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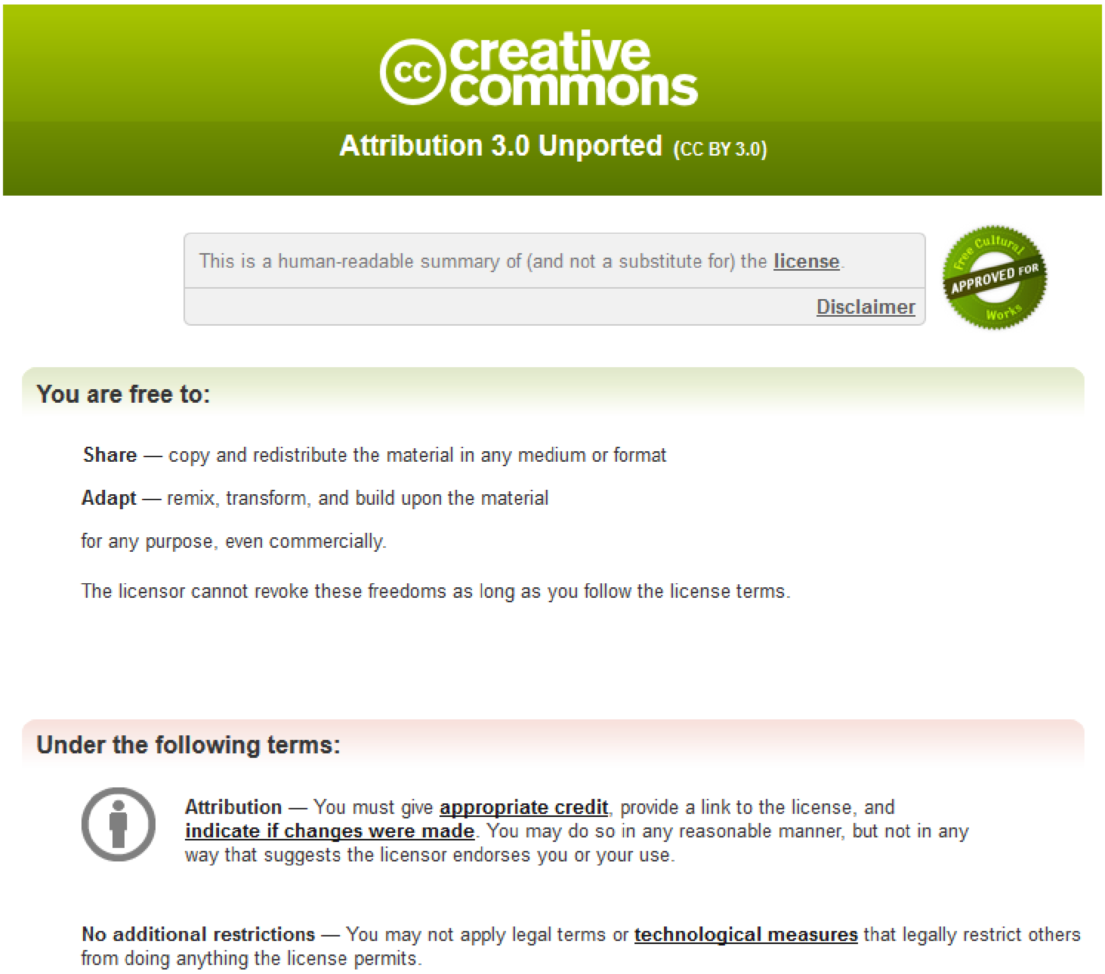

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RESEARCH ARTICLE

Rehabilitating Seagrass by Facilitating Recruitment: Improving Chances for Success

Andrew D. Irving,[1,2,3] Jason E. Tanner,[1] and Greg J. Collings[1]

Abstract

Attempts to arrest seagrass loss through numerous rehabilitation methods have traditionally produced inconsistent results. On Australia's southern coast, hessian bags made from biodegradable jute fibers show promise for rehabilitating *Amphibolis antarctica* by facilitating recruitment of seedlings in situ. Testing ways to improve the performance of bags (i.e. increasing seagrass recruitment and establishment) showed that bags with a coarse outer weave of hessian facilitated greater seedling densities (approximately 1700 individuals/m^2) than bags with a fine outer weave, but the content of bags (sand vs. sand and rubble mixture) had little effect. Isolated bags facilitated greater longer term densities than bags grouped together, while similar densities were sampled up to 80 m away from a natural meadow. Lastly, bags that had spent less time in situ initially facilitated more recruits than older bags, but longer term (21–32 months) retention was similar among bag ages. Collectively, the results suggest hessian bags can be a relatively simple, cost-effective, and environmentally friendly method for rehabilitating *Amphibolis* seagrass, with few considerations in their use other than their physical architecture and arrangement (e.g. isolated coarse-weave bags).

Key words: ***Amphibolis antarctica*, habitat loss, meadow, recovery, restoration, seedling.**

Introduction

Coastal habitats are facing unprecedented scales of anthropogenic stress (Orth et al. 2006*a*; Connell 2007). Seagrass meadows are particularly threatened because the sheltered and well-illuminated estuaries and embayments they thrive in are also favored by humans for urbanization (Larkum & West 1990; Ralph et al. 2006). Since 1879, approximately 29% of the world's seagrass has been lost, equating to over 51,000 km^2 (Waycott et al. 2009). These losses jeopardize fundamental ecosystem services such as primary production, nutrient cycling, and carbon sequestration (Mateo et al. 2006), sediment stabilization to reduce turbidity and coastal erosion (Orth 1977), and the maintenance of biodiversity (Heck et al. 1995), including commercially prized species (Connolly 1994).

Many seagrass meadows expand slowly and take decades to recover from anthropogenic disturbances (Kirkman & Kuo 1990; Bryars & Neverauskas 2004; González-Correa et al. 2005). In an attempt to accelerate recovery, various seagrass rehabilitation and restoration methods are used (Fonseca et al. 2000; Orth et al. 2006*a*). Transplanting seagrass from healthy donor meadows to impacted sites is most common (Fonseca et al. 1994; Paling et al. 2001) but is labor intensive, damages donor meadows, and may require up to three transplants for every one survivor (Fonseca et al. 1998), ultimately causing a net habitat loss (Bull et al. 2004). Planting seeds (Harwell & Orth 1999), cultured seedlings (Balestri et al. 1998), and rhizome fragments (Durako et al. 1993) are also used with varying degrees of success. Indeed, the overall historical success rate for rehabilitation is 35–50% (Fonseca et al. 1998), leaving considerable room for improvement through continued methodological development.

Since 2003, several rehabilitation methods have been tested in the waters adjacent to the city of Adelaide, South Australia (population approximately 1.2 million). Here, nutrient-rich wastewater increased epiphytic overgrowth that inhibited seagrass photosynthesis and caused the loss of approximately 5200 hectares since the 1930s (Neverauskas 1987). In recent years, improved wastewater management has facilitated localized seagrass recovery of approximately 4% (Bryars & Neverauskas 2004), but efforts to accelerate recovery through transplants and outplanting laboratory-cultured seedlings have produced poor to average results that do not justify large-scale application (Irving et al. 2010). Such ineffectiveness is largely attributable to the erosion of sand and transplanted seagrass in the high wave energy environments that characterize much of the southern Australian coastline (Paling et al. 2003; Van Keulen et al. 2003).

More promising results have come from using hessian bags made from biodegradable jute fibers (also known as

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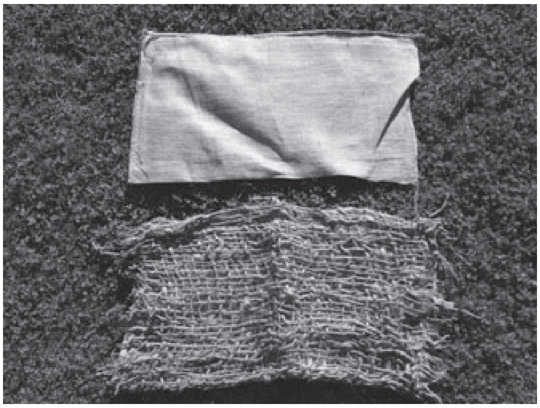

Figure 1. Components of hessian bag recruitment units. The standard unit consisted of a fine-weave hessian bag (top) filled with approximately 25 kg of sand and sewn into a course outer weave (bottom). The presence versus absence of the outer weave was tested as a potential improvement.

burlap; Fig. 1) that facilitate in situ recruitment of *Amphibolis* seedlings, particularly *Amphibolis antarctica* (Wear et al. 2010), which has suffered considerable losses in the region (Bryars & Rowling 2009). *Amphibolis antarctica* seedlings are produced viviparously and posses a distinctive basal "grappling hook" structure (Kuo & den Hartog 2006) that anchors them to stems and exposed rhizome of other seagrasses, after which they grow roots and establish (Clarke & Kirkman 1989). The fibrous hessian provides an excellent surrogate for anchorage, facilitating seedling densities up to 660 individuals/m^2 (Wear et al. 2010) during the peak recruitment season (May–September; Clarke & Kirkman 1989).

Previous work compared the effectiveness of hessian bags, mats, and strips of different structure and orientation for the recruitment of *A. antarctica*, and found that the bags filled with sand were the most promising design (Wear et al. 2010). We build on this knowledge by testing if the performance of hessian bags (i.e. the recruitment and retention of seagrass) could be enhanced by varying their use over space and time, and also by modifying their design. Specifically, we tested whether densities of *A. antarctica* on hessian bags would differ among (1) bags placed at varying distances from natural *A. antarctica* meadows, (2) different grades of hessian weave (fine vs. coarse weave), (3) bags with different types of filling (sand vs. a sand and rubble mixture), (4) different spatial arrangement of bags (isolated vs. grouped), and (5) bags of different age (i.e. time in situ). These tests were designed to clarify how hessian bags may best be used to maximize the success of future large-scale rehabilitation efforts.

Methods

Study Sites and Hessian Bag Design

All research was done along the temperate and moderately exposed metropolitan coast of Adelaide from 2006 to 2012. The predominantly sandy coastline supports seagrass meadows primarily comprising *Amphibolis antarctica*, *Posidonia angustifolia*, and *P. sinuosa*, as well as *Heterozostera tasmanica* in more sheltered areas (Bryars et al. 2008). Experiments were done at approximately 8 m depth and within known areas of seagrass loss at Grange (34°32′S, 138°17′E) and Brighton (35°1′S, 138°18′E). Unless otherwise stated, bags were always placed on sand near the edge of natural *A. antarctica* meadows to ensure a nearby source of recruits.

Wear et al. (2010) showed the most promising hessian bag design consisted of a fine-weave (10 oz) bag filled with approximately 25 kg of clean playpit sand and encased in a coarse outer weave ("soil saver") (Fig. 1). This bag design was used for all experiments, barring specific alterations tested as potential improvements (described below). When constructed, bags measure approximately 0.76 × 0.46 m and are easily deployed from a boat and arranged in situ by divers if necessary.

Depending on the rate of hessian degradation and burial under sand, most bags recruit two cohorts of seedlings, with the first typically more numerous because hessian degradation over time reduces its capacity to entangle seedlings. Even so, the second cohort may provide a useful boost to recruit densities as the first cohort typically undergoes considerable thinning (76–89% decline over approximately 12 months; unpublished data). For experiments described herein that were sampled for more than 12 months, no attempt was made to partition the responses of individual cohorts as the goal in each experiment was to test the overall performance of hessian bags regardless of the number of cohorts they supported.

Distance from Meadow

To test how recruitment varies with distance from a meadow, 40 hessian bags were deployed at Grange in September 2006 and arranged along five transects at the following distances from the meadow edge: −10 m (i.e. within the meadow), 0, 5, 10, 20, 40, 60, and 80 m. Bags were oriented similarly to waves and tide, and were individually marked for relocation. The density of *A. antarctica* recruits on each bag was sampled in October 2007, with least-squares linear regression testing the relationship between distance and recruit density.

Fine- Versus Coarse-Weave Hessian

Wear et al.'s (2010) comparison between bags with and without a coarse outer weave (termed coarse- and fine-weave bags, respectively) showed that *A. antarctica* recruitment was often greater on coarse-weave bags, but this did not always equate to greater long-term densities. We sought to clarify the short-term and longer term performance of both bag designs by deploying five of each at Grange in February, April, May, August, and October 2009. For each deployment, bags were randomly arranged approximately 0.5 m apart and oriented similarly to waves and tide. Recruitment of *A. antarctica* was sampled approximately 1 month after deployment, with densities again sampled after approximately 12 and 24 months to quantify longer term retention. Analyses were done using repeated measures analysis of variance (RM-ANOVA), treating “month of deployment” as random and “bag design” as fixed and orthogonal effects.

Type of Filling

Substratum composition can affect seagrass root growth and establishment (Kenworthy & Fonseca 1977), ultimately limiting their survival. We tested whether hessian bags perform better if filled with sand, which appears suitable for root growth and establishment, or a mixture of sand and rubble (20-mm quartzite aggregate), which may be less susceptible to erosion as hessian bags degrade. Bags containing each fill type were deployed at Brighton ($n = 10$) and Grange ($n = 9$) in September 2007. Densities of *A. antarctica* were sampled approximately 1, 12, 29, and 40 months after deployment, with RM-ANOVA treating “site” as random and “fill” as fixed and orthogonal effects.

Spatial Arrangement

Testing how the spatial arrangement of bags affected recruitment was done by comparing recruit densities on single isolated bags to groups of five adjoining bags (i.e. a grid of 2×2 bags with the fifth bag placed along one edge), and to a group of five bags with the same 2×2 grid but with the fifth bag placed centrally on top to provide greater vertical relief. The experiment was established at Grange in September 2007 ($n = 5$ for each arrangement), with the density of *A. antarctica* sampled after approximately 1, 12, and 52 months. Data were analyzed using RM-ANOVA.

Age of Bags

A benefit of hessian bags is that they are biodegradable, yet this may also impact seagrass recruitment or retention. We tested if older bags, having spent more time in situ and thus being more degraded, recruit and retain fewer *A. antarctica* than younger bags. In September 2007, 10 bags were deployed at Grange and then approximately bimonthly until the 2008 recruitment season beginning in May/June. This process was repeated in September 2008. All bags were spaced approximately 0.5 m apart and were oriented similarly to waves and tide. Seagrass densities were sampled approximately bimonthly for the first year to quantify recruitment and then approximately annually thereafter to measure retention. Differences among bag ages were tested with ANOVA.

Results

Distance from Meadow

Amphibolis antarctica recruits on hessian bags were generally sparse throughout the experiment, peaking at 34 individuals/m^2 on a bag 20 m from the meadow edge, and averaging 10.51 individuals/m^2 across all bags after 13 months. Recruit density was positively related to distance from the meadow (Fig. 2; ANOVA: $F_{[1,38]} = 4.805$, $p = 0.035$), but an r^2 value of 0.112 suggests little predictive power.

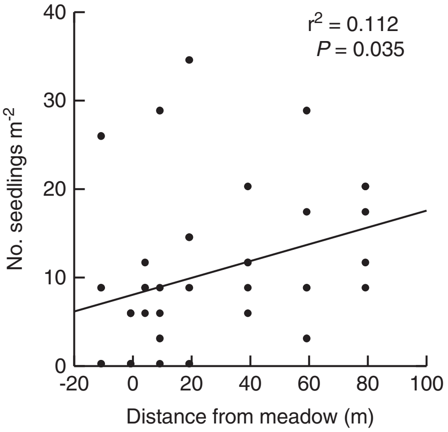

Figure 2. Least-squares linear regression of *Amphibolis antarctica* recruit density on hessian bags against distance from a natural meadow at Grange. Densities were sampled after the 2007 recruitment season (approximately 13 months after the bags were deployed).

Fine- Versus Coarse-Weave Hessian

Seedling densities after 1 month varied among deployment times, ranging from approximately 4 individuals/m^2 on bags deployed in February to greater than 1400 individuals/m^2 on bags deployed in August. Greater recruitment was generally observed on coarse-weave bags, with this pattern becoming more pronounced with each subsequent deployment until October (Fig. 3; 1 month). The interaction of bag design with deployment month was also dependent on time (Table 1; RM-ANOVA, time × design × month interaction: $F_{[8,80]} = 42.732$, $p < 0.001$). After 12 months, densities declined on all bags yet remained greater on coarse-weave bags for all deployments except February (Fig. 3; 12 months). After 24 months, densities were similar between bag designs for all months (Fig. 3; 24 months), averaging approximately 25 individuals/m^2. However, comparison of rank abundance showed greater mean densities on coarse-weave bags for three of the five deployments. Notably, bags deployed in August consistently supported the highest densities among all deployment times, although by 24 months, bags deployed in October supported near-similar densities.

Type of Filling

Amphibolis antarctica densities were generally greater at Grange than Brighton throughout the experiment, but only differed slightly between fill types at Grange at 12 months (Fig. 4; sand > rubble, RM-ANOVA, time × fill interaction: $F_{[3,108]} = 4.223$, $p = 0.018$). While densities subsequently declined to a single recruit at Brighton by 29 months, greater retention occurred at Grange where comparison of rank abundance showed greater mean densities on bags filled with sand and rubble at both 29 and 40 months (Fig. 4).

Spatial Arrangement

Differences in *A. antarctica* densities among bag arrangements were dependent on time (Fig. 5; RM-ANOVA,

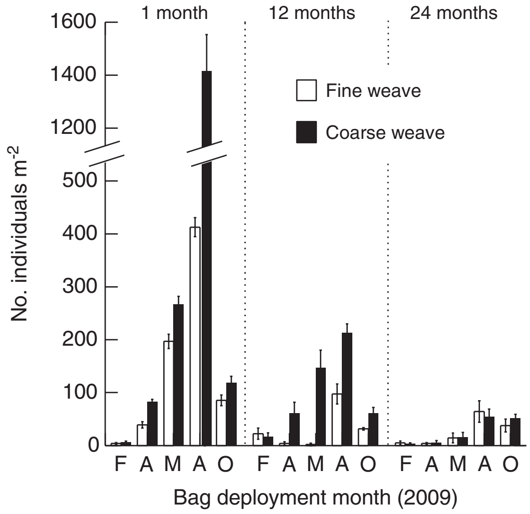

Figure 3. Mean (± SE) density of *Amphibolis antarctica* on fine- versus coarse-weave hessian bags deployed at Grange in February, April, May, August, and October 2009. Data were sampled approximately 1, 12, and 24 months after deployment.

Table 1. Result of RM-ANOVA testing for differences in *Amphibolis antarctica* recruit density between bag designs (fine vs. coarse weave) and deployment months (February, April, May, August, and October 2009).

Source	*df*	*MS*	*F*	*P*
Month	4	665805.14	141.15	<0.001
Design	1	372450.29	78.96	<0.001
Month × design	4	175857.69	37.28	<0.001
Error	40	4717.08	—	—
Time	2	806967.94	228.25	<0.001
Time × month	8	383237.39	108.40	<0.001
Time × design	2	174195.46	49.27	<0.001
Time × month × design	8	151078.72	42.73	<0.001
Error	80	3535.48	—	—

Bags were sampled 1, 12, and 24 months post-deployment. For each test, p-values were conservatively adjusted using the Greenhouse–Giesser ε to compensate for inflated type I error rate associated with departures from sphericity (Myers & Well 2002).

time × arrangement interaction: $F_{[4,24]} = 4.878$, $p = 0.010$). During the first year, densities were similar among arrangements, averaging approximately 22 individuals/m^2 after 1 month, and approximately 108 individuals/m^2 after 12 months. However, densities on both grouped arrangements declined substantially to approximately 6 individuals/m^2 after 52 months, while single bags retained densities of approximately 100 individuals/m^2 (Fig. 5).

Age of Bags

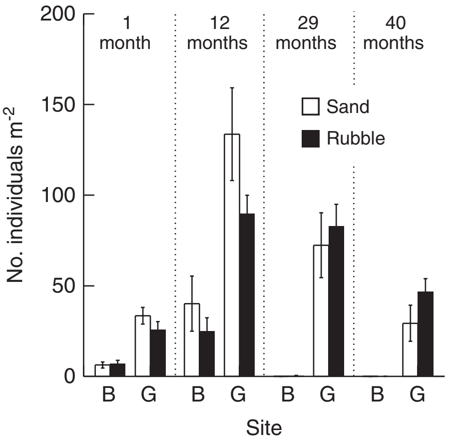

Figure 4. Mean (± SE) density of *Amphibolis antarctica* on bags deployed at Brighton (B) and Grange (G) that were filled with either sand or a mixture of sand and rubble. Data were sampled approximately 1, 12, 29, and 40 months after deployment.

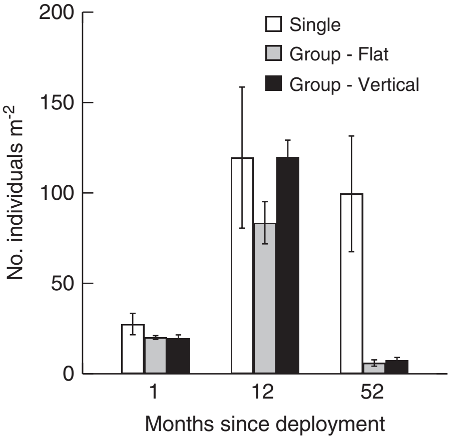

Figure 5. Mean (± SE) density of *Amphibolis antarctica* on bags at Grange that were arranged either as an isolated bag ("single"), a group of five adjoining bags flat on the seafloor ("group flat"), or a group of four adjoining bags with the fifth bag stacked on top to increase vertical relief ("group vertical"). Data were sampled approximately 1, 12, and 52 months after deployment.

Few recruits were observed from September 2007 to May 2008, after which recruitment peaked at approximately 604 individuals/m^2 on bags most recently deployed (Fig. 6a; May 2008). Older bags recruited fewer seedlings during peak period recruitment than younger bags (Fig. 6a; July 2008 samples, ANOVA: $F_{[4,44]} = 56.69$, $p < 0.001$; post hoc tests: bags deployed in May 2008 > April 2008 > February 2008 > November 2007 = September 2007). At this time, bags deployed in September and November 2007 had begun to tear and fray. Despite differential recruitment, *A. antarctica* densities approximately 21 months later (February 2010) had declined substantially and were similar among bag ages (approximately 40 individuals/m^2; Fig. 6a; ANOVA: $F_{[4,44]} = 0.975$, $p = 0.431$).

Similar outcomes occurred when the experiment was repeated in September 2008. Greatest peak recruitment occurred on bags more recently deployed (approximately 590 individuals/m^2; Fig. 6b; May 2009), but unlike the previous experiment, all other bags supported similar densities (ANOVA: $F_{[4,45]} = 3.512$, $p = 0.014$; post hoc

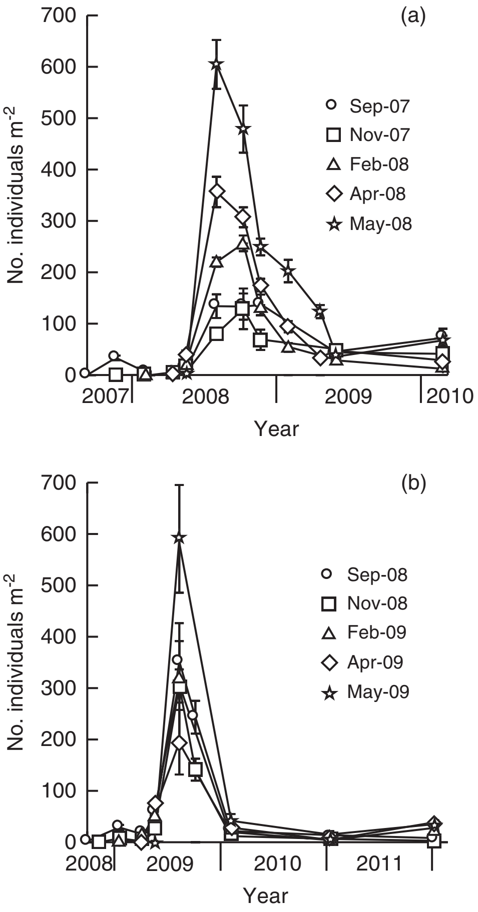

Figure 6. Effect of hessian bag age on the mean (± SE) density of *Amphibolis antarctica* at Grange. Two independent experiments were run from (a) September 2007 to February 2010 and (b) September 2008 to January 2012.

tests: May 2009 > April 2009 = February 2009 = November 2008 = September 2008). Over time, densities again declined on all bags, with the oldest bags supporting fewer individuals after 32 months (Fig. 6b; ANOVA: $F_{[4,45]} = 19.625$, $p < 0.001$; post hoc tests: May 2009 = April 2009 = February 2009 > November 2008 = September 2008).

Discussion

Facilitating the recruitment of *Amphibolis antarctica* seedlings using hessian bags represents a novel approach to seagrass rehabilitation (Wear et al. 2010), borne from unreliable outcomes of more traditional methods such as transplantation (Van Keulen et al. 2003; Irving et al. 2010). The goal now is to improve the technique to maximize recruitment and long-term seagrass survival such that the application of hessian bags to expensive and time-consuming rehabilitation projects can be done with confidence of success.

Seagrass propagule density often correlates to supply (Reed et al. 2009), with supply declining with distance due to physiological and environmental constraints on dispersal (e.g. propagule viability, strength of currents, and herbivore abundance) (Orth et al. 2006*b*). Over a short spatial scale of 80 m, a positive relationship between distance from a natural *A. antarctica* meadow and seedling densities on hessian bags was observed. While the relationship is not robust ($r^2 = 0.112$), it indicates that bags located within approximately 100 m of a natural meadow are effective at intercepting seedlings. *A. antarctica* seedlings are produced viviparously and are well developed after abscission (Kuo & den Hartog 2006), likely affording them physiological capacity for lengthy dispersal times and distances. Indeed, genetic similarities observed across approximately 1100 km of Western Australian coastline suggest high levels of connectivity within and among populations (Waycott et al. 1996). While such dispersal capacity suggests that bags could be effective greater than 80 m from natural meadows, this hypothesis is yet to be tested. There must certainly be a distance at which seedling encounter rate and survival would decline to render bags ineffective, but identifying such spatial limitations could be particularly useful for planning the rehabilitation of large degraded areas.

Providing a surface material that not only anchors *A. antarctica* seedlings but also facilitates their longer term establishment is a primary consideration for bag design. Similar to Wear et al. (2010), we found that coarse-weave bags generally captured more seedlings than fine-weave bags, but that longer term seedling retention was statistically similar. For the majority of tests, however, seagrass density still ranked higher on coarse-weave bags after 24 months, which is noteworthy if rehabilitation aims to maximize the abundance of new habitat. The coarse outer weave is more fibrous and rugose than fine-weave bags, which probably causes stronger entanglement with grappling hooks of *A. antarctica* seedlings. Indeed, coarse-weave bags facilitated the greatest recruit densities observed so far (1705 individuals/m^2), surpassing the previous record of 660 individuals/m^2 (Wear et al. 2010). Coarse-weave bags are, however, more expensive than fine-weave bags (US$12.51 vs. $3.38, respectively), but compensation through greater recruitment may reduce costs to US$0.51 per seedling versus US$1.66 per seedling (fine weave) after 12 months (Wear et al. 2010).

Substratum composition and particle size affects seagrass growth, distribution, and abundance (Kenworthy & Fonseca 1977). Over a period of 40 months, however, *A. antarctica* densities did not consistently differ between bags filled with sand or a mixture of sand and rubble, even though recruits had grown numerous roots (A. D. Irving, J. E. Tanner, and G. J. Collings 2011, personal observation). *Amphibolis antarctica* produce relatively short roots, meaning substratum composition may affect establishment and survival less than factors such as substratum mobility (Clarke & Kirkman 1989). Even so, different results may arise from more comprehensive testing of substratum composition, including the addition of fertilizer that can improve seagrass establishment (Fonseca et al. 1994). Based on the data available, however, using bags filled only with sand does not impact seagrass density but is less time-consuming than filling with a mixture, suggesting that it is the simpler option for this rehabilitation method.

The interception of mobile *A. antarctica* seedlings by hessian bags could be enhanced by altering their spatial arrangement, but we observed no differences in the per-unit-area performance of bags whether isolated or grouped, or with greater vertical structure. As such, using isolated bags appears the most cost-effective approach as they can simply be dropped overboard and do not necessarily require in situ arrangement by divers as groups do. Furthermore, isolated bags supported greater densities of *A. antarctica* than groups after 52 months (approximately 100 vs. 6 individuals/m^2), possibly creating the "seed" for a persistent population. On this point, our most recent surveys (February 2013) have shown seagrass expansion beyond the original bags (Fig. S1 and Video S1), which appears entirely driven by clonal growth of the original recruits. Patch expansion certainly endorses the use of hessian bags for rehabilitation, but a further critical step is to assess whether rehabilitated seagrass can be self-sustaining. Flowering and seedling production in rehabilitated patches have not been obvious, which perhaps is not surprising given their relatively young age (<5 years) and the naturally low rate of flowering by *A. antarctica* (Marba & Walker 1999). Nevertheless, expanding patches have already facilitated recruitment of *Heterozostera* sp. seagrass (Video S1), demonstrating that artificial rehabilitation using hessian bags can subsequently create suitable conditions for natural seagrass recovery.

A major advantage of using hessian bags is that they not only avoid destructive approaches such as transplants, but the natural fibers also completely degrade to leave no environmental impact. Degradation, however, can reduce entanglement of recruits, and thus it is not surprising that we observed younger bags, having spent less time in situ and being less degraded, generally facilitated greater seedling densities than older bags during peak recruitment. Even so, longer term densities were similar across all bag ages, suggesting bags deployed at any time of year ultimately produce a similar outcome. Nonetheless, we suggest that the best approach to rehabilitation is to deploy bags immediately prior to peak recruitment periods to capture the greatest number of recruits and give them the maximum possible time to establish before hessian inevitably degrades, and also to avoid burial of bags by sediment before recruitment. This approach may also help avoid substantial seedling loss that can occur when storms tear and dislodge hessian that has been in situ for approximately 12 months (Wear et al. 2010).

In summary, seedling densities of approximately 1700 individuals/m^2 and survival up to approximately 192 individuals/m^2 after 4 years further underscores the potential of hessian bags for rehabilitating *Amphibolis* seagrass (Irving et al. 2010; Wear et al. 2010). Indeed, accurately surveying some bags has become difficult because seagrass is starting to coalesce between bags (Fig. S1 and Video S1), demonstrating seagrass expansion following long-term retention on bags. In the context of applying outcomes from our experiments to large-scale rehabilitation, it appears that coarse-weave bags facilitate the greatest recruit densities and that filling them only with sand is adequate. Individual bags located at least up to 80 m away from a natural meadow seem to produce equally good results as other spatial configurations, and while long-term seagrass densities are generally unaffected by the age of bags, hessian degradation and burial remain good reasons to coordinate deployment with peak recruitment periods.

Importantly, many of our experiments are not spatiotemporally replicated and thus the consistency of reported results is largely unknown. However, an independent test of fine- versus coarse-weave bags approximately 100 km from Grange produced similar results (unpublished data), further emphasizing benefits of coarse-weave bags. Even without fully understanding spatiotemporal consistency, hessian bags clearly present a relatively simple and cost-effective method of *Amphibolis* rehabilitation. The cost of rehabilitating one hectare of *Amphibolis* using 1000 bags/hectare is approximately US$16,737 (Wear et al. 2010), comparing favorably with the value of resources and ecosystem services that seagrasses provide (approximately US$27,039 hectare/year; Costanza et al. 1997). Scaling up to even larger scales of rehabilitation is likely to reduce overall costs by a factor of 2–3. As noted, however, local hydrodynamic conditions may disproportionately affect the performance of hessian bags through sediment erosion and storm damage (Paling et al. 2003; Van Keulen et al. 2003), suggesting a need for careful site selection.

The primary goal of seagrass rehabilitation is usually to initiate or accelerate recovery from disturbance by reestablishing a functional, self-sustaining habitat in a degraded area (Fonseca et al. 2000; Bell et al. 2008). Global success rates below 50% emphasize the complex nature of this task, while the expense and effort needed for rehabilitation often justifies continued development and refinement of methods to improve the chances of success. To this end, hessian bags appear to be a relatively simple, inexpensive, and promising method to facilitate the recovery of *Amphibolis* seagrass. Further improvements and applications of this method continue to be tested, such as planting *Posidonia* seeds in the stabilized sediment within bags, which is showing early promise, in the hope that it can soon be used for large-scale multispecies rehabilitation.

Implications for Practice

- Hessian bags with a course outer weave and filled with sand appear most effective at facilitating recruitment of *Amphibolis antarctica*.
- Successful rehabilitation appears most likely when single bags are deployed within 80 m of a natural meadow and coordinated with natural periods of recruitment.
- Bags deployment should coincide with the beginning of the recruitment season.

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LITERATURE CITED

Balestri, E., L. Piazzi, and F. Cinelli. 1998. Survival and growth of transplanted and natural seedlings of *Posidonia oceanica* (L.) Delile in a damaged coastal area. Journal of Experimental Marine Biology and Ecology **228:**209–225.

Bell, S. S., A. Tewfik, M. O. Hall, and M. S. Fonseca. 2008. Evaluation of seagrass planting and monitoring techniques: implications for assessing restoration success and habitat equivalency. Restoration Ecology **16:**407–416.

Bryars, S., and V. Neverauskas. 2004. Natural recolonisation of seagrasses at a disused sewage sludge outfall. Aquatic Botany **80:**283–289.

Bryars, S., and K. Rowling. 2009. Benthic habitats of eastern Gulf St Vincent: major changes in benthic cover and composition following European settlement of Adelaide. Transactions of the Royal Society of South Australia **133:**318–338.

Bryars, S., R. Wear, and G. Collings. 2008. Seagrasses of Gulf St Vincent and Investigator Strait. Pages 132–147 in S. Shepherd, S. Bryars, I. Kirkegaard, P. Harbison, and J. T. Jennings, editors. Natural history of Gulf St Vincent. Royal Society of South Australia, Inc., Adelaide, Australia.

Bull, J. S., D. C. Reed, and S. J. Holbrook. 2004. An experimental evaluation of different methods of restoring *Phyllospadix torreyi* (surfgrass). Restoration Ecology **12:**70–79.

Clarke, S. M., and H. Kirkman 1989. Seagrass dynamics. Pages 304–345 in A. W. D. Larkum, A. J. Mccomb and S. A. Shepherd, editors. Biology of seagrasses: a treatise on the biology of seagrasses with special reference to the Australian region. Elsevier, Amsterdam, The Netherlands.

Connell, S. D. 2007. Water quality and the loss of coral reefs and kelp forests: alternative states and the influence of fishing. Pages 556–568 in S. D. Connell, and B. M. Gillanders, editors. Marine ecology. Oxford University Press, Melbourne, Australia.

Connolly, R. M. 1994. A comparison of fish assemblages from seagrass and unvegetated areas of a southern Australian estuary. Australian Journal of Marine & Freshwater Research **45:**1033–1044.

Costanza, R., R. D'arge, R. De Groot, S. Farber, M. Grasso, B. Hannon, et al. 1997. The value of the world's ecosystem services and natural capital. Nature **387:**253–260.

Durako, M. J., J. L. Shup, C. J. Andress, and D. A. Tomasko. 1993. Restoring seagrass beds: some new approaches with *Ruppia maritima* L. (Widgeongrass). Pages 88–101 in E. J. Webb, Jr., editor. Proceedings of the Twentieth Annual Conference on Wetlands Restoration and Creation. Hillsborough Community College, Institute of Florida Studies, Plant City, Florida.

Fonseca, M. S., W. J. Kenworthy, F. X. Courtney, and M. O. Hall. 1994. Seagrass planting in the United States: methods for accelerating habitat development. Restoration Ecology **2:**198–212.

Fonseca, M. S., W. J. Kenworthy, and G. W. Thayer. 1998. Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters. NOAA Coastal Ocean Program, Silver Spring, Maryland.

Fonseca, M. S., B. E. Julius, and W. J. Kenworthy. 2000. Integrating biology and economics in seagrass restoration: how much is enough and why? Ecological Engineering **15:**227–237.

González-Correa, J. M., J. T. Bayle, J. L. Sánchez-Lizaso, C. Valle, P. Sánchez-Jerez, and J. M. Ruiz. 2005. Recovery of deep *Posidonia oceanica* meadows degraded by trawling. Journal of Experimental Marine Biology and Ecology **320:**65–76.

Harwell, M. C., and R. J. Orth. 1999. Eelgrass (*Zostera marina* L.) seed protection for field experiments and implications for large-scale restoration. Aquatic Botany **64:**51–61.

Heck, K. L., K. W. Able, C. T. Roman, and M. P. Fahay. 1995. Composition, abundance, biomass, and production of macrofauna in a New England estuary: comparisons among eelgrass meadows and other nursery habitats. Estuaries **18:**379–389.

Irving, A. D., J. E. Tanner, S. Seddon, D. Miller, G. J. Collings, R. J. Wear, S. L. Hoare, and M. J. Theil. 2010. Testing alternate ecological approaches to seagrass rehabilitation: links to life-history traits. Journal of Applied Ecology **47:**1119–1127.

Kenworthy, W. J., and M. S. Fonseca. 1977. Reciprocal transplant of the seagrass *Zostera marina* L. Effect of substrate on growth. Aquaculture **12:**197–213.

Kirkman, H., and J. Kuo. 1990. Pattern and process in southern Western Australian seagrasses. Aquatic Botany **37:**367–382.

Kuo, J., and C. Den Hartog. 2006. Seagrass morphology, anatomy, and ultrastructure. Pages 51–87 in A. W. D. Larkum, R. J. Orth, and C. M. Duarte, editors. Seagrasses: biology, ecology and conservation. Springer, Dordrecht, The Netherlands.

Larkum, A. W. D., and R. J. West. 1990. Long-term changes of seagrass meadows in Botany Bay, Australia. Aquatic Botany **37:**55–70.

Marba, N., and D. I. Walker. 1999. Growth, flowering, and population dynamics of temperate Western Australian seagrasses. Marine Ecology Progress Series **184:**105–118.

Mateo, M. A., J. Cebrián, K. Dunton, and T. Mutchler. 2006. Carbon flux in seagrass ecosystems. Pages 159–192 in A. W. D. Larkum, R. J. Orth and C. M. Duarte, editors. Seagrasses: biology, ecology and conservation. Springer, Dordrecht, The Netherlands.

Myers, J. L., and A. D. Well. 2002. Research design and statistical analysis. Lawrence Erlbaum Associates, Philadelphia, Pennsylvania.

Neverauskas, V. P. 1987. Monitoring seagrass beds around a sewage sludge outfall in South Australia. Marine Pollution Bulletin **18:** 158–164.

Orth, R. J. 1977. The importance of sediment stability in seagrass communities. Pages 281–300 in B. C. Coull, editor. Ecology of marine benthos. University of South Carolina Press, Colombia, South Carolina.

Orth, R. J., T. J. B. Carruthers, W. C. Dennison, C. M. Duarte, J. W. Fourqurean, K. L. Heck, et al. 2006a. A global crisis for seagrass ecosystems. BioScience **56:**987–996.

Orth, R. J., M. C. Harwell, and G. J. Inglis. 2006b. Ecology of seagrass seeds and seagrass dispersal processes. Pages 111–133 in A. W. D. Larkum, R. J. Orth and C. M. Duarte, editors. Seagrasses: biology, ecology and conservation. Springer, Dordrecht, The Netherlands.

Paling, E. I., M. Van Keulen, K. Wheeler, J. Phillips, and R. Dyhrberg. 2001. Mechanical seagrass transplantation in Western Australia. Ecological Engineering **16:**331–339.

Paling, E. I., M. Van Keulen, K. Wheeler, J. Phillips, and R. Dyhrberg. 2003. Influence of spacing on mechanically transplanted seagrass survival in a high wave energy regime. Restoration Ecology **11:**56–61.

Ralph, P. J., D. Tomasko, K. Moore, S. Seddon, and C. M. O. Macinnis-Ng. 2006. Human impacts on seagrasses: eutrophication, sedimentation, and contamination. Pages 567–593 in A. W. D. Larkum, R. J. Orth and C. M. Duarte, editors. Seagrasses: biology, ecology and conservation. Springer, Dordrecht, The Netherlands.

Reed, D. C., S. J. Holbrook, C. A. Blanchette, and S. Worcester. 2009. Patterns and sources of variation in flowering, seed supply and seedling recruitment in surfgrass *Phyllospadix torreyi*. Marine Ecology Progress Series **384:**97–106.

Van Keulen, M., E. I. Paling, and C. J. Walker. 2003. Effects of planting unit size and sediment stabilization on seagrass transplants in Western Australia. Restoration Ecology **11:**50–55.

Waycott, M., D. I. Walker, and S. H. James. 1996. Genetic uniformity in *Amphibolis antarctica*, a dioecious seagrass. Heredity **76:**578–585.

Waycott, M., C. M. Duarte, T. J. B. Carruthers, R. J. Orth, W. C. Dennison, S. Olyarnik, et al. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences of the United States of America **106:**12377–12381.

Wear, R. J., J. E. Tanner, and S. L. Hoare. 2010. Facilitating recruitment of *Amphibolis* as a novel approach to seagrass rehabilitation in hydrodynamically active waters. Marine and Freshwater Research **61:** 1123–1133.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Image of hessian bags supporting substantial densities of *Amphibolis antarctica* recruits after approximately 6 months in situ. Clearly defined patches of seagrass can be seen where bare hessian bags were originally placed. These patches have subsequently expanded beyond the original dimensions of the hessian bags (see Video S1).

Video S1. Video footage showing patches of rehabilitated seagrass that have expanded beyond the original dimensions of the hessian bags (compare with Fig. S1). The patches of *Amphibolis antarctica* in the video are approximately 2.5–3.5 years old, and interspersed among them are recruits of *Heterozostera* sp. seagrass, which have only colonized since rehabilitated *A. antarctica* has expanded.