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Naturally-detached fragments of the endangered seagrass *Posidonia australis* collected by citizen scientists can be used to successfully restore fragmented meadows

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ABSTRACT

Posidonia australis is a slow-growing seagrass that forms extensive meadows in sheltered coastal locations which are often popular areas for recreational boating. Traditional block-and-chain boat moorings can directly impact *P. australis* meadows, with the action of heavy chains eroding the seafloor and creating bare sand scars that fragment meadows. The installation of new environmentally friendly moorings (EFMs) can reduce damage to seagrasses, but natural re-establishment by *P. australis* to scars can be very slow. Given the endangered status of this species in New South Wales, Australia, we developed an innovative restoration procedure to re-establish *P. australis* transplants within old scars without damaging existing meadows. Naturally-detached rhizome fragments were collected from the shore by citizen-scientists, stored within aquaculture tanks and then planted underwater. We planted a total of 863 fragments into six mooring scars at three different times. Survival of fragments after one year was significantly greater for those planted in June (54%) than in January (31%). The planting techniques (with or without natural fibre mats to stabilize sediments) and environmental conditions (surrounding habitat, depth and presence of the EFM) did not influence survival. Many surviving fragments (36.3%) had produced new shoots during the year. Our results show that naturally-detached seagrass fragments can be used to effectively restore *P. australis* meadows. This is an important new approach for supplying propagules for restoration without damaging remaining populations of an endangered seagrass, and presents a compelling management approach that engages local communities and enhances conservation efforts.

1. Introduction

Human impacts have caused extensive habitat and biodiversity losses worldwide, reducing the benefits that people receive from nature and threatening the quality of life of future generations (Díaz et al., 2019). Habitat restoration is an increasingly important management tool to counter and reverse these losses and, in the last few decades, restoration efforts have greatly accelerated (McDonald and Williams, 2009; McLeod et al., 2018; Waltham et al., 2020). Habitat restoration is often used for the conservation of threatened plant species (Volis, 2016; Zimmer et al., 2020). In marine habitats, restoration of key vegetated habitats such as seagrass meadows and kelp forests, is quickly gaining traction as an important management tool (McLeod et al., 2018; Wood et al., 2019).

Seagrasses are marine flowering plants that underpin one of the most productive coastal ecosystems in the world (Larkum et al., 2006). Many of the large, persistent species significantly modify their environment, transforming relatively featureless soft sediments into structurally complex and diverse habitats that support a wide variety of fauna. Some faunal species are permanently associated with seagrasses habitats while

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others use seagrasses only as nursery areas (Duffy, 2006; Heck et al., 2003; Jackson et al., 2001; Lilley and Unsworth, 2014). More recently, seagrass meadows are heralded as globally important sites for carbon sequestration (Mcleod et al., 2011). Seagrasses are among the most threatened ecosystems in the world and their rate of decline (7% yr^{-1} since 1990) is comparable to that of coral reefs (Waycott et al., 2009). The cause of their decline varies, but is largely linked to human activities. Climate change, coastal development, degraded water quality and boating activities are among the main causes for seagrass declines (Orth et al., 2006). The coastal embayments that are the preferred locations for seagrasses are also popular areas for recreational boating, and boating activities represent a global threat to seagrass cover (Glasby and West, 2018; Sagerman et al., 2020; Serrano et al., 2016; Unsworth et al., 2017).

Mitigation approaches such as restoration are becoming an important tool for revegetating damaged seagrass meadows. Seagrass restoration techniques were first developed in the 1940s, and recent efforts are increasingly providing encouraging results (Tan et al., 2020). Before starting any restoration, it is essential that the threats to seagrass survival are addressed (van Katwijk et al., 2016). Following this, most seagrass restoration involves destructive techniques to source donor material from existing meadows, such as collecting seagrass cores (or 'plugs') or rhizomes with shoots (also defined as 'runners', 'sprigs', 'shoots') from existing meadows (Ganassin and Gibbs, 2008; Sanchez-Lizaso et al., 2009; Statton et al., 2012; Tan et al., 2020). Restoration methods using seeds are also proving useful for larger scale restoration projects in some species (Orth et al., 2012; Sinclair et al., 2021). Micropropagation has also showed encouraging results in terrestrial plants but difficulties have been encountered in seagrasses (Ailstock and Shafer, 2006). Following planting, inadequate anchorage of fragments is one of the major causes of seagrass transplant failure (Bastyan and Cambridge, 2008). Site selection is also very important, with depth and sediment stability influencing success (Aoki et al., 2020; Meehan and West, 2000; Pirrotta et al., 2015; van Katwijk et al., 2009). Destabilized sediments can prevent natural recolonization and limit survival of transplanted fragments. Biodegradable anchoring material is showing promising results (Ward et al., 2020) and the deployment of organic mats, such as those made of jute (also called hessian or burlap) that stabilize the sediment can, in some instances, promote survival of transplanted fragments (Campbell and Paling, 2003; Paling et al., 2009; Piazzi et al., 2021; Temmink et al., 2020). The timing of replanting efforts is also important, with seasonal patterns in seagrass growth also likely to affect transplant performance (Alcoverro et al., 1995).

Posidonia australis Hook.f. is an endemic seagrass in the southern half of Australia, widely distributed in subtidal temperate marine or estuarine waters (Larkum et al., 2006). The largest meadows of *P. australis* are found on soft sediment environments, in sheltered estuaries and marine dominated coastal lakes (Creese et al., 2009). Like other seagrass species, *P. australis* meadows act as a nursery habitat for economically important fish and crabs (Beck et al., 2001; Burchmore et al., 1984; Middleton et al., 1984).

Due to ongoing impacts and historical declines in areal extent (Butler and Jernakoff, 1999; Larkum and West, 1990), populations of *P. australis* in some estuaries in New South Wales (Australia) were listed as endangered under state legislation in 2012 and as threatened ecological communities under national legislation in 2015 (*EPBC Act*). Since the 1980s, there have been ongoing declines in aerial extent of *P. australis* in three NSW estuaries (West & Glasby, in review), plus more recent declines in area of individual meadows at numerous locations (Evans et al., 2018).

One of the ongoing causes for loss of *P. australis* in NSW estuaries is the impact from traditional block and chain swing moorings (Glasby and West, 2018). These moorings are composed of a large concrete block connected to a heavy chain that drags along the seafloor as the boat swings due to shifting wind and tides, directly removing seagrass shoots and rhizomes (Fig. A1c, d) (Demers et al., 2013). Swing moorings create bare patches or scars that destabilize the sediment and change hydrodynamic conditions. Scars will eventually widen and join together, resulting in fragmented meadows and over time in meadow loss. Alternative mooring designs – environmentally friendly moorings (EFMs) – that efficiently reduce damage to sensitive seagrass habitats now exist and are being trialled as replacements for swing moorings in some NSW embayments (Fig. A1e) (Demers et al., 2013). *Re*-establishment of bare areas and recovery of damaged *P. australis* meadows can be slow in NSW, as they typically depend on vegetative growth. There is little to no viable seed production in this region of Australia (Larkum et al., 2006). Damaged meadows in many cases are unlikely to re-establish naturally after major disturbance (Meehan and West, 2000). Re-planting is thus an appropriate technique to re-establish *P. australis* and speed up the recovery process.

In New South Wales, the options for obtaining material to restore *P. australis* are limited due to the low seed production (Larkum et al., 2006) and the protected and declining status of seagrass meadows that could provide donor material. Here, we present and test an alternative option for restoration: the collection of naturally-detached *P. australis* fragments that have washed ashore among other vegetation debris (i.e. wrack). Fragments consist of at least one shoot attached to the rhizome (Fig. 4) and, once replanted, each can potentially produce new shoots and roots to spread over bare sand (Campbell, 2003). This method has been used successfully in the Mediterranean Sea, where the tidal range is microtidal (Balestri et al., 2011; Piazzi et al., 2021; Ward et al., 2020). No studies to date have examined this technique in areas with a higher tidal range, where fragments vary in the time taken to reach the shore (depending on the intensity and direction of the waves and winds) and are potentially exposed to longer periods in air once beached.

We present a novel approach that aims to improve the availability of fragments for *P. australis* restoration by engaging citizen-scientists to help collect naturally-detached fragments washed ashore. Citizen science is rapidly becoming a widely established new approach for supporting research that also creates awareness and inspires environmental stewardship (Bonney et al., 2009; Cooper et al., 2007; Merenlender et al., 2016; Silvertown, 2009). "Citizen science" is already being used successfully to monitor seagrass (e.g. Seagrass-Watch, SeagrassSpotter). Given that seagrass restoration is laborious and time demanding (Bayraktarov et al., 2016), there is great potential for public involvement to enhance restoration efforts.

Specifically, we test (a) whether naturally-detached fragments of *P. australis* collected from wrack and re-planted can survive and re-establish, (b) whether citizen scientists can collect enough fragments to support the restoration efforts, and (c) how the use of stabilizing natural fibre mats (hereafter jute mats), planting season, sedimentation rate, and scar characteristics (depth, surrounding habitat, presence of EFM) influence survival of restored fragments.

2. Materials and methods

2.1. Study site

The study area was Port Stephens, a natural embayment in New South Wales, eastern Australia (32° 43′ 03.7″ S 152° 10′ 41.2″ E) and part of the Port Stephens Great Lakes Marine Park (Fig. A1a). This estuary is permanently open to the ocean with a tidal range of ~1.9 m and has extensive seagrass meadows (14.392 km^2) (Fig. A1a). The 846 block and chain moorings installed within those meadows have caused an estimated loss of 30,556 m^2 of *P. australis* habitat (Creese et al., 2009; Glasby and West, 2018) (Fig. A1c, d). Restoration of scars was conducted in Shoal Bay, a protected area on the southern shore of Port Stephens (Fig. A1a). Shoal Bay is close to the entrance of the estuary and exposed to waves from the northeast, typically during summer, and protected from eastern and southeastern directions during the rest of the year (Short and Trenaman, 1992; Vila-Concejo et al., 2007).

2.2. "Operation Posidonia": a citizen-science project for fragment collection

In 2018, we created and launched a citizen science project called 'Operation Posidonia' (Sinclair et al., 2021) to engage local communities in the collection of naturally detached *P. australis* fragments washed up on the beach after storms, strong winds and high tides. This involved liaising with multiple local community groups such as the 'Ocean and Coastal Care Initiatives (OCCI)', 'Salamander Bay Community' and 'Shoal Bay Community'. Two short films ('Look After Your Bottom' and 'How Operation Posidonia works') were produced to explain the environmental problem and the methods of restoration. Social media pages (Facebook, Instagram and Twitter) were used to share recommendations for the best weather conditions for *P. australis* collection. We organized guided seagrass "Walk and Talk" meetings with local groups and high schools (Fig. 4), and advertised the project in local news media to engage more citizen scientists.

Citizen scientists collected fragments along the shore and deposited them at collection stations, where fragments were submerged in seawater. Fragments were then planted in commercially-available building sand (80 mm deep) in individual Coreflute® boxes within large outdoor tanks at the Port Stephens Fisheries Institute with flow-through estuarine water (salinity >28 ppt) (Fig. 4). Boxes floated near the surface of the water so that the sediment was 350 mm below the water. This type of sediment and method of storage were optimised after a range of pilot studies (Glasby, unpublished data). Each box had a numeric tag that identified the date fragments were collected. Fragments were individually tagged and the initial number of shoots was recorded to monitor the collection and survival of fragments over time. The day before replanting in the field, fragments were carefully removed from the sediment by fully opening the (flat pack) Coreflute® boxes in a shallow saltwater bath and wafting away the sediments to expose the roots.

2.3. Replanting P. australis fragments in mooring scars

The fragments were planted in two types of old boat mooring scars in Shoal Bay: (i) scars where block and chain moorings had been removed (bare scars) or (ii) scars where an EFM had been recently installed. EFMs consisted of an anchor weight, a rope and short chain, with the latter two sections kept off the substratum by a tough and flexible rubber shock chord, so that no elements were scarring the seafloor (Fig. A1e). We replanted *P. australis* fragments in two bare scars in January 2019 and two in June 2019. In November 2019, restoration took place in two EFM scars.

In January and June six restoration plots (each 1 × 1.5 m) were established in each scar, three with stabilizing mats made of natural biodegradable fibre (jute mesh) and three without (Fig. 1a, b). In November we set up a total of eight plots in one EFM scar (four with jute mats/four without) and a total of four plots in the other EFM scar (two with jute mats/two without) due to differences in total scar size. Restoration plots were established at least 1 m away from the EFM. Each plot had a total of 24 fragments, planted by SCUBA-divers into bare sand at ~20 cm spacing and distributed in four rows of six fragments each (Fig. 1e). We gently excavated the sediment and secured the fragments with an anchoring technique appropriate for the growth-form of each fragment (Ward et al., 2020): either 150 mm long starch-based pegs (GreenStake™) with biodegradable budding tape (Ryset Australia) for orthotropic rhizomes (Fig. 1c) or 150 mm long metal Weed Mat Pins (Whites Outdoor) for plagiotropic rhizomes. For the June and November planting events, we used 200 mm long bamboo pegs instead of the metal pins (Fig. 1d).

2.4. Environmental characteristics of replanting sites

We included two environmental characteristics of each site (surrounding habitat and depth) as predictors of survival, both recorded on site by SCUBA-divers. In Shoal Bay we had (i) scars among natural *P. australis* and (ii) scars among other seagrasses. The dominant seagrass in the study site is *P. australis*, with scattered areas of *Zostera muelleri* subsp. *capriconi* and *Zostera nigricaulis* and smaller amounts of *Halophila* spp. Depth varied from 2 to 6 m.

Sedimentation within the scars was quantified throughout the study as Port Stephens has highly variable sedimentation patterns, and Shoal Bay is particularly influenced by erosion (Austin et al., 2018; Vila-Concejo et al., 2007). In each scar, measures of sedimentation were made on two plots for each planting method (with/without jute mat), hereinafter referred as sedimentation plots (Fig. 1e). Changes in sedimentation were measured using the depth of disturbance (DOD) rod method (Vila-Concejo et al., 2014). DODs have been mostly used in intertidal zones, but recent tests have shown that they are a reliable tool in subtidal sites (Potouroglou et al., 2017; Vila-Concejo et al., 2014). DODs can give measurements of both sediment erosion and accumulation. We used maximum erosion as it is the most stable measurement and more appropriate for Shoal Bay (more details in Supplementary material).

2.5. Survival and growth of replanted fragments

Each restoration plot was monitored by SCUBA divers every 2 to 4 months to assess fragment survival. Individual fragments were recorded as 'alive' or 'not alive' (either dead or lost) and the individual tag of 'not alive' fragments were removed. Restoration plots planted in January and June were monitored for fragment survival over 12 months, while plots from November were monitored over 8 months. In addition, growth of the fragments planted in January and in June was recorded by the change in the number of shoots of each fragment over time.

2.6. Statistical analyses

We used generalised linear mixed models (GLMMs) to test the influence of our predictor variables on survival as a binomial response variable. We used five models to analyse the data: for survival data after 7 to 8 months for the January, June and November plantings, model A included maximum erosion, and model B excluded maximum erosion as a variable; similarly, for survival data after 12 months for the January and June plantings, models C and D either included or excluded maximum erosion as a variable, respectively; model E was used to test if the presence of jute mats was having an effect on growth after 12 months. Separate models were used for plots with and without erosion data because maximum erosion was only measured on some of the plots. Model A compared fragment survival in bare and EFM scars with the following fixed factors (levels in parenthesis): 'type of scar' (bare and EFM), 'depth' (2, 4 and 6 m), 'surrounding habitat' (*P. australis* and other seagrasses), 'planting treatment' (jute and no jute), 'maximum erosion' and 'Plot number' as a random factor. Model B included the same variables in Model A except 'maximum erosion'. Models C and D had a similar design (except having 'planting month' instead of 'type of scar') and they were applied to survival after 12 months. We fit our GLMMs using the glmmTMB function in the glmmTMB package (Magnusson et al., 2017). Hypothesis tests between full and reduced models were used to calculate *p-values*. Statistical analyses and graphs were performed using the software R (version 4.0.2; R Core Team 2020) and relied heavily on the tidyverse workflow (Wickham et al., 2019) and ggplot2 (Wickham, 2016).

3. Results

3.1. Fragment collections by citizen scientists

About 1000 *P. australis* fragments were collected by citizen scientists between September 2018 and November 2019. The numbers collected

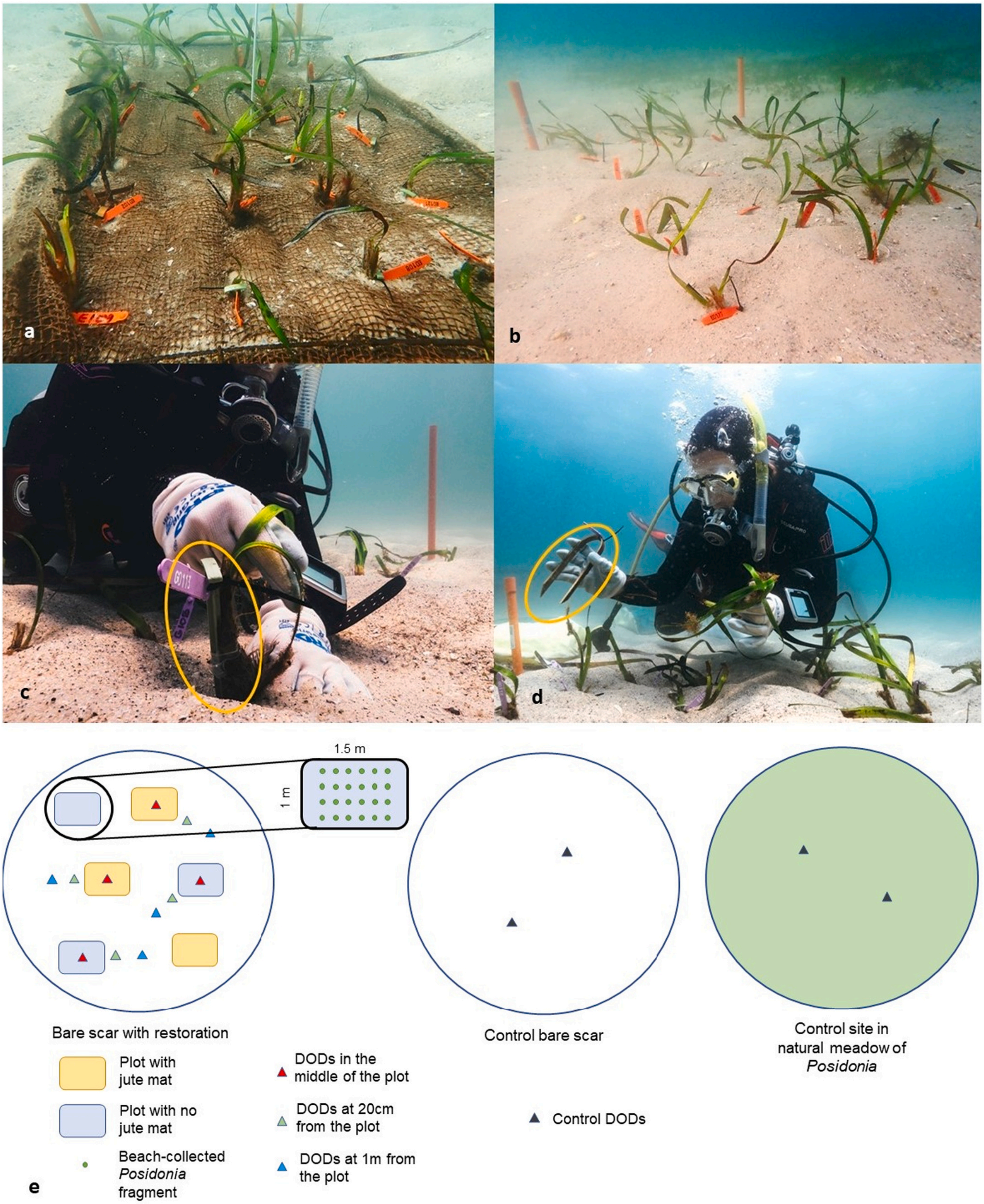

Fig. 1. The technique of replanting *Posidonia australis* fragments. Example of a plot with (a) and without (b) a jute mat to stabilize sediments; a SCUBA-diver securing a fragment with a starch-made pin (c) and a bamboo peg (d), in the yellow circles; (e) experimental design: bare scar with six restoration plots (three DODs per restoration plot). Close up: example of a restored plot. Control sites in bare scars and natural meadow of *P. australis* were set up for sedimentation measurements (DODs). DOD stands for depth of disturbance rod. Photos: Giulia Ferretto (a, b), Harriet Spark (c) and Richard Woodgett (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

varied among months of the year (Fig. 2). Condition of fragments collected was variable, but the fragments that survived after being stored in tanks (between 2 weeks to 7 months) were those replanted. Collections of *P. australis* fragments generally increased after outreach events organized by the 'Operation Posidonia' team, such as engagement through social media and meetings/walks with community members and local schools (Fig. 2). Collections increased particularly during summer school holidays (December and January) and after autumn storms (April and May) (Fig. 2). The months with highest visits on the website overlapped with highest views on the Facebook page and generally corresponded with periods of the greatest fragment collection (Fig. 2).

3.2. Survival and growth of replanted fragments

We planted a total of 863 fragments of *Posidonia*: 285 in January, 287 in June and 291 in November. The overall survival of *P. australis* fragments after 7 to 8 months was 52% (± 3.9%) (Fig. 3a), with no difference detected between bare scars or those with an EFM ($p = 0.85$). The presence of other seagrasses as a surrounding habitat increased survival ($p < 0.05$) after 7 to 8 months, while the presence of jute mats did not influence survival ($p = 0.2$). Fragments at deeper sites had reduced survival ($p < 0.05$) (Model B).

Average survival after 12 months was higher for the fragments planted in June (54% ± 3.9%) than those planted in January (31% ± 4.2%) ($p < 0.01$) (Fig. 3a). *P. australis* survival after 12 months was not influenced by either the surrounding habitat, the planting treatment or depth ($p > 0.05$) (Model D).

Mortality was highest in the first three months, especially for fragments planted in January (Fig. 3a). The number of shoots of the surviving fragments initially declined but increased 150–200 days after planting, meaning fragments were producing new shoots (Fig. 3b). Numerous surviving fragments planted in January (35.5%) and in June (37.2%) had produced at least one new shoot throughout the year. Growth was not related to planting treatment (bare or jute mats) ($p = 0.16$).

Erosion did not have an effect on survival after 8 months ($p = 0.83$) or after 12 months ($p = 0.97$) (Model A and C, respectively), and this result was consistent for plots with and without jute mats.

4. Discussion

We show that naturally-detached fragments of *P. australis* collected from the beach by citizen-scientists can successfully be maintained in tanks and replanted into old mooring scars to revegetate fragmented seagrass meadows. The use of rhizome and shoot fragments in restoration of *Posidonia* spp. is common both in the Mediterranean (Procaccini and Piazzi, 2001) and Australia (Bastyan and Cambridge, 2008; Tan et al., 2020) but this study extends that research to naturally-detached wrack from beaches, reducing the need for harvesting plants from donor meadows. This represents a significant advantage, especially where a seagrass species is listed as threatened or near threatened. Overall survival was higher for fragments planted in winter than those planted in summer, and survival was not dependent on using jute mats to stabilize sediments or the presence of an environmentally friendly mooring within the restoration scar. This indicates that the combination of improved mooring designs and seagrass restoration using naturally-detached fragments can be a valuable solution to restore fragmented meadows.

Storms, strong winds and boating activities often result in the detachment of parts of marine plants and algae that are then transported by winds and tides and deposited as wrack on shores. Wrack is a natural phenomenon that can become a coastal problem unless it is properly managed (Macreadie et al., 2017; Misson et al., 2020). We show that wrack can contribute to the recovery of seagrass meadows if washed up fragments with rhizomes are actively collected before they dry and housed in appropriate conditions prior to replanting. A similar approach using naturally detached seagrass fragments for restoration has previously been used in the Mediterranean (Balestri et al., 2011; Piazzi et al., 2021; Ward et al., 2020). Our study shows that this approach can also be

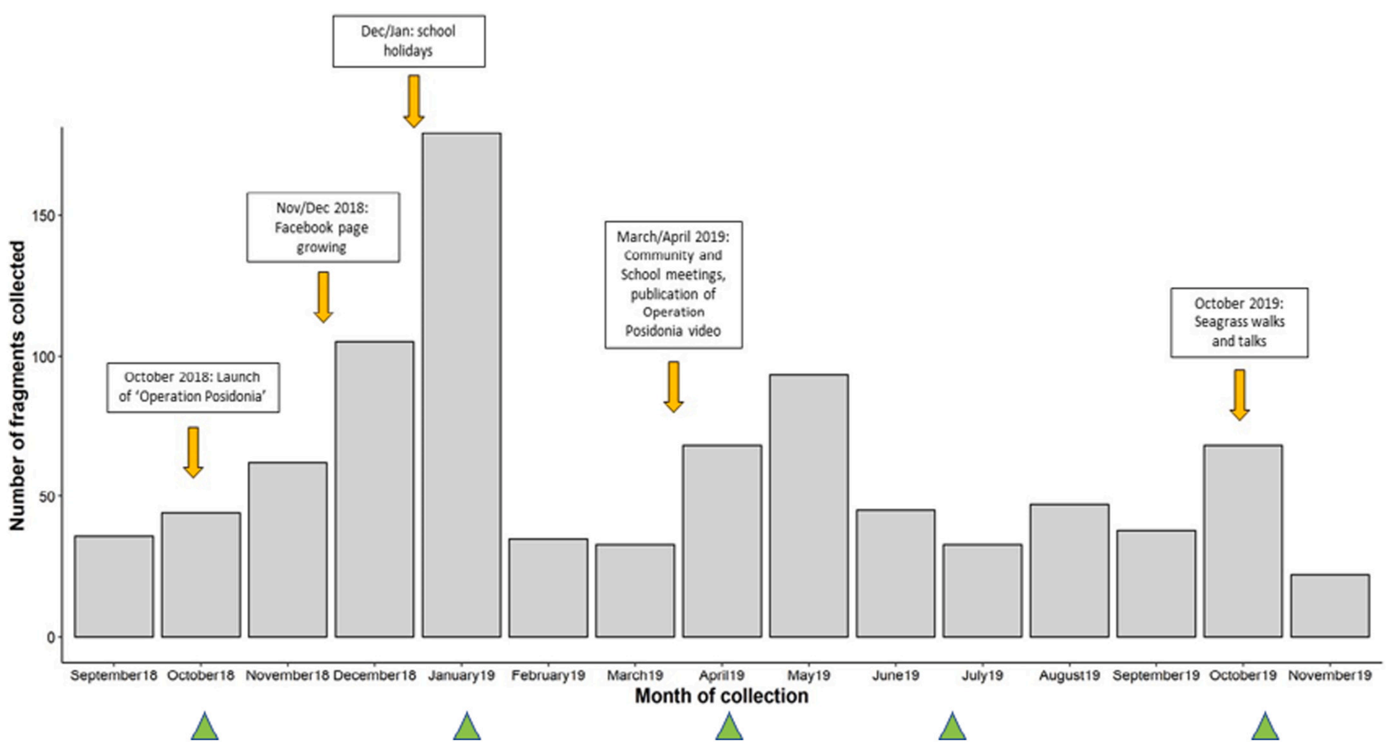

Fig. 2. 'Operation Posidonia' fragment collection from September 2018 until November 2019. Green triangles represent the months with highest views on Operation Posidonia Facebook page and website. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

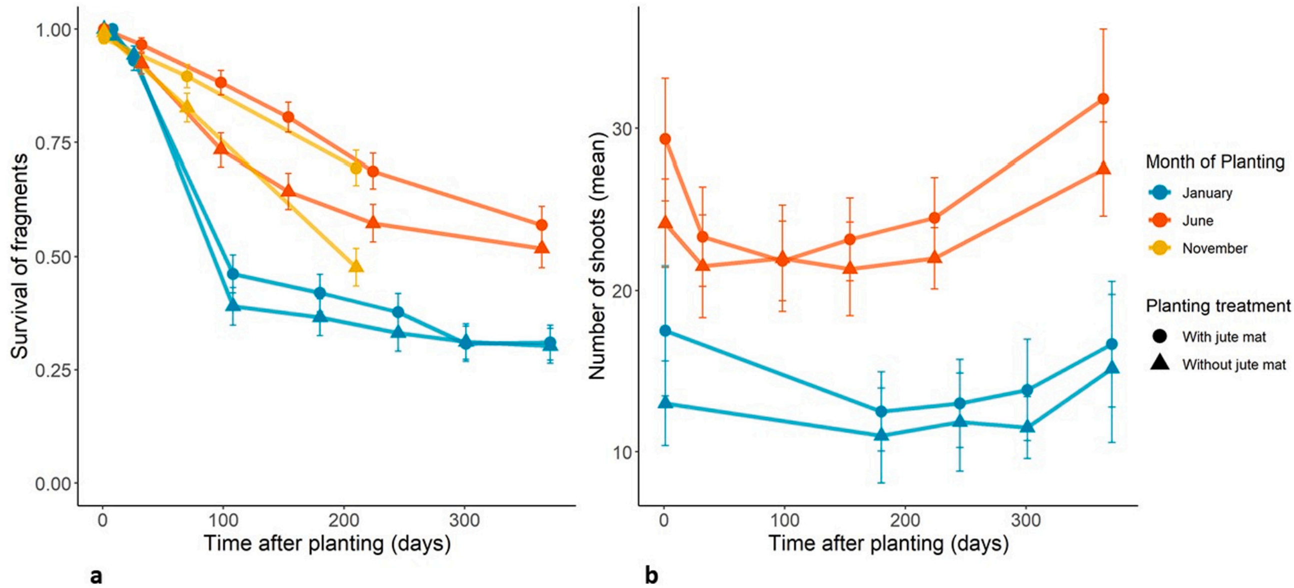

Fig. 3. Survival (a) and growth (b) of fragments over time. Only surviving fragments were included in the plot (b). Fragments planted in January (blue), June (red) and November (yellow). Fragments planted with jute mats (circle) and without jute mats (triangle). Data are represented in mean per plot, error bars represent standard error (± SE). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

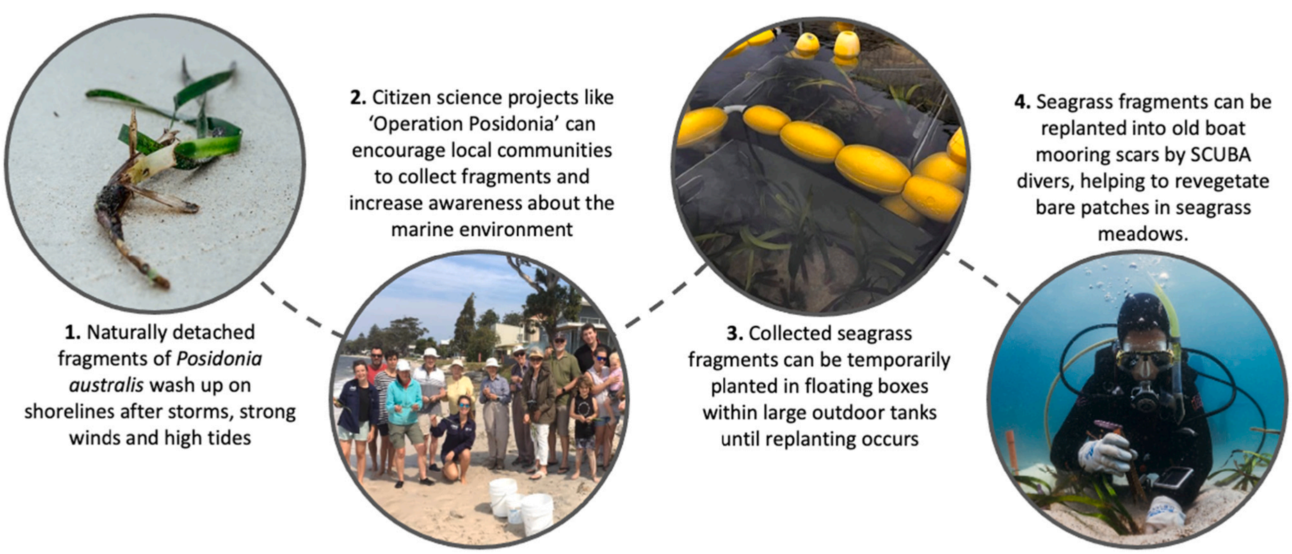

Fig. 4. How *Posidonia australis* fragments are collected for restoration. (1) Example of a *P. australis* fragment suitable for restoration washed up on the shore; (2) Seagrass Walk & Talk, one of the community engagement efforts 'Operation Posidonia' held in Port Stephens; (3) Some Coreflute® boxes where seagrass fragments were stored before being replanted underwater; (4) A SCUBA-diver replanting a *P. australis* fragment.

effective in environments with a greater tidal range (up to 2 m) such as are found in southeastern Australia, where shoots could be exposed to air longer once beached.

Our findings demonstrate that substantial amounts of donor material can be collected by citizen-scientists through community engagement efforts, extending contribution of citizen-science from monitoring purposes (e.g. Seagrass-Watch and SeagrassSpotter) to restoration. Citizen-scientists that frequent local shores can be easily trained to recognize the seagrass fragments suitable for restoration. In Port Stephens, the contributions from citizen-scientists greatly enhanced the success of the project. When conditions were favourable (strong northerly winds preceding an outgoing tide, in our sites), a one-hour beach walk could collect as many as 30 viable fragments. The collection effort varied over time, but the presence of an organizer of 'Operation Posidonia' on site was the best way to facilitate consistent collections. When this was not possible, we organized talks and events regularly (every 2–3 months) to keep the local community engaged. Having a collaboration with local schools that organize semi regular fieldtrips as part of science class can also be a good solution.

Keeping fragments in tanks prior to planting was an efficient way to naturally select those that were most viable for restoration (non-viable fragments would die during storage) and enabled us to build up a stockpile of material that could be used for replanting in large batches over multiple days. Without stockpiling fragments, replanting would have had to occur soon after fragment collection, which was not logistically possible and would likely have resulted in some non-viable fragments being planted. Unlike *Posidonia oceanica* (Balestri et al., 2011), fragments of *P. australis* could not survive floating in water for long periods without being planted. This floating storage method was trialled at the beginning of the project (summer 2018–2019) and resulted in the greening of roots (exposure to light) and the burning of leaves (exposure to high temperatures).

Many seagrass restoration studies have failed due to planting in unsuitable habitats, often because of sediment movement (Irving et al., 2010; Meehan and West, 2002; Paling et al., 2009; Van Keulen et al., 2003) or because the factors causing the seagrass decline were not completely solved (van Katwijk et al., 2009). Lack of an adequate anchoring system for replanted fragments is also a common reason for restoration failure (Bastyan and Cambridge, 2008). Emerging techniques such as the use of hessian bags (Irving et al., 2010), trait-based mimic structures (Temmink et al., 2020) and mats (Piazzi et al., 2021; Seddon, 2004) have had good success over much longer time periods (Tan et al., 2020). In our study, the coarse weave jute mats did not affect fragment survival and growth, however in highly exposed environments the use of mats improves seagrass transplant survival (Piazzi et al., 2021). Erosion in the scars with EFMs was higher than in natural *P. australis* meadow but this did not affect overall survival, probably because the presence of jute mats was compensating for the higher level of erosion.

Transplant survival varied among seasons and sites, confirming that time of planting and site selection can be crucial (Meehan and West, 2002; van Katwijk et al., 2009). Fragments planted in winter (June) had higher survival after 12 months than those planted in summer (January). Transplant mortality during the first few months is usually the highest (Balestri et al., 2011; Meinesz et al., 1991; Sanchez-Lizaso et al., 2009). *Posidonia* spp. usually have higher biomass growth in summer when light availability is at maximum levels. *Posidonia* spp. during this season are more vulnerable, as this is the season when they accumulate energy reserves (Meinesz et al., 1991; Wittmann and Ott, 1982). The high temperature of summer could have been responsible for stressing the fragments both during collection and handling prior to planting, causing greater mortality. Storms are common between April and September on the New South Wales coast (Harley et al., 2010; McLean and Hinwood, 1999) and the study site was hit by a large storm three months after January planting (in April 2019). Transplants may not have had time to anchor securely in sediments by this time, which may have also contributed to the lower survival of fragments planted in January compared to the other two planting times. Surprisingly, the presence of other seagrasses as a surrounding environment of the mooring scar was related to higher survival after 8 months but not at 12 months, which suggests positive interactions among seagrass species may be more important during the early stages of fragment re-establishment (Valdez et al., 2020). Restoration at shallower depths is sometimes more successful, this could be because seagrasses, by receiving more light at a lower depth, grow faster and establish more quickly.

Seagrass restoration success is currently highly variable (Irving et al., 2010; Meehan and West, 2002; Statton et al., 2018). Encouragingly, the overall survival levels recorded in this study are comparable or higher to those harvesting transplants from natural meadows (Ganassin and Gibbs, 2008). These positive results need to be considered with some caution, nevertheless, given that the overall monitoring period for this study was relatively short (maximum one year) and previous studies on *Posidonia* spp. show that one year monitoring may not be sufficient to detect a long-term success (Pirrotta et al., 2015). Ongoing studies with *P. australis*, however, show that the greatest loss of transplants typically occurs in the first 3–6 months and survival can be >90% thereafter, although can be site specific (Statton et al., 2020). The replanting/attachment method used here was trialled at a relatively exposed site in Botany Bay, NSW (using *P. australis* rhizomes collected from a meadow) and has had long-term success, with numbers of shoots almost doubling over 8 years (Glasby, unpublished data). Restored areas are expected to take >5 years to achieve shoot densities similar to natural undisturbed meadows, depending of course on the initial planting density (Statton et al., 2020). Other than one small trial using transplants of laboratory-reared seedlings (Glasby et al., 2014), previous *P. australis* restoration projects in NSW have primarily relied on harvesting the plants from healthy meadows (Ganassin and Gibbs, 2008; Seddon, 2004). In our study, most surviving fragments started growing new shoots around 5–6 months after planting, meaning that they recovered from any collection and planting stress within a few months and started spreading in the surrounding environment. As sexual reproduction in *P. australis* meadows in NSW is not as common as other parts of Australia (Larkum et al., 2006), it is encouraging to see evidence of clonal reproduction from replanted fragments.

We demonstrate that healthy seagrass fragments collected from the beach, when replanted in suitable conditions, have the capacity to establish and start expanding into nearby areas after only a few months. Naturally-detached fragments thus represent a promising donor source for *Posidonia* restoration efforts that does not involve any damage to existing meadows. By engaging citizen scientists for seagrass fragment collection, we demonstrate that this is a successful method to increase the amount of donor material, reduce costs of restoration and inform the public about marine conservation. This method therefore helps optimise current restoration techniques, as advocated for the current "UN Decade on Ecosystem Restoration" (Waltham et al., 2020). As seagrass collection, handling and planting methodologies have developed over the past two decades, there is a growing number of success stories worldwide and within Australia. The challenge now is to scale-up restoration projects by ensuring resources are available to enhance communication and co-ordination among stakeholders, including industry partners, local Indigenous Ranger groups and environmental organizations. Thus, knowledge obtained by this study was also shared with councils, policy makers and general public in form of guidelines to increase knowledge exchange (Blignaut et al., 2013).

CRediT authorship contribution statement

Giulia Ferretto: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Tim M. Glasby:** Funding acquisition, Conceptualization, Investigation, Methodology, Resources, Writing – review & editing, Visualization. **Alistair G.B. Poore:** Funding acquisition, Conceptualization, Methodology, Formal analysis, Writing – review & editing, Visualization. **Corey T. Callaghan:** Methodology, Formal analysis, Writing – review & editing, Visualization. **Graham P. Housefield:** Investigation, Methodology, Resources. **Madelaine Langley:** Investigation, Methodology, Writing – review & editing. **Elizabeth A. Sinclair:** Funding acquisition, Methodology, Writing – review & editing. **John Statton:** Funding acquisition, Methodology, Writing – review & editing. **Gary A. Kendrick:** Funding acquisition, Methodology, Writing – review & editing. **Adriana Vergés:** Funding acquisition, Conceptualization, Investigation, Methodology, Resources, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109308.

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