis Lake (Table 3). It is important to note that this estimate for Port Stephens was based on the 2004 seagrass map (i.e. the last time the entire estuary was mapped) when there was much more *Z. capricorni* than is currently present. Thus this is an overestimate of the number of moorings currently impacting on *Z. capricorni* for Port Stephens.

Of the moorings impacting seagrass, 34 were outside of designated areas in Lake Macquarie, 21 in Port Stephens and 13 in Wallis Lake (Table 4). Most of the moorings outside designated mooring areas were situated over non-vegetated sediment. Of these “out of area” moorings, most in Lake Macquarie and Wallis Lake were impacting *Z. capricorni*, whereas in Port Stephens where most were impacting *P. australis* (Table 4).

Table 1. Total number and size of RMS-designated mooring areas in the three Hunter estuaries where *Posidonia australis* is present. Note that seagrass does not occur in all these designated mooring areas.

Estuary	# of designated mooring areas	Total area (ha)	Total area (km ²)
Lake Macquarie	126	301.94	3.02
Port Stephens	34	223.63	2.24
Wallis Lake	7	51.79	0.52
Total	167	577.36	5.77

Table 2. Total number of moorings in in the three Hunter estuaries where *Posidonia australis* is present and their relationship to the RMS-designated mooring areas. Any mooring within 10 m of a designated mooring area was deemed to be within the mooring area (to account for GPS error)

Estuary	In mooring areas	Outside mooring areas	Total moorings	% outside mooring areas
Lake Macquarie	2480	122	2602	4.7%
Port Stephens	782	64	846	7.6%
Wallis Lake	24	79	103	76.7%
Grand Total	3286	265	3551	7.5%

Table 3. Spatial relationship of moorings to mapped seagrass. Data are numbers of moorings (anywhere in an estuary) per habitat. Mixed seagrass habitat is *P. australis* and *Z. capricorni* and often species of *Halophila*. Total moorings impacting *P. australis* includes those moorings located amongst mixed seagrass.

Mooring location	Lake Macquarie	Port Stephens [#]	Wallis Lake	Total
On non-vegetated sediment	1967	591	79	2637
In <i>P. australis</i>	194	149	1	344
Within 7 m of <i>P. australis</i>	16	27	0	43
In <i>Z. capricorni</i>	226	55	16	297
Within 7 m of <i>Z. capricorni</i>	199	21	7	227
Within 7 m of mixed seagrass	0	3	0	3
Total moorings impacting <i>P. australis</i>	210	179	1	390
Total moorings impacting <i>Z. capricorni</i>	425	76	23	524

[#] Seagrass mapped for entire estuary in 2004 when there was more *Z. capricorni* than is currently present. This is therefore an overestimate of the numbers of moorings currently impacting *Z. capricorni* in Port Stephens.

Table 4. Number of moorings outside of RMS-designated mooring areas per habitat. This is a subset of all moorings listed in Table 3. All other details as in Table 3.

Mooring location (outside RMS-designated area)	Lake Macquarie	Port Stephens [#]	Wallis Lake	Total
On non-vegetated sediment	82	43	60	185
In <i>P. australis</i>	2	8	0	10
Within 7m of <i>P. australis</i>	2	3	0	5
In <i>Z. capricorni</i>	28	6	13	47
Within 7m of <i>Z. capricorni</i>	8	3	6	17
Within 7m of mixed seagrass	0	1	0	1
Total moorings impacting <i>P. australis</i>	4	12	0	16
Total moorings impacting <i>Z. capricorni</i>	30	9	13	52

[#] Seagrass mapped for entire estuary 2004 when there was more *Z. capricorni* than currently present. Thus, this is an overestimate of the numbers of moorings currently impacting *Z. capricorni* in Port Stephens, but is reflective of how many have impacted *Z. capricorni* within the last 10 years.

Mooring scar size versus depth

Areas of mapped moorings scars in contiguous beds of seagrass were compared to depth in both Lake Macquarie and Port Stephens using regression analyses. There was a significant relationship between depth and mapped mooring scar area for *P. australis* ($r = 0.53$, $F_{1,60} = 23.86$, $P < 0.001$) and *Z. capricorni* ($r = 0.56$, $F_{1,42} = 19.20$, $P < 0.001$) beds in Lake Macquarie. The nature of the relationships between scar size and depth differed for the two seagrass species (Figure 2). The largest mapped scars were found in deep beds of *P. australis* while the smallest were in shallow beds of *Z. capricorni* (Figure 2). The average scar size amongst *P. australis* in Lake Macquarie was 167 m² (ranging from 55 – 463 m²), whereas amongst *Z. capricorni* the average scar size was 111 m² (ranging from 18 – 343 m²). The regression models accounted for ~30% of the variability within the data; $r^2 = 0.30$ for *P. australis* (Figure 2) and $r^2 = 0.26$ for *Z. capricorni* (Figure 2). Nevertheless, these linear regression relationships provide the best available estimates of scar sizes created by moorings at a particular depth in either *P. australis* or *Z. capricorni*.

Analysis of the Port Stephens data for the *P. australis* habitat also identified a significant relationship between mooring scar area and depth ($r = 0.52$, $F_{1,13} = 4.77$, $P < 0.05$). Again, however, depth accounted for only ~30% of the variance in the data ($r^2 = 0.27$). Mooring scar area in *P. australis* increased with depth in a similar fashion in both Port Stephens and Lake Macquarie, but interestingly the size of scars in Port Stephens tended to be larger than in Lake Macquarie for a similar depth (Figure 3). Consequently, the mean scar size in *P. australis* in Port Stephens across all depths was 305 m² (ranging from 113 - 706 m²) as compared to 167 m² for Lake Macquarie.

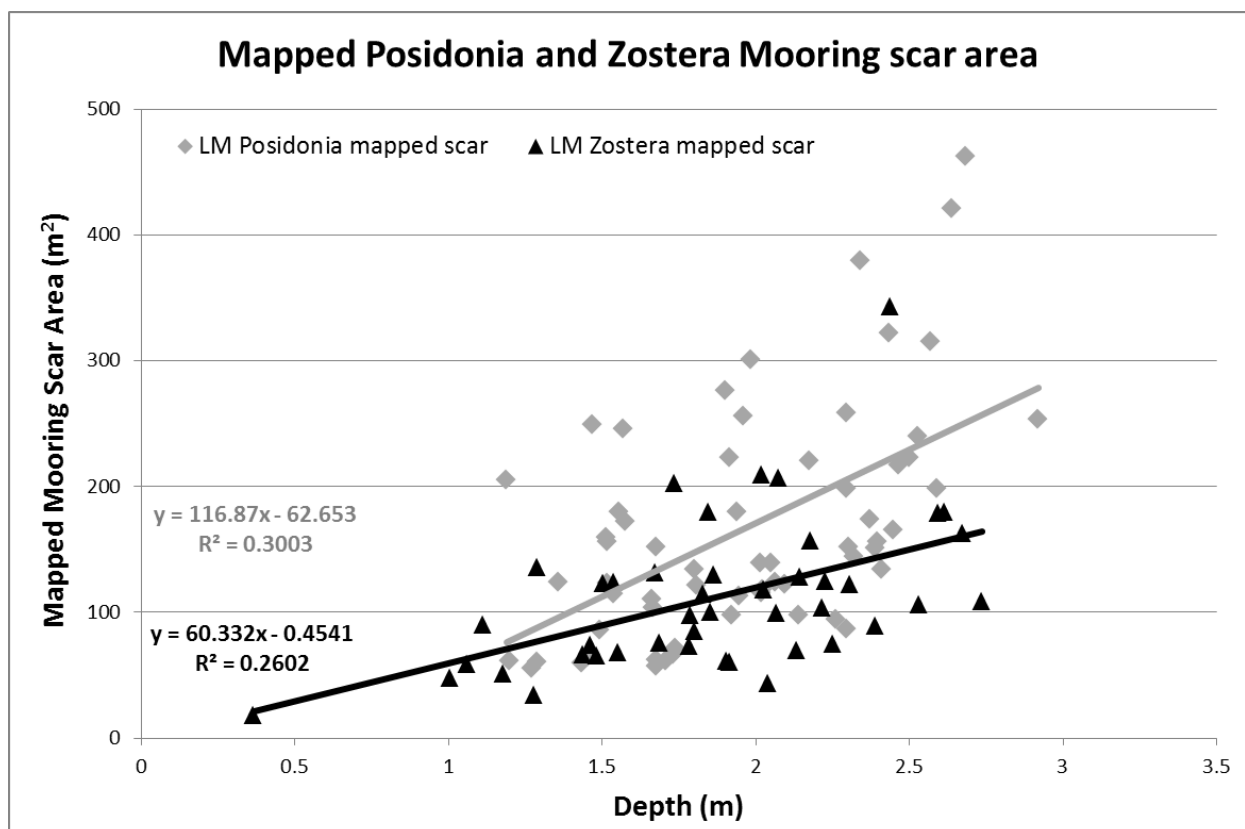


Figure 2. Regression of mooring scar area against depth for *P. australis* (grey diamonds) and *Z. capricorni* (black triangles).

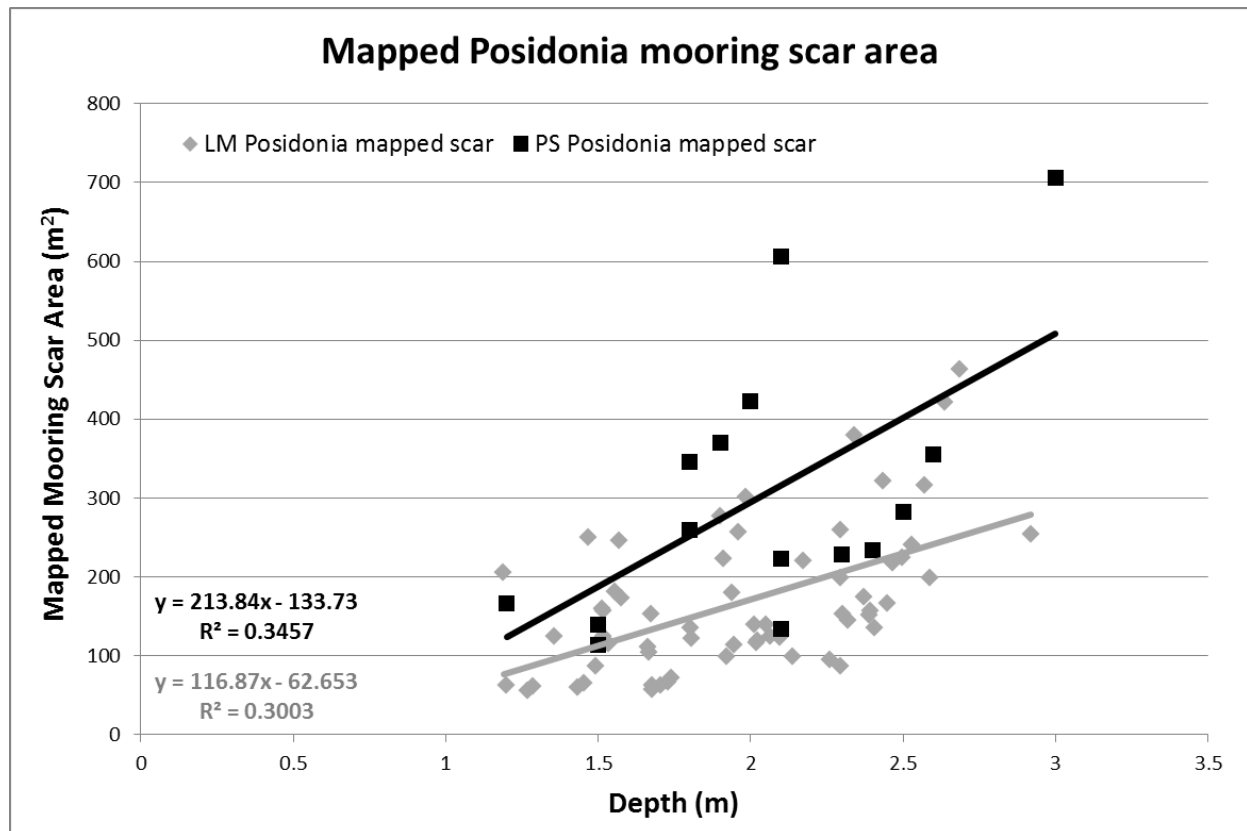


Figure 3. Regression of mooring scar area against depth in *P. australis* meadows in Port Stephens (black squares) and Lake Macquarie (grey diamonds)

Mapped mooring damage estimates

The primary aim of this project was to estimate the amount of mooring damage to *P. australis*, measured as the total mapped area of mooring scars. Beds of *P. australis* are far more temporally stable than are beds of *Z. capricorni*, meaning that the mooring loss estimates for *P. australis* are likely to be meaningful for many years, unlike those for *Z. capricorni*. This became particularly apparent in Port Stephens where large areas of *Z. capricorni* that were mapped in 2004 were no longer present in 2014. The beds of *Z. capricorni* in Lake Macquarie do not appear to have changed to the same extent as those in Port Stephens (although there have been losses in *Z. capricorni* over the last 5 years). Thus we attempted to estimate losses of *Z. capricorni* due to moorings only in Lake Macquarie.

Lake Macquarie

The 2012 seagrass map for Lake Macquarie was lacking some fine detail needed to accurately estimate the mooring damage in the fragmented *P. australis* bed in the Belmont Bay and Marks Point areas. This region was remapped in 2014 and the updated data appended to the original seagrass map. This 2014 map shows a revised total seagrass area for Lake Macquarie of 11.945 km² (1,194.5 ha), compared to the previous total area of 11.976 km² (1,197.6 ha). This discrepancy was driven by the area of *P. australis* being overestimated as 1.002 km² (100.2 ha) in 2012, with the more accurate 2014 area estimate being 0.975 km² (97.5 ha). This smaller area from the more detailed mapping reflects the many moorings scars that are present within the *P. australis* beds.

The fragmentation of *P. australis* around Belmont Bay and Marks Point, particularly around the deeper margins of the beds, meant that it was not straightforward to estimate how much *P. australis* had been removed due to moorings. It was, therefore, necessary to generate a theoretical deep edge of *P. australis* in this region (Figure 4), which was approximated as the 3.5 m depth contour. This depth defined the limit of the naturally contiguous bed of *P. australis* in the absence of any mooring scars. Thus, within mooring areas, any holes in the fragmented *P. australis* bed shallower than 3.5 m were deemed to be created by moorings (either past or present), as depicted in Figure 5B. To estimate losses of *P. australis* in naturally fragmented beds (i.e. those deeper than 3.5 m) we first estimated the average natural percentage cover of *P. australis* in these areas (36 %). The loss estimate was then calculated relative to this natural coverage of seagrass.

The estimated total loss of *P. australis* in Lake Macquarie due to moorings was 76,467 m² (i.e. 0.076 km² or 7.6 ha), of which the vast majority (98%) was lost from beds in water shallower than 3.5 m, that is, from contiguous or ostensibly contiguous beds (Table 5). Losses of *Z. capricorni* due to moorings, estimated only for contiguous beds of this seagrass (and thus underestimates of total damage) were 38,408 m² (i.e. 0.038 km² or 3.8 ha).

One of the larger mooring scars in Lake Macquarie was ~520 m² and was located amongst *P. australis* at Marks Point. There were many scars in Belmont Bay and Marks Point that appear to have coalesced, perhaps due to sand blow outs or the movement of existing moorings, but might also represent historical moorings (that have been removed). These coalesced scars could be very large, one having an area of 760 m². The smallest mapped mooring scar in *P. australis* in Lake Macquarie was 55 m².

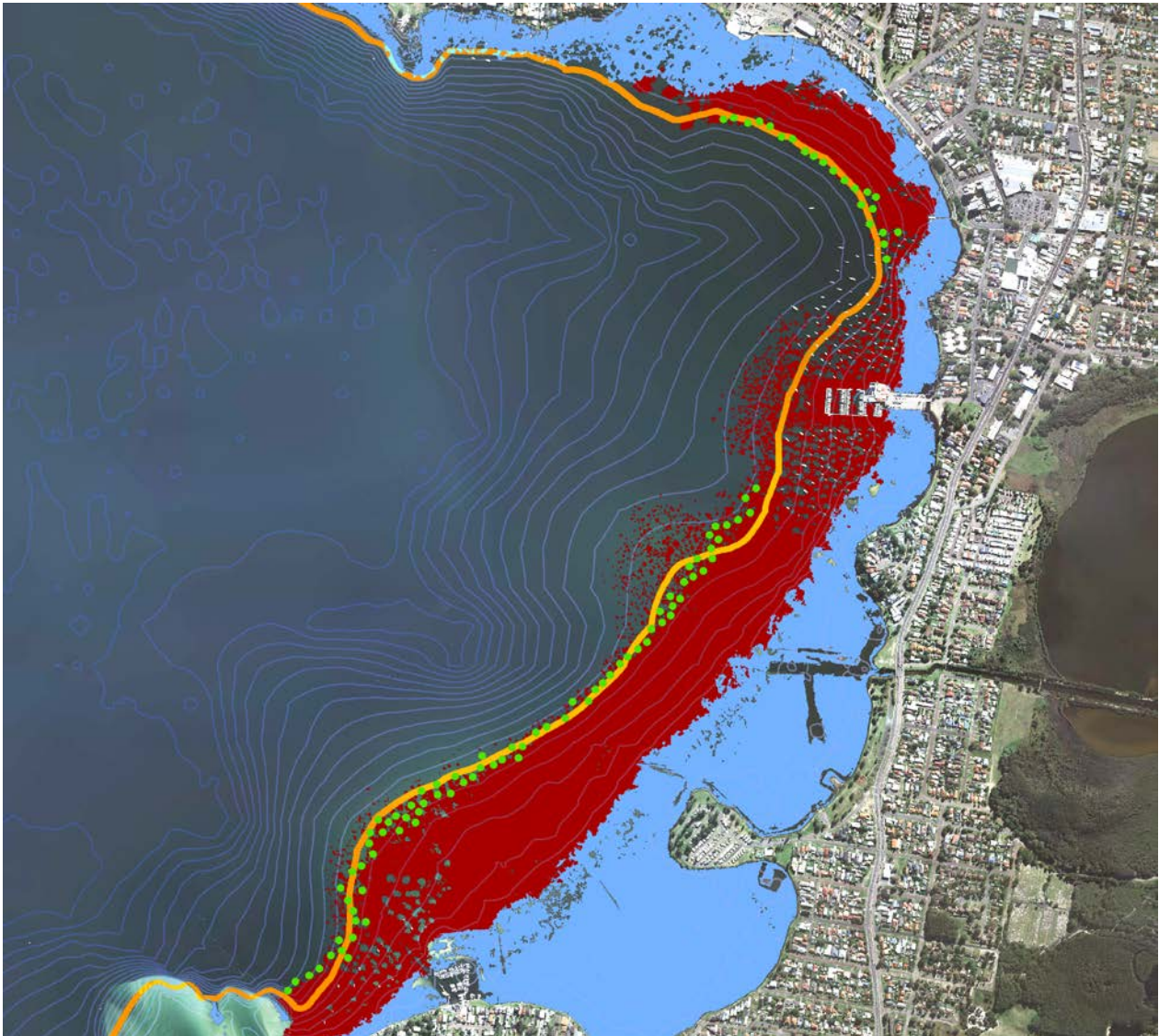


Figure 4. Determination of the deep edge of contiguous *P. australis* (red) in Belmont Bay. Green dots represent random points used to estimate the average depth contour (orange line) defining the edge of ostensibly contiguous *P. australis* in more fragmented areas (such as Belmont Bay marina). Blue represents *Z. capricorni*.

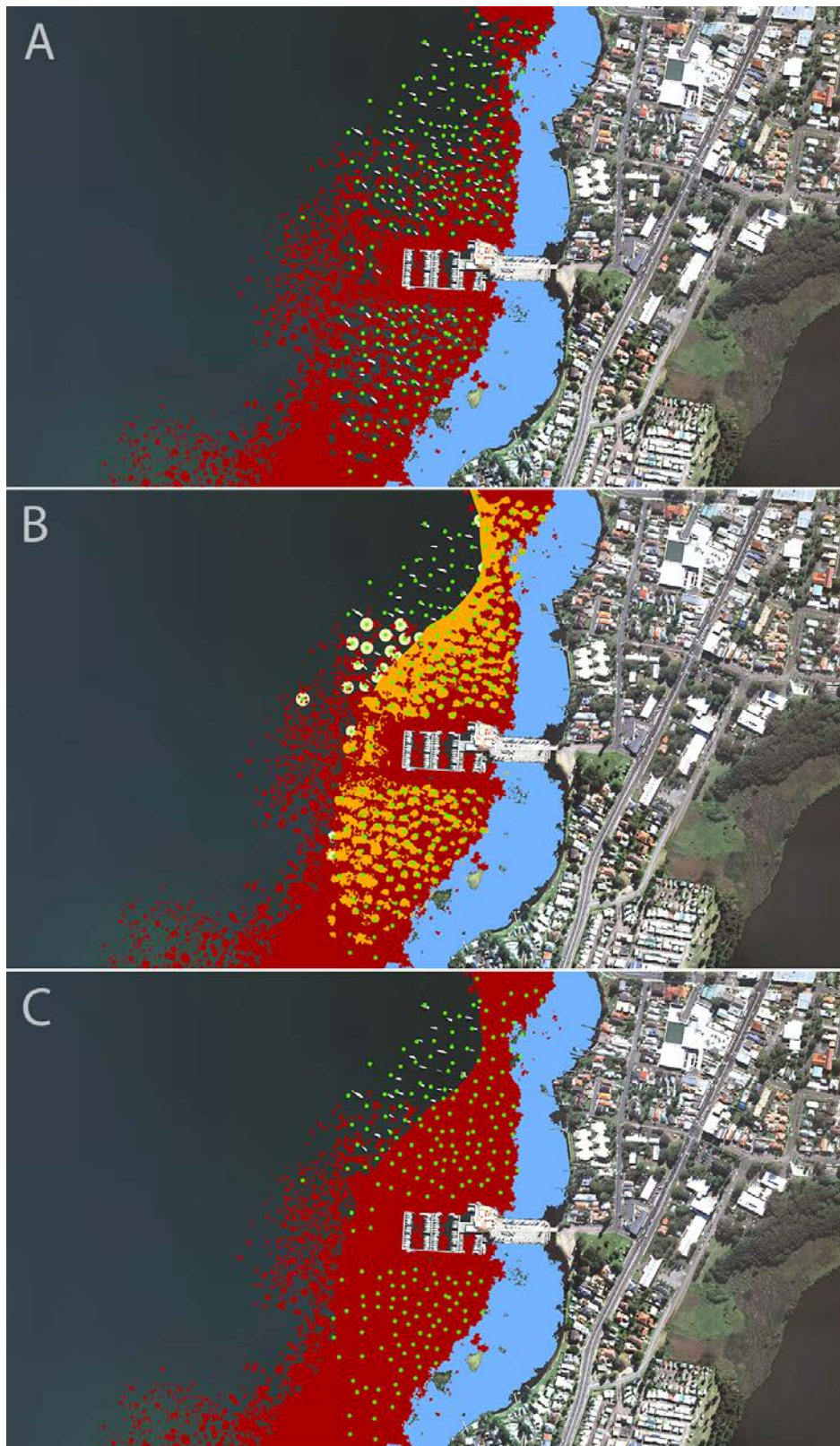


Figure 5. Seagrass mooring losses in Belmont Bay, discriminating *P. australis* (red) from *Z. capricorni* (blue), with moorings identified as green dots. (A) 2015 seagrass map showing significant mooring damage. (B) Indication of *P. australis* lost to moorings in shallow contiguous seagrass (orange fill, 100% loss) and deeper fragmented areas (yellow dots, loss estimate based on % cover of *P. australis* in naturally fragmented area) using modelled scar areas for areas > 3.5 m deep. (C) Potential distribution of *P. australis* in the absence of mooring scars (the reconstructed *P. australis* losses around moorings in deeper fragmented beds are not depicted).

Table 5. Estimated losses (m²) of seagrass due to mooring scars for each of the three estuaries. Losses have been calculated separately for contiguous beds and fragmented beds (the former being the more reliable estimate). Losses of *Z. capricorni* were not estimated (NE) in Port Stephens or Wallis Lake, except in areas where it co-occurred with *P. australis*.

Habitat Lost	Lake Macquarie	Port Stephens [#]	Wallis Lake
Contiguous <i>P. australis</i> *	75,251	10,118	320
Fragmented <i>P. australis</i>	1,216	2,226	0
Contiguous <i>P. australis</i> / <i>Z. capricorni</i>	0	7,500	0
Contiguous <i>Z. capricorni</i>	38,408	NE	NE
Total <i>P. australis</i> loss (m ²) [#]	76,467	19,844	320
Total seagrass loss (m ²)	114,875	NE	NE

* includes 'ostensibly contiguous' beds in Lake Macquarie only

[#] i.e. total area that contained some *P. australis*

Port Stephens

Moorings scars in *P. australis* were mapped in all parts of Port Stephens where this seagrass was known to occur. Damage to *Z. capricorni* was not specifically estimated, although there were areas where *Z. capricorni* was mixed with *P. australis* (primarily along the southern shore from Tomaree Head to Soldiers Point).

The estimated natural percentage cover of seagrass in fragmented beds of *P. australis* in Port Stephens was 37% (i.e. very similar to Lake Macquarie). This value was used to reconstruct how much *P. australis* had been lost due to moorings in fragmented beds of *P. australis*.

An estimated total of 19,844 m² of *P. australis* has been lost due to moorings in Port Stephens, which includes *P. australis* mixed with other seagrasses in either contiguous or fragmented beds (Table 5). As for Lake Macquarie, the majority (91%) of *P. australis* that has been lost has been removed from contiguous beds of either pure *P. australis* or *P. australis* mixed with *Z. capricorni*.

The largest mapped mooring scar amongst *P. australis* in Port Stephens was 706 m² and was located in Shoal Bay. The smallest mapped mooring scar in Port Stephens was 113 m². Mean scar sizes in *P. australis* were larger in Port Stephens (305 ± 45 m² averaged over all depths) than in Lake Macquarie (167 ± 12 m² averaged over all depths).

Wallis Lake

The total amount of seagrass mapped in Wallis Lake was 31.90 km² (i.e. 3,189.7 ha). Of this total seagrass, 92% was *Z. capricorni*. Only one mooring in Wallis Lake was located in *P. australis*, which was estimated to have removed 320 m² of the seagrass (Table 5). Losses of *Z. capricorni* were not estimated.

Mooring damage estimates using simplified methods

Mooring scars with clearly defined boundaries and situated in contiguous beds of *Z. capricorni* or *P. australis* were measured in two dimensions (N-S and E-W) as depicted in Figure 6. In total, 106 scars were measured in Lake Macquarie (44 in *Z. capricorni* and 62 in *P. australis*) and 15 in Port Stephens (only in *P. australis*). Wallis Lake was not sampled because it had only one mooring in *P. australis*. Mean scar diameters were used to estimate scar areas and for each sampled scar in the mapped seagrass bed, depth values were extracted from the centre of the scar using bathymetric data (Lake Macquarie) or depth contour data (Port Stephens). These data were then compared to the mapped (more accurate) scar areas.

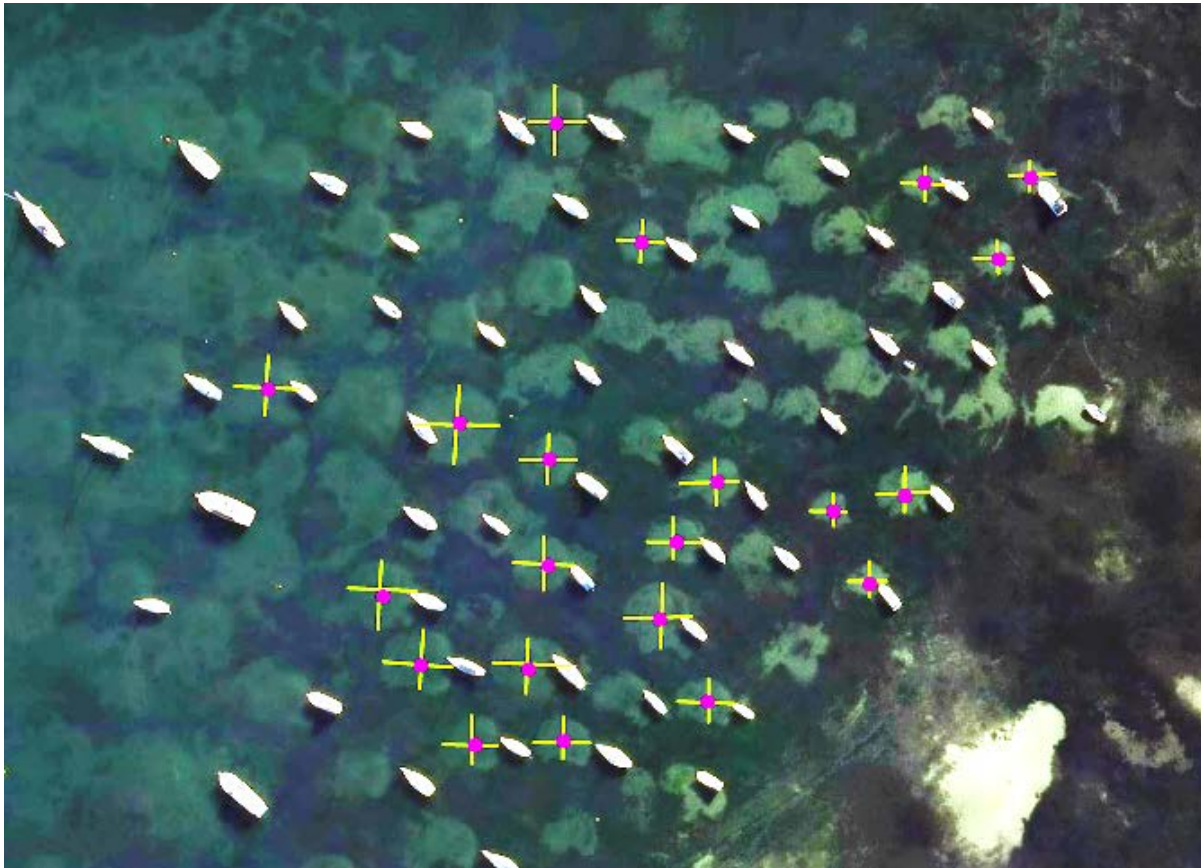


Figure 6. Examples of mooring scar measurements used to test for relationships between depth and scar size

There was a very strong relationship between estimated and mapped mooring scar sizes ($r = 0.97$, $F_{1,60} = 888.08$, $P < 0.001$) and relatively little variability within the data ($r^2 = 0.94$; Figure 7). Thus the simplified methods for estimating scar sizes was generally very accurate, although in some cases could over or underestimate the actual scar area. It would appear that the estimated scar sizes became less accurate as scar size increased, but there were relatively few very large scars ($>300 \text{ m}^2$) with which to test the strength of this pattern (Figure 7).

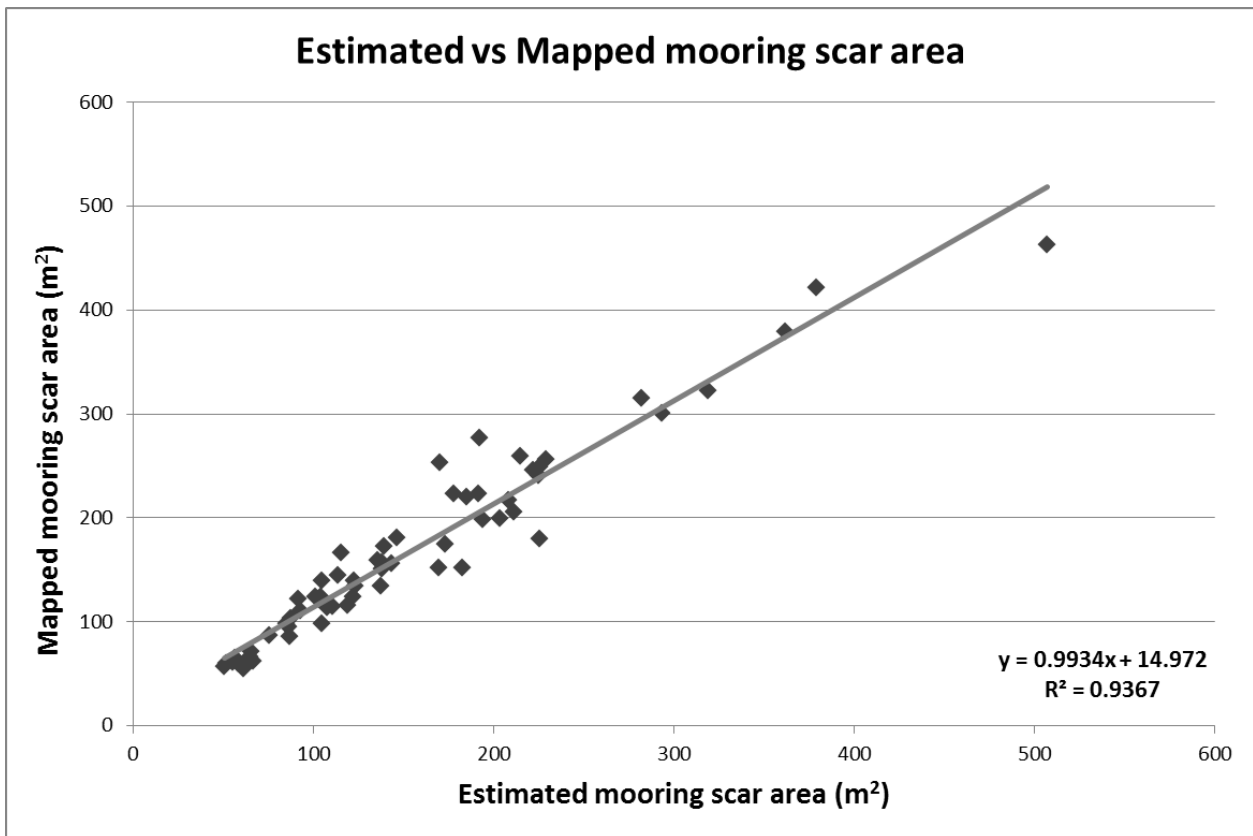


Figure 7. Relationship between mapped mooring scar area and estimated area (based on mean diameter and calculated using the area of a circle).

The simplified method for estimating estuary-wide losses of *P. australis* due to moorings in Lake Macquarie resulted in an estimate that was 14,603 m² less than the mapped (and more accurate) estimate (Table 6). The underestimate was due to there being far fewer current moorings than scars, particular around Marks Point (Figure 8). Importantly, the simplified estuary-wide loss method greatly overestimated the seagrass loss in fragmented beds of *P. australis* because it could not utilise the detailed seagrass mapping.

Table 6. Mapped losses (m²) of *P. australis* versus simplified estimate based on mooring numbers × mean scar size for Lake Macquarie. Estimates have been distinguished for contiguous seagrass beds and naturally fragmented beds.

Habitat	Mapped estimate	Simplified estimate
Contiguous <i>P. australis</i>	75,251	58,986
Fragmented <i>P. australis</i>	1,215	2,878
Total	76,467	61,864

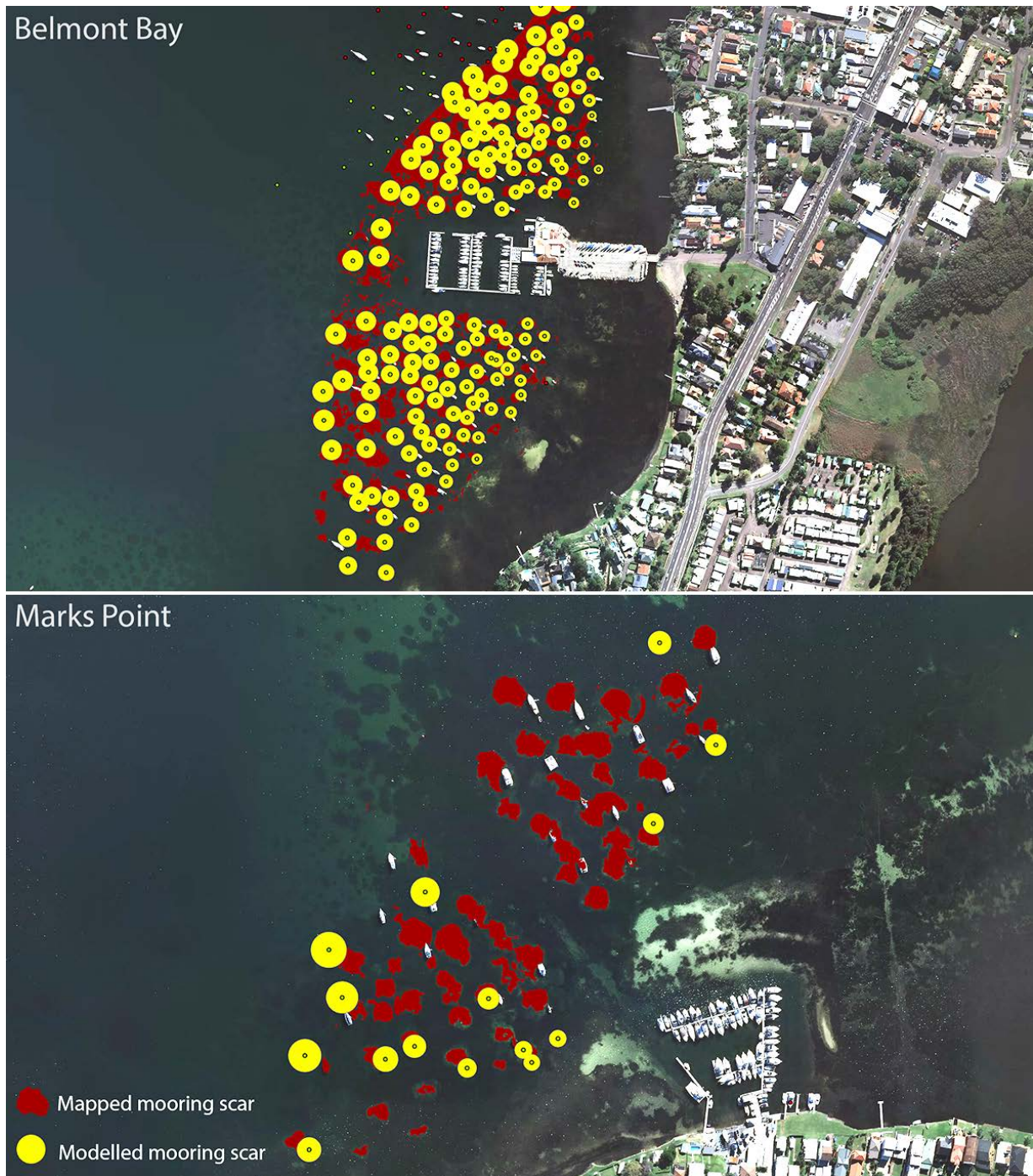


Figure 8. Mooring scar estimates derived from the detailed mapping (red) compared to the simplified method using average scar size of current (RMS-plotted) moorings (yellow). Note how many more boats there are at Marks Point compared to the RMS-plotted moorings. Also note how the predicted scar size increases with depth (distance from shore in this image).

Discussion

Across the three Hunter estuaries examined in this study, the greatest loss of *P. australis* due to boat moorings was in Lake Macquarie. Estimates of seagrass losses due to moorings were relative to the latest seagrass maps for each estuary, namely 2014 for Lake Macquarie and Port Stephens and 2011 for Wallis Lake. In all three estuaries, the greatest losses were in water less than 3.5 m deep where the seagrass formed contiguous beds, or could have formed contiguous beds in the absence of moorings (which fragmented the seagrass). As water depth increased, so too did the size of mooring scars in seagrass, although the nature of this relationship differed between Lake Macquarie and Port Stephens. The average scar size in *P. australis* in Lake Macquarie across all depths was 167 m² (ranging from 55 – 463 m²) as compared to 305 m² in Port Stephens (ranging from 113 - 706 m²). The total impact of moorings on *P. australis* in Wallis Lake (one mooring having removed 320 m²) is currently insignificant in comparison to the other estuaries. It is important to note that we did not distinguish between different densities of seagrass in this study and acknowledge that the total biomass of seagrass lost per mooring will differ greatly depending on the density of the seagrass bed in which the mooring is located (see La Manna et al. 2015).

There were far more moorings impacting seagrasses in Lake Macquarie (635) than in Port Stephens (255) or Wallis Lake (24). Of these moorings, the percentage affecting *P. australis* also varied among estuaries; 33% in Lake Macquarie, 70% in Port Stephens and 3% in Wallis Lake. Despite Lake Macquarie and Port Stephens having roughly similar numbers of moorings that were impacting *P. australis* (210 and 179 respectively), the estimated total loss of *P. australis* was far greater in Lake Macquarie (76,467 m²) than in Port Stephens (19,844 m²). This large discrepancy is most likely due primarily to the fact that we underestimated losses in Port Stephens as we were not able to accurately reconstruct “ostensibly contiguous” *P. australis* beds due to a lack of detailed bathymetric data. But it is also noteworthy that in Lake Macquarie there were many mooring scars that were not directly related to any currently occupied moorings on the latest RMS spatial layer. In some cases, boats were clearly visible on moorings that were supposedly unoccupied according to the most recent RMS shapefile. In other cases, the scars appeared to be ‘residual’ (i.e. apparently no mooring currently present within the scar), perhaps due to the mooring being repositioned or removed, but this cannot be verified without access to historical mooring data. For this reason, it is not appropriate to estimate the scar size *per mooring* based simply on the number of currently mapped moorings divided by the area of seagrass lost. Instead the mapped scar sizes used in the regression analysis (Figure 3) need to be used to compare scar sizes between these two estuaries, which demonstrate that scars tended to be far larger in Port Stephens.

Our estimate for loss of *P. australis* in Lake Macquarie is 27% greater than the 60,000 m² estimated by Wright et al. (2013). The difference is likely due in part to the latter study (a) using a less sophisticated technique for estimating seagrass losses in fragmented beds and at different depths and (b) focussing only on damage within designated mooring areas.

Loss estimates for *Z. capricorni* are less reliable than those for *P. australis* due to the transient nature of many beds of *Z. capricorni* and the variable depth of the edge of contiguous beds in the estuaries examined here. Nevertheless, it is noteworthy that despite roughly twice as many moorings impacting *Z. capricorni* compared to *P. australis* in Lake Macquarie (Table 3), there was almost half as much *Z. capricorni* lost due to moorings (Table 5). This difference would be due in part to us not estimating losses of *Z. capricorni* in fragmented beds (i.e. only in contiguous

beds), but almost certainly reflects the fact that scars in *P. australis* were typically larger than those in *Z. capricorni*. We did not estimate losses of *Z. capricorni* due to moorings in Port Stephens or Wallis Lake, but based solely on numbers of moorings, *P. australis* was likely to be more affected in Port Stephens, whereas *Z. capricorni* was almost certainly impacted in Wallis Lake.

Of the 2,602 moorings in Lake Macquarie, 122 (5%) were outside RMS-designated mooring areas. The percentage was similar in Port Stephens (8% of the 846 moorings), while in Wallis Lake 77% of the 103 moorings were outside RMS-designated mooring areas (according to the data provided to us by RMS). Relatively few of these “out of area” moorings were impacting *P. australis* (4 in Lake Macquarie, 12 in Port Stephens, 0 in Wallis Lake), whereas the numbers were typically greater for *Z. capricorni* (30 in Lake Macquarie, 9 in Port Stephens, 13 in Wallis Lake).

We demonstrated that good estimates of scar sizes can be obtained by using the mean scar diameter and the formula for an area of a circle. The extent of damage around moorings measured for Port Stephens is similar to that reported for swing moorings amongst *P. australis* in Jervis Bay. Demers et al. (2013) estimated a mean scar radius of ~ 9 m at depths of 3 – 6 m in Jervis Bay, while our results over a 1 – 3 m depth range equate to mean scar radius of 9.9 m for Port Stephens and 7.3 m for Lake Macquarie. Notably, however, the maximum mapped scar size amongst *P. australis* in Port Stephens (706 m²) equates to a scar radius of 15 m. Although many scars are roughly circular, blowouts of sand (or movement of the mooring block) can result in areas that are greater than those of a circle, particularly for larger scars in deeper water. Nevertheless, this method is much quicker and simpler than mapping seagrasses and scars, but of course still relies on some knowledge of the distribution of seagrasses.

The simplified method for estimating estuary-wide mooring damage based on mean mooring scar size and numbers of moorings in the RMS spatial layer was not particularly useful. For Lake Macquarie, the simplified seagrass loss estimate was 14,603 m² less than the mapped (more accurate) estimate. This underestimate was due in part to using an average scar size per estuary, which does not reflect the variability in scar sizes that occurred at any particular depth (which may have been due to difference in boat sizes or mooring types). But the major reasons for the discrepancy between the simplified estuary-wide and detailed mapping estimation methods were that (i) moorings had clearly been moved over time, leaving a scar, but there was no information about past mooring locations in the RMS mooring spatial layer that we were provided and (ii) the mooring spatial layer did not accurately identify some moorings which were apparent in the recent (2014) imagery. Ongoing monitoring of mooring damage to seagrasses in the Hunter region and mapping of mooring scars in other NSW estuaries could be improved dramatically with the provision of accurate current mooring locations (see below) and, ideally, information about historical locations of moorings. Such data could improve any estimate of seagrass loss, especially loss estimates using the simplified method. This would provide a rapid low-cost preliminary estimate for management agencies in the absence of resources to undertake detailed and expensive mapping of seagrass beds. Such preliminary findings could be used by agencies to determine the potential extent of the issue, and help determine whether a more intensive investigation or management intervention is warranted.

It is important to highlight that the relationships between average mooring scar size and depth described for the two estuaries accounted for only about 1/3 of the variability in the data. Other sources of variability in scar size that were not investigated here include differences in (i) the

type of mooring (e.g. size or type of block or length of chain (Demers et al. 2013)), (ii) boat size (which may co-vary with depth) and (iii) physical characteristics of the mooring site (which might affect exposure to wind and waves and hence scar size; Hastings et al. 1995). Mooring scars in Port Stephens were substantially larger than those in Lake Macquarie, which is possibly a result of the former estuary tending to have larger boats, or it might reflect differences in the tidal regime and exposure to oceanic swell in the two estuaries. The construction of mooring blocks within Port Stephens was observed to be highly variable, ranging from a collection of small lead weights up to a single concrete block about 1 m in diameter.

The practices of mooring contractors who maintain moorings have the potential to affect the size of a scar. For example, if contractors replace a mooring in exactly the same position after lifting it for maintenance, then the scar size is unlikely to change markedly in comparison to situations where the mooring is moved a few metres after being lifted. Our observations suggested that moorings are often moved, which might be a consequence of maintenance procedures and/or adverse weather conditions dragging the mooring. Moreover, the damage to *P. australis* from a mooring can be created quickly. In a moderately exposed location in Botany Bay, a mooring placed amongst *P. australis* in ~4 m of water was observed to increase at an average rate of ~9 m²/month over 26 months to a size of 255 m² before the mooring was removed (unpubl. data).

More stringent policies in relation to the practices of mooring contractors, or the minimum standards for mooring blocks, would very likely help to minimise future damage to seagrasses. An important first step for this would be obtaining accurate mooring positions based on the position of the mooring block rather than the mooring buoy (which can move considerably). We acknowledge that it is more difficult to record the positions of blocks than floats (the former requiring the mooring chain to be pulled taught prior to marking the position), but suggest that this information is needed in order to compel mooring contractors to replace blocks in the same position. Of course, the use of environmentally friendly moorings (which screw into the seabed) could eliminate problems associated with the movement of moorings (by contractors or adverse weather), in addition to minimising physical damage to seagrasses (caused by mooring chains) or indeed other vessels and infrastructure.

Harming of seagrass habitat in NSW is regulated by NSW DPI through a permit system. NSW DPI policy generally does not support proposals to install new, replace or relocate existing moorings in *P. australis* seagrass and other seagrass beds greater than 5 m². But in situations where the harm of seagrass is permitted, adequate compensation measures are required. Monetary habitat compensation is calculated on a minimum 2:1 basis for seagrasses, which equates to a cost of \$112/m² (indexed to inflation; NSW DPI 2013). Using this monetary value, the average environmental cost of a new block and chain mooring in seagrass in Hunter estuaries would be \$18,368 (based on a mean scar area of 164 m² across all habitats, depths and estuaries). This value could be up to \$79,072 for a mooring in *P. australis* in Port Stephens (largest mapped scar area of 706 m²). An effective environmentally friendly mooring (which has little physical contact with the seabed) causes minimal damage to seagrass (Demers et al. 2013) and, when used to replace a block and chain mooring, can allow recolonization of seagrass (mainly *Halophila* spp. and *Z. capricorni*) in old scars (Gladstone 2012). The cost of an effective environmentally friendly mooring (~\$3,500 purchase price plus annual maintenance costs) is considerably less than the cost of damage to seagrass based on monetary values for habitat compensation. A compensation value of \$112/m² is, however, a conservative figure that underestimates the true costs of rehabilitation (Glasby unpubl. data), and does not incorporate the (indeterminate) costs of so-called ecosystem services provided by the habitat.

The substantial and widespread impacts to seagrasses caused by boat moorings are just one of many anthropogenic disturbances that potentially threaten these habitats. Large-scale losses of seagrasses such as *P. australis* have been documented for some NSW estuaries (Larkum 1976, Larkum & West 1990), probably due largely to dredging activities, and it is likely that there were even greater losses in the Sydney region during the early development of the major ports (West 2011). The impacts to seagrasses from boating (e.g. mooring and propeller scars, West 2011) may be smaller in spatial scale than impacts from dredging, but they should not be underestimated. As noted by Larkum (1976), continual small-scale losses of seagrass can result in a seagrass bed becoming increasingly fragmented, which increases the likelihood of erosion and large-scale losses of this important habitat.

Recommendations

Given the findings of this and other studies, it would be prudent to continue to implement strategies to protect seagrasses and minimise damage to seagrass beds, particularly those dominated by *P. australis*. Such strategies could include the following:

- ensuring that block and chain moorings are not (accidentally or otherwise) deployed in seagrass beds, which requires accurate positioning of moorings and the utilisation of available maps of seagrass beds;
- ensuring that existing block and chain moorings are not moved within seagrass beds either by contractors during maintenance, or due to inadequate weight for the size of a vessel or exposure of the mooring site. This would require minimum standards for moorings and accurate co-ordinates for the position of the blocks;
- relocating existing block and chain moorings out of seagrass beds wherever possible;
- where moorings must be in seagrass beds, ensuring that they be environmentally friendly swing moorings that do not scour the seabed;
- phasing out of the lawful use of traditional block and chain moorings in other sensitive aquatic habitats; and
- creating the appropriate regulatory and market environment to reduce (or subsidise) the purchase and ongoing cost of environmentally friendly moorings and increase the demand for their use.

Recommendations for future research work include:

- working with RMS to obtain mooring spatial layers that more accurately represent the position of currently-occupied moorings and indicate the number and position of previous moorings (that have been removed).
- investigating the extent to which mooring damage might vary according to the environmental characteristics of the site (e.g. exposure) and boat size.
- obtaining more accurate bathymetric data for Port Stephens to enable an estimate of *P. australis* losses in ostensibly contiguous beds.
- investigating options for reconstructing the position of ostensibly contiguous seagrass beds that do not rely on accurate bathymetric data (which might not be available for many estuaries).
- expanding the work of this study to other NSW estuaries in order to estimate the total amount of damage to seagrass by boat moorings in NSW and examine the generality of scar size versus depth relationships.

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