A review of seagrass planting as a means of habitat compensation following loss of seagrass meadow

C. Ganassin & P.J. Gibbs

NSW Department of Primary Industries
Cronulla Fisheries Research Centre of Excellence
PO Box 21, Cronulla, NSW 2230
Australia

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PROJECT SUMMARY

The NSW Department of Primary Industries seeks to ensure that there is no net loss of seagrass habitat in NSW estuaries. As part of this process, seagrass restoration can be used as a measure to compensate for the loss of seagrass habitat resulting from development activities. The policy concerning habitat compensation for marine vegetation in NSW recommends the re-creation of the type of habitat lost on a 2:1 basis so that both the indirect and direct impacts of development can be compensated for. It is known from reviews completed up to the late 1990s that seagrass restoration techniques have only been successful in replacing small areas of habitat, and efforts to replace larger areas of habitat on a one-to-one basis often fall short of that goal.

This report examines the efficacy of using existing techniques to restore seagrass as a habitat compensation measure in NSW, by reviewing restoration studies published since the late 1990s. Emphasis is placed on reporting current developments in seagrass restoration, identifying factors that contribute to the success of seagrass restoration, and highlighting possible improvements in seagrass restoration.

The review concluded that seagrass restoration is a costly process that is still somewhat developmental. Although innovative restoration techniques have been developed, and improvements to the success of restoring some seagrass species have been made, seagrass restoration projects conducted since 2000 have shown large variations in success. This is largely due to natural variability among sites, the local biology and ecology of restored species and environmental conditions during the restoration process. Seagrass restoration and other restoration techniques have not been developed to the extent that particular methods could be recommended for different species in different situations. Seagrass restoration techniques are still only successful in replacing small areas of habitat.

It was concluded that current seagrass restoration techniques cannot be depended upon to achieve 2:1 habitat compensation. Some reasons for this are:

- there is a paucity of information on the growth of seagrasses in NSW; such information would greatly assist in the development of successful techniques for seagrass restoration;
- success cannot be guaranteed with the use of any current seagrass restoration technique;
- large-scale seagrass habitat restoration is yet to be achieved with the use of any current technique on any seagrass species;
- many seagrass restoration techniques are still at a developmental stage; and
- most seagrass restoration attempts conducted in NSW have failed.

To increase the confidence of using seagrass restoration techniques to successfully compensate for habitat losses in NSW, an adaptive strategic research-based approach is recommended. Any future seagrass restoration attempts in NSW should place importance on the project planning and site selection stages. Consideration of specific local factors during these stages should improve the survival of seagrass restoration attempts or ultimately result in the development of techniques that are suited to local environmental conditions. Research is needed on the development of cost-effective techniques that are suited to local conditions and on the filling of information gaps concerning both the growth parameters of local seagrass species in NSW and the environmental parameters of NSW estuaries.

Until such techniques can be reliably used in NSW, the protection of existing seagrass beds will remain the most important, efficient and effective priority for sustaining seagrass resources. Further, a review of the use of seagrass restoration techniques to achieve the 2:1 habitat compensation policy for seagrass loss in NSW is warranted as success using these techniques under local conditions cannot be guaranteed.

1. INTRODUCTION

1.1. Background and need

Under the *NSW Fisheries Management (FM) Act 1994*, the NSW Department of Primary Industries is obliged to protect seagrass habitat. The current management of seagrasses in NSW is focussed on ensuring that there is no net loss of seagrass habitat in the state. One measure used to achieve this is to assess and modify all proposed developments that could impact upon seagrass habitat so that damage to seagrass, especially *Posidonia australis*, can be minimised. In circumstances where harm to seagrass cannot be avoided and the activity is permitted by the Minister of Primary Industries under the FM Act, seagrass restoration techniques, such as seagrass transplanting, can be used as a measure to compensate for seagrass habitat losses (NSW Fisheries, 1999). In NSW, the policy concerning habitat compensation for marine vegetation recommends the re-creation of the type of habitat lost on a 2:1 basis so that both the indirect and direct impacts of development can be compensated for (NSW Fisheries, 1999).

Seagrass beds are found in over 130 estuaries and some semi-enclosed embayments in NSW, and predominantly consist of *Zostera capricorni*[1], *Halophila ovalis* and, in the southern half of NSW, *Posidonia australis* (West *et al.*, 1985). Each of these species has a significantly different ability to recover from disturbance. In south eastern Australia, *Halophila* spp are known as early colonising species that respond to change relatively quickly and may recover from damage within months (Meehan and West, 2000). *Zostera* spp in south eastern Australia can be quite ephemeral and may take several years to recolonise denuded areas (West, 1990; Larkum and West 1990). However, it is worth noting that a bed of *Z. capricorni* that was heavily grazed by dugongs in south east Queensland returned to pre-grazing levels in less than a year as a result of high incidence of sexual reproduction at this location (Peterken and Conacher, 1997). In terms of ability to recover from loss, *P. australis* is the most sensitive seagrass occurring in NSW. It has been suggested that sexual reproduction plays a negligible role in the maintenance of beds of this species and it is extremely slow growing (Meehan and West, 2002). Therefore, it is unlikely to naturally re-establish from losses in the short term (Meehan and West, 2002).

Seagrass distribution within estuaries is naturally influenced by light penetration, depth, salinity, nutrient status, bed stability, wave energy, estuary type, and the evolutionary stage of the estuary (Roy *et al.*, 2001). Many of these factors in NSW estuaries have been altered by anthropogenic influences such as water pollution, dredging, reclamation, flood mitigation and land management practices (Poiner and Peterken, 1995; Williams and Meehan, 2004). Like other areas around Australia and the world, large-scale declines in the area of seagrass in the 1970s have been detected in some NSW estuaries. For example, seagrass coverage in Port Hacking that was initially stable at 180 ha declined to 73 ha in 1977 (Williams and Meehan, 2004). From the early 1980s to 2000s, on the basis of the methods used, seagrass coverage appears to have declined by more than 10% in 43 of 110 NSW estuaries located outside of the Sydney metropolitan region (Williams *et al.*, 2006). A decline of more than 10 ha in seagrass coverage was recorded in 17 of these estuaries (Williams *et al.*, 2006).

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[1] Taxonomic distinction of some species of the subgenus Zostrella, including *Zostera capricorni* and *Zostera muelleri* which are known to occur in NSW, is known to be difficult. Les *et al.* (2002) re-examined the four species members of the subgenus Zostrella (*Z. capricorni, Z. muelleri, Zostera mucronata* and *Zostera novaezelandica*) and suggested that all should be merged within the single species, *Z. capricorni*.

Seagrasses significantly contribute to the nearshore productivity and food webs of estuarine ecosystems, and provide structural habitat and shelter for a wide variety of plants and animals (Zieman and Wetzel, 1980; Bell and Pollard, 1989; Edgar and Shaw, 1995; Short and Wyllie-Echeverria, 1996; Connolly *et al.*, 1999; Hemminga and Duarte, 2000; Borum *et al.*, 2006; Romero *et al.*, 2006). In particular, seagrasses are widely recognised as important spawning and nursery areas for many fish species targeted by commercial fishers or recreational anglers (Middleton *et al.*, 1984; Bell and Pollard, 1989; Connolly, 1994). Seagrasses also filter suspended matter from the water column and bind sediment, providing protection against wave-induced erosion (Fonseca and Fisher, 1986; Hemminga and Duarte, 2000). The loss of seagrass habitat has numerous effects including a disruption of estuarine food webs, altered species composition, reduced density and diversity of estuarine fish and crustaceans, and increases in turbidity and erosion (Fonseca *et al.*, 1998; Wyda *et al.*, 2002; Orth *et al.*, 2006a).

As the natural recovery of some seagrass species from disturbance is often a slow process that can take decades to centuries (Clarke and Kirkman, 1989; Kirkman and Kuo, 1990; Hastings *et al.*, 1995; Marba and Walker, 1999; Meehan and West, 2000; Bryars and Neverauskas, 2004), techniques have been developed to accelerate the recovery of seagrass. Such techniques are usually used once the causes of seagrass decline have been mitigated, or to compensate for anticipated or actual losses of seagrass habitat. Serious attempts to directly restore the large-scale rapid decline of seagrass habitat around the world began in the 1960s (Gordon, 1996). Since then, many attempts to grow seagrass beds have been conducted for different reasons, over different time scales, under a variety of conditions and met with varying degrees of success (Gordon, 1996). Techniques that have been trialled involve: transplantation of seagrass from a donor bed to a nearby location; use of seeds and aquarium-reared seedlings; and facilitation of natural recruitment and succession (Wear, 2006).

Reviews of seagrass restoration attempts completed up to the late 1990s found that seagrass restoration was still a developing science that remained very costly, difficult and challenging (Gordon, 1996; Lord *et al.*, 1999). These reviews stated that the restoration of several hundred hectares of seagrass through transplanting and other techniques was still to be realised, and seagrass beds planted to replace habitat on a one-to-one basis usually fall short of that goal. At that time, seagrass restoration techniques were only successful in replacing small areas of seagrass, especially for fast growing species such as *Zostera* spp. (Gordon, 1996; Lord *et al.*, 1999). In Australia, seagrass transplanting efforts conducted before 1999 had not created a permanent, functional seagrass bed, nor had techniques been developed to the extent that particular methods could be recommended for different seagrass species (Lord *et al.*, 1999).

1.2. Project aim

To assist in ensuring no net loss of seagrass habitat in the face of increasing development pressure along the NSW coast, the aim of this review was to provide updated information about the latest developments in seagrass habitat restoration technology from Australia and overseas. This information will be used to qualitatively assess the efficacy of these techniques as possible habitat compensation measures in NSW estuaries.

1.3. Terminology

Numerous terms are used to refer to the modification of seagrass habitats. Seagrass '*restoration*' refers to returning a seagrass ecosystem to a close approximation of its pre-disturbance condition (Gordon, 1996). Seagrass '*rehabilitation*' refers to returning seagrass to an area where seagrass meadows previously existed or improving or enhancing degraded seagrass beds, without necessarily replacing or approximating the original species, abundance or equivalent ecosystem function (Gordon, 1996; Seddon, 2004). The ‘*creation*’ of seagrass habitat involves bringing into existence new areas of seagrass (Gordon, 1996).

The term ‘seagrass restoration’ is used in this review in any generic discussion about restoring, rehabilitating and creating seagrass habitat. This generic term is used to simplify reading and avoid complication. Its use is deemed legitimate as there are few differences in the techniques used to achieve any of these three aims and, ultimately, this review is concerned with the efficacy of using such techniques as a habitat compensation measure.

Other terms regularly used in the field of seagrass habitat restoration are defined as follows:

- The ‘mitigation’ of impacts to seagrass habitat refers to reducing seagrass loss by changing the project design or enhancing or creating seagrass areas to compensate for anticipated or actual permitted seagrass losses (Gordon, 1996). ‘Environmental or habitat compensation’ is a term used to describe the latter mitigation definition above.
- The ‘*success*’ of a seagrass transplanting project has variable definitions that can either be based on the survival of plantings over some agreed time, or may require transplanted plots to demonstrate evidence of other features such as spreading and introduction of functional attributes. These definitions are usually set with respect to project goals and performance criteria (Gordon, 1996).
- The ‘*failure*’ of a seagrass transplanting project results when stated performance criteria linked to stated project objectives are not achieved within a specified time period (Gordon, 1996).

With respect to seagrass transplanting, there have been traditionally two general types of transplant units used – sediment intact and bare-root transplant units. These are described below. Various terms are used for these general transplant unit types, and the specific configuration of these units can vary amongst and within transplanting attempts.

1. ‘*Sediment intact*’ transplant units are extracted from the donor seagrass bed as a whole unit with the shoots, leaf blades, roots, rhizomes and surrounding sediment in tact. Extraction of such transplant units occurs through a hand driven coring or mechanical method that retains the sediment around the rhizomes and minimises root and rhizome disturbance. The size of these units tends to be smaller when manual extraction methods are used. Specific terms used for this type of transplant unit include ‘*plugs*’, ‘*cores*’ or ‘*sods*’.
2. ‘*Bare-root*’ transplant units consist of seagrass rhizome sections (approximately 10 – 25 cm in length) with a certain small number of leaf-bearing shoots and rhizome/root nodes. These transplant units are selectively removed from the donor seagrass bed by hand. They can be referred to as ‘*sprigs*’, ‘*shoots*’ or ‘*rhizomes*’. They can be planted by being anchored/secured into the sediment or unanchored, singly or in units of multiple rhizome sections that can be referred to as ‘*bundles*’ or ‘*clumps*’.

2. METHODS

This review extends upon the comprehensive review of seagrass restoration efforts conducted at an International and Australian level by Lord *et al.* (1999). The review focuses on any further developments in seagrass restoration techniques, increased knowledge of the factors that contribute to the success of seagrass restoration techniques, and improvements to the effectiveness of seagrass restoration reported in Lord *et al.* (1999). International and Australian literature was reviewed separately with a focus on the commonly occurring seagrass families in NSW.

The literature reviewed in this study was found through searching bibliographic databases (Table 1) and the internet, contacting scientists, managers, consultants and proponents involved in Australian seagrass restoration projects, and checking the reference lists of reviewed literature. The literature included in this review was that which directly related to seagrass restoration (from an experimental, planning, management, outcome or survival perspective), was released or conducted between 1997 – 2007 (for International literature[2]) and 2000 – 2007 (for Australian literature[3]), and was written in English. Of all the citations in this report, 61 are journal publications, seven are book chapters, 17 are government reports, nine are consultant reports, and one is a conference proceedings.

Table 1: Details of the bibliographic database searches conducted in this study.

Search terms used	15 separate search terms were entered into each database. In these search terms, each of the words seagrass, zostera, posidonia, eelgrass and strapweed, were separately followed with each of the terms restorat*, rehabilitat*, and transplant*. These terms were searched for anywhere throughout the document.
Timeframe searched over	1997 – 2007 for all searched databases except Ovid. This was searched from 2002 – 2007
Databases searched and when	CSA (18/10/06, 14/12/07); Scopus (19/10/06); Google scholar (20/10/06, 17/12/07); Ovid (20/10/06, 17/12/07); Biblioline (20/10/06, 17/12/07)

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[2] Although this study builds upon the review conducted by Lord *et al.* (1999), the International literature is reviewed from 1997 onwards as in their review of International seagrass restoration efforts Lord *et al.* (1999) made significant reference to the comprehensive review conducted by Gordon (1996) and did not build upon this work.

[3] Australian literature released prior to 2000 is not reviewed in this study as it was comprehensively reviewed by Lord *et al.* (1999).

3. RECENT SEAGRASS RESTORATION STUDIES

Since 1997 seagrass restoration techniques have been conducted at an increasing number of locations around the world, in both estuarine and oceanic areas, and with an increasing number of seagrass species. This review will document the scope of this work. Some seagrass restoration work conducted since 1997 focussed on the planning phase of seagrass restoration programs and stressed the importance of monitoring restoration programs over the long-term, for at least five years (Den Hartog, 2000; Thom, 2000; Campbell, 2002). Thom (2000) argues that adaptive management is an important tool that could be used to systematically assess and improve coastal ecosystem restoration technology and performance.

3.1. International studies

Since 1997, the USA has continued to be the dominant country for seagrass restoration studies. These studies have largely been conducted in estuarine environments in locations such as Chesapeake Bay, Delaware, Texas and San Francisco. Their focus has been primarily on developing new techniques for the restoration of *Zostera marina*, trialling seagrass restoration attempts across a greater number of latitudes, and improving the project planning phase of restoration projects. Most of the seagrass restoration efforts conducted in Europe since 1997 focused on the transplantation of *Zostera marina or Zostera noltii* or on the development of techniques to restore *Posidonia oceanica* in the Mediterranean Sea. Seagrass restoration attempts since 1997 have also been conducted on *Zostera marina* in Japan and Korea. All these studies conducted since 1997 are reviewed in this section on a genus-specific basis.

3.1.1. Posidonia species

3.1.1.1. Transplantation and seedling methods

From 1997, restoration efforts on *P. oceanica* in the Mediterranean Sea continued to focus various transplanting and seedling techniques at a small experimental scale. To date, no large-scale mitigation transplant projects with this species have been reported. It was found that natural and laboratory-reared seedlings of *P. oceanica* may be successfully grown and planted for restoration purposes in the Mediterranean (Balestri *et al.*, 1998; Piazzi *et al.*, 2000). Transplant success was influenced by the nature of the substratum, with dead ‘matte’ habitat showing higher survival and growth rates than pebbly habitat. Also, horizontal rhizomes showed higher survival and growth rates than their vertical counterparts (Balestri *et al.*, 1998; Piazzi *et al.*, 2000). Transplant donor populations of *P. oceanica* with the highest genetic variability showed the best growth performance (Procaccini and Piazzi, 2001).

Some studies on *P. oceanica* in the Mediterranean focussed on a major cause of transplant failure, i.e., inadequate anchorage and nutrient uptake of seedlings and rhizomes due to small root systems (Balestri and Bertini, 2003; Lepoint *et al.*, 2004; Balestri and Lardicci, 2005). *P. oceanica* cuttings can take 3 – 12 months to form roots (Balestri and Lardicci, 2005). The application of auxins (growth regulators) was found to significantly accelerate both root formation in cuttings and seedlings, and root growth in germinated seeds, perhaps resulting in quicker seedling establishment (Balestri and Bertini, 2003; Balestri and Lardicci, 2005).

3.1.2. *Zostera species*

3.1.2.1. *Transplantation methods*

Since 1997, seagrass restoration efforts have included the transplantation of adult *Z. marina* plants in the USA (Davis and Short, 1997; Orth *et al.*, 1999; Short *et al.*, 2002a), Europe (Van Katwijk *et al.*, 1998; Van Katwijk and Hermus, 2000; Bos *et al.*, 2005; Bos and van Katwijk, 2007), Japan (Tamaki *et al.*, 2002) and Korea (Park and Lee, 2007) and *Zostera noltii* plants in Europe (Hughes *et al.*, 2000; Martins *et al.*, 2005).

New methods of transplanting *Z. marina* have been developed since 1997. In particular, the transplantation of *Z. marina* shoots secured horizontally onto sediment with a bamboo staple has been successful on two occasions. One year after transplanting, survival rates were 75 – 95% and 98 – 99% and shoot densities of transplanted sites were equivalent to those at control sites within two years (Davis and Short, 1997). Good survival was also reported with the transplantation of single unanchored shoots of *Z. marina* that were planted with their rhizomes being placed into the sediment at an angle, i.e., the unanchored shoot method (Orth *et al.*, 1999). Relatively high survival rates of 76.5% – 81.3% were reported with the use of oyster shells to anchor shoots of transplanted *Z. marina* in muddy and silty sediments, but low survival rates were reported when this technique was used in sandy sediments (Park and Lee, 2007).

In an effort to improve the cost-effectiveness of seagrass transplanting, the Transplanting Eelgrass Remotely with a Frame System (TERFS) was developed (Short *et al.*, 2002a). In this method, a rubber-coated weighted wire frame, to which *Z. marina* shoots are tied with biodegradable plastic ties, is dropped into position from a boat. The frame is removed once the ties have degraded after three to five weeks and the shoots have anchored into the sediment. The initial trial of this technique showed an increase in *Z. marina* shoot abundance at three out of four one acre sites (Short *et al.*, 2002a,b) and after four years these patches produced their own seed and formed a continuous seagrass bed (F. Short, *pers. comm.*, 2007). Other plantings using this method have shown survival rates of 47 – 86% after one month in the USA (Short *et al*., 2002b) and 58.7 – 69.0% after 14 months in Korea (Park and Lee, 2007). Studies that compared this method with that used by Davis and Short (1997), showed initial success rates were higher with the TERFS method (Short *et al.* 2002b).

The efficiency of using a mechanised planting boat to transplant bundles of *Z. marina* was compared against the manual transplantation of these bundles (Fishman *et al.*, 2004). In its tested configuration, the mechanised planting boat was not a significant improvement over the manual method of transplanting *Z. marina* because mechanised planting resulted in a lower initial planting success rate (Fishman *et al.*, 2004).

Many eelgrass transplanting studies conducted since 1997 have reported on the factors that influenced transplant success. Factors identified as reducing transplant survival included seasonal turbidity pulses (Moore *et al.*, 1997); bioturbation by animals such as crabs (Davis *et al.*, 1998) and polychaetes (Hughes *et al.*, 2000); exposure to strong wave dynamics (De Jonge *et al.*, 2000; Bos and van Katwijk, 2007); and deposition of sediment on the seagrass bed (Tamaki *et al.*, 2002). Other factors identified to influence the growth of seagrass were the season of planting, with higher success rates reported when planting occurred in autumn and winter in Portugal (Martins *et al.*, 2005) and autumn to spring in Korea (Park and Lee, 2007); the density of planting in unsheltered conditions, with higher density planting having favourable effects on survival (Bos *et al.*, 2005; Bos and van Katwijk, 2007); and the reduction of sediment mobility using shells and mussels beds, which had a positive effect on transplant survival in the Wadden Sea (Van Katwijk and Hermus, 2000; Bos *et al.*, 2005; Bos and van Katwijk, 2007).

Recent models have been developed to determine optimal sites for *Z. marina* transplantation (De Jonge *et al.*, 2000; Short *et al.*, 2002b; Seddon *et al.*, 2004). Site selection is an important step in any seagrass restoration attempt. The model developed by Short *et al.* (2002b) synthesizes available historic and literature-based information, reference data and simple field measurements to identify and prioritise locations for large-scale *Z. marina* restoration. The model considers the biological and physical factors that can influence the success of seagrass transplants. Factors include sediment type, wave exposure, water depth, water quality, human activities in the area, light availability, bioturbation, existing and historical eelgrass distribution, distance of the site from existing seagrass beds, human activities at the site, and survival and growth of test transplants. With the use of this model, success was recorded at 62% of the selected transplant sites after two years (Short *et al.*, 2002b), an improvement on the ‘best professional judgement’ technique of site selection (Seddon *et al.*, 2004). Short and Burdick (Seddon *et al.*, 2004) expanded this model so that it can function within a GIS structure where maps of potential sites for eelgrass restoration can be produced.

Studies on the effects of transplanting *Z. marina* on genetic diversity found reduced genetic diversity in transplanted beds (Williams and Orth, 1998; Williams, 2001). Genetically diverse *Z. marina* populations grow and spread faster, produce more flowers, and have better rates of germination (Williams, 2001) than less diverse *Z. marina* beds. These findings have implications for restoration programs which seek to preserve genetic diversity.

3.1.2.2. Re-seeding methods

There has been an increased focus on the use of *Z. marina* seeds to restore seagrass habitat on the east coast of the USA (Harwell and Orth, 1999; Granger *et al.*, 2000; Nixon *et al.*, 2002; Goshorn, 2006; Orth *et al.*, 2006b; Orth *et al.*, 2006c). Compared to the transplantation of adult plants, the use of seeds for seagrass restoration requires less labour, is cheaper, results in less donor bed damage, can result in genetically diverse restored seagrass beds, and is more suitable for large-scale seagrass restoration projects (Williams and Orth, 1998; Harwell and Orth, 1999; Granger *et al.*, 2000; Nixon *et al.*, 2002). Also, the seeds can be easily transported, require little storage space and can be held for months before planting (Granger *et al.*, 2000). Technical processes for harvesting, preparing and storing large quantities of viable *Z. marina* seed have been developed (Granger *et al.*, 2002).

Seed planting shows promise for seagrass restoration as it has been used to successfully revegetate a large area of a coastal bay of the Delmarva Peninsula (USA) that had been denuded since the 1970s as a result of wasting disease (Orth *et al.*, 2006c). In all, 5 – 15% of 24 million *Z. marina* seeds broadcast over 46 ha germinated and after three years 38% of this area was vegetated (Orth *et al.*, 2006c). In general, *Z. marina* seeds did not disperse far from the area they were broadcast due to micro-topographic barriers (Orth et al. 1994). Losses of *Zostera* seed in the environment can result from predation, burial or the lateral transport of seeds by bottom currents and erosion events (Fonseca *et al.*, 1998; Harwell and Orth, 1999). Other factors found to influence broadcasted *Z. marina* seed germination rates included: local variations in bottom micro-topography (Orth *et al.*, 2006b); the depth and sometimes the density of seeds (Granger *et al.*, 2000; Nixon *et al.*, 2002); and the suitability of prevailing conditions for germination and establishment of seedlings (Goshorn, 2006). Seeding methods that have been trialled with varying success include broadcasting by hand and from floating bags (Goshorn, 2006; Orth *et al.*, 2006b; Orth *et al.*, 2006c), the placement of seeds into small anchored hessian bags (Harwell and Orth, 1999), and planting with a seeding machine (Nixon *et al.*, 2002).

3.1.3. Other seagrass species

3.1.3.1. Transplantation methods

A novel seagrass transplanting technique was developed to restore seagrass into propeller scars in Florida (USA). This involved erecting bird roosting stakes and then transplanting the fast-growing *Halodule wrightii* into propeller scars amongst them. This encouraged the defecation of nitrogen and phosphorus enriched faeces by birds into the transplant area and resulted in extremely high recovery rates (Kenworthy *et al.*, 2000). This recovery rate was much greater than that from the injection of water soluble fertilisers and plant growth hormones into sediments adjacent to propeller scars (Kenworthy *et al.*, 2000). The theory behind the bird stake approach is that of 'compressed succession', where the establishment of fast-growing colonising species, e.g., *H. wrightii*, is thought to assist the restoration of slower-growing climax species, e.g., *T. testudinum* (Kenworthy *et al.*, 2000).

Seagrass transplantation studies, using more traditional techniques, have also been conducted on *H. wrightii* in Texas (Sheridan *et al.*, 1998; Kaldy *et al.*, 2004). Sheridan *et al.* (1998) found the survival of transplanted *H. wrightii* to be affected by site, and noted greater survival rates of transplanted *H. wrightii* when planted at higher densities or in relatively shallow water. Kaldy *et al.* (2004) stressed the importance of assessing site history and sediment geochemistry before transplanting seagrass. Their transplantation of *H. wrightii* onto unconsolidated dredged materials in Texas failed to survive more than a few months due to susbtratum loss from erosion, reduced light from sediment resuspension, and high sediment ammonia concentrations (Kaldy *et al.*, 2004). Transplanted *H. wrightii* beds in the Texas area were observed to have different and less dense faunal communities than natural *H. wrightii* beds (Sheridan *et al.*, 2003; Sheridan, 2004).

Investigations into the use of various methods to transplant *Cymodocea nodosa* in the Canary Islands found that methods where transplant units were kept intact with original sediments around their roots held the greatest promise. Of these, the sod method was the most cost-effective, with a survival rate after 15 months of 43.2% (Ruiz de la Rosa *et al.*, 2006).

A study investigating transplanting techniques for *Phyllospadix torreyi* found the transplantation of sprigs to be the most effective restoration approach for this species (Bull *et al.*, 2004). Although transplanted plugs of this species also had good survivorship, damage sustained to the donor bed from this process resulted in a net overall loss of this species (Bull *et al.*, 2004).

3.2. Australian studies

By 1999, a total of 21 seagrass restoration projects, on *Posidonia* spp., *Amphibolis* spp., and *Zostera* spp., had been completed in Australia over the previous 20 years, with 67% of these based in Western Australia (Lord *et al.*, 1999). The strong focus on the development of techniques to restore *Posidonia* spp. and *Amphibolis* spp. in Western Australia has continued since 2000. This work included many trials of various transplanting techniques, attempts at restoring two large areas of seagrass habitat around Cockburn Sound and Albany, and studies to investigate donor bed damage and the return of ecosystem function to restored areas. Since 2000, South Australia has used a co-ordinated approach towards seagrass restoration. This involved three studies and a workshop, to develop techniques to restore large-scale *Posidonia* spp. and *Amphibolis antarctica* declines off the Adelaide coast.

In NSW, the eight seagrass restoration attempts conducted on *P. australis* and *Z. capricorni* since 2000 (see Appendix 1) were largely to trial seagrass transplanting techniques or restore small areas of seagrass lost to development-related impacts. In Queensland, only one trial seagrass transplanting attempt (using *H. ovalis* and *Z. capricorni*) has been reported since 2000. The only other documented seagrass restoration work conducted in Australia since 2000 is in Victoria where pilot trials to restore *Zostera* spp. have been completed in Western Port Bay, and the feasibility of using *Zostera* seeds to restore large-scale seagrass loss has been investigated.

All these studies since 2000 are briefly reviewed below on a genus specific basis.

3.2.1. *Posidonia species*

3.2.1.1. Transplantation methods

High wave-energy oceanic environment

Numerous short-term pilot trials of seagrass transplanting methods have been undertaken at the Cockburn Sound area of Western Australia to develop improved survival of transplant units in the high wave-energy oceanic environment. Artificial seagrass mats were used by Campbell and Paling (2003) to stabilise sediment around transplant units. However, these mats did not prevent erosion and accretion around the transplant units. The survival of *P. australis* transplants amongst these mats (up to 50% after 18 months in 60% of sites) was significantly greater than transplant units that were placed in bare sand without any sediment stabilisation method, but rhizome extension only occurred in 8% of all transplanted sites. Van Keulen *et al.* (2003) trialled the use of plastic mesh to stabilise sediments around transplanted plugs of *Posidonia sinuosa*, but the success of this measure was difficult to determine as none of these transplant units survived beyond one year. Paling *et al.* (2003) found that in this high-energy environment the spacing of *Posidonia coriacea* and *Amphibolis griffithii* transplant units did not influence sediment movement and suggested that the ability of seagrass communities to influence sediment movement appears to vary with the prevailing hydrodynamic regime.

It was thought that large sods of transplanted seagrass would have a higher chance of success in the oceanic environment of Success Bank at Cockburn Sound. Underwater mechanical seagrass harvesting and planting machines (known as ECOSUB I and ECOSUB II) were developed and used to transplant large sods of *Posidonia* spp. and *A. griffithii* in this wave-exposed oceanic environment. From 1996 – 1999, ECOSUB I was used to plant over 2000 0.25 m^2 sods into an approximate area of 3,000 m^2 of 25% seagrass cover (Paling *et al.*, 2001a). The large sods seemed to provide sufficient anchorage in the high-energy environment and markedly improved transplant success in the area (Paling *et al.*, 2001a). *Posidonia* species showed good survival rates two years after planting – 76.8% for *P. sinuosa* and 75.8% for *P. coriacea* (Paling *et al.*, 2001b). Sods planted in spring or summer, were more likely to survive than those planted in autumn or winter (Paling *et al.*, 2001b). In early 2000, 280 0.55 m^2 seagrass sods were planted by the more efficient ECOSUB II (Paling *et al.*, 2001a). These transplants showed comparable survival rates to those from ECOSUB I, and the restored area showed natural infilling by seagrass seedlings (Paling *et al.*, 2002). It is worth noting that it cost $AUD2.5 million to plant three hectares of seagrass with ECOSUB I and ECOSUB II over five years (equivalent to $AUD830,000/ha) (Lord and Associates, 2005).

In recognition of the fact that manual transplantation techniques are relatively low in cost compared to mechanical methods, a trial transplantation of plugs and sprigs of *P. sinuosa* was conducted in 2000 to examine seagrass rehabilitation feasibility in the Cockburn Sound area (Paling *et al.*, 2007). After two years, this trial found plugs (41% survival) to be more successful than sprigs (15% survival) and under good conditions a faster rhizome extension rate was reported in transplanted sprigs (Paling *et al.*, 2007). Plugs were more expensive to transplant than sprigs and it was thought that this cost benefit may outweigh the reduced survival of sprigs when transplanting options for rehabilitation projects are chosen (Paling *et al.*, 2007). Sprig transplant units were found to have the greatest survival in shallow water with fine sands, good light and moderate water movement (Paling *et al.*, 2007).

Campbell (2002) conducted an experimental trial transplantation of plugs of *P. australis* at Success Bank. This trial used a decision-based management framework that was developed to aid the planning and implementation of seagrass transplanting projects. A moderate success rate of 42% survival and 39% growth was reported from this transplanting attempt when used at Cockburn Sound. The decision-based framework, which could be applied in other locations and with other species, consists of five steps: (1) objective setting – where success criteria are stated after stakeholders have been consulted, funding sources are secured and the biology and ecology of the target species has been considered; (2) site selection – where factors such as light, water quality, water motion, depth and epiphyte loading are considered; (3) transplant unit and technique – where factors such as seed production, viability and establishment and rhizome growth rate are considered; (4) habitat enhancement – ensuring the inclusion of mechanisms to improve sub-optimal sites, such as sediment stabilisation techniques in high energy environments; and (5) review of objectives – includes cost-benefit analysis, monitoring and evaluation of project success (Campbell, 2002). In applying this framework, Campbell (2000) reported on some important growth parameters for *P. australis*, such as light requirements and type of substratum.

In the Cockburn Sound area, a large area (2.1 ha) of seagrass habitat is required to be restored as a habitat compensation measure for nearby dredging operations by 2011. Compared to other seagrass habitat restoration attempts around Australia, this is relatively large in scale. To achieve this compensation, the manual transplantation of sprigs of *P. australis* and *P. sinuosa* was used. The trial planting of both plugs and sprigs of *P. australis* and *P. sinuosa* at two sites in the area found that, although the individual site seemed to influence the survival of each species, the sprig method provided the highest growth rates of both species (Oceanica Consulting, 2006). In the habitat compensation planting, sprigs were planted over the warmer months (Nov – Apr) of 2004/05 and 2005/06. Survival of the 2004/05 planted sprigs was low, 10% by November 2005, because the twine used to tie the sprigs to the staple anchor degraded too quickly. Improvements to this technique have resulted in higher initial survival rates in the 2005/06 season than the previous year (Oceanica Consulting, 2006) and in 2007 initial survival rates of 50% were reported (Oceanica Consulting, pers. comm., 2007). The objective of 2.1 ha of restored habitat is yet to be achieved, and further plantings using this method are being conducted. Based on a predicted transplant survival rate of 40%, an overall area of 6 ha is to be planted to achieve the 2.1 ha objective (Oceanica Consulting, 2006).

Sheltered estuarine environment

In the sheltered estuarine waters of Oyster Harbour and embayment waters of Princess Royal Harbour around Albany in Western Australia, high survival rates of manually transplanted anchored *P. australis* sprigs have been reported, sometimes over the long-term. In Oyster Harbour, these reported survival rates were 95% over six years from 1994, and 94% over four years from 1997. These sprigs, planted 1 m apart, began to merge during the fourth year after transplanting, and by the end of the fifth year a complete seagrass bed with a plant density similar to adjoining natural seagrass beds was established (DAL Science and Engineering, 2003). In a separate transplanting trial of sprigs of *P. australis*, Cambridge *et al.* (2002) reported rhizome growth rates for transplanted sprigs of 15 – 18 cm per year over four years. In Princess Royal Harbour, similar *P. australis* transplanting trials were not as successful. The current activity at one site resulted in 14% survival over four years, and bioturbation at two other sites resulted in 86% survival over five years (DAL Science and Engineering, 2003).

Other transplant trials conducted in 2003 using anchored sprigs of *P. australis* and *P. sinuosa* in the Albany area reported survival rates greater than 80% at all sites in Oyster Harbour and one site in Princess Royal Harbour 2.5 years after transplanting (Oceanica Consulting, 2006). Examination of rhizome expansion rates found *P. australis* extended more rapidly than *P. sinuosa*, and non-apical sprigs extended far less than apical sprigs (Oceanica Consulting, 2006). Comparison of average shoot growth figures in this trial with those from the trials conducted in 1994 and 1997 found much lower growth in the more recent trial, tentatively attributed to considerable differences in freshwater conditions from floods and high spring flows (Oceanica Consulting, 2006).

During 2004/05 and 2005/06, a new planting pattern was used to transplant a large area (1.04 ha) of anchored sprigs of *P. australis* and some *P. sinuosa* in Oyster Harbour. Rather than planting in a 1 m x 1 m grid pattern, plants were spaced 1.5 m apart and planted into staggered rows that were 1 m apart. Although no reduction in the time for these transplant units to reach coalescence was expected, the new planting pattern should reduce the cost of transplanting and resulting donor bed damage as a significantly reduced number of planting units are required. After one year, the seagrasses planted in this new pattern in 2004/05 showed survival rates of 90% (Oceanica Consulting, 2006).

As an indication of the cost of using manual seagrass transplanting techniques in shallow relatively quiescent waters, it has been estimated that $AUD125,000 has been spent to plant 0.5 – 1.0 ha/year in Albany Harbour (Lord and Associates, 2005).

In NSW since 2000, the three attempts at transplanting a small amount of *P. australis* in estuaries for experimental purposes had mixed success which varied considerably among sites (Appendix 1). After 14 months, 92% of plugs of *P. australis* transplanted in a small pilot experiment at Narooma had survived (Paling and van Keulen, 2003). In Port Hacking, high survival rates of transplanted rhizome segments of *P. australis* were reported after 16 months at three out of five sites, with the growth dynamics of transplanted rhizomes at one site being similar to those of naturally growing plants. The transplants at two sites in this experiment failed due to erosion and large scale sand movement (Meehan and West, 2002). In St Georges Basin, transplanted *P. australis* rhizome segments did not survive beyond two months due to the use of an inadequate anchoring system, burial with sand from heavy swell conditions and commercial hauling across the transplants (Alex Meehan, pers. comm., 2006).

Return of ecological function of transplanted seagrass beds

Research on the ecological functions (primary production, secondary production, biogeochemical cycling and storage, habitat function and physical setting) of long surviving transplanted *Posidonia* spp. beds has been conducted in the Albany area in 2002/03. After four years, the majority of these ecological functions in transplanted beds were comparable to natural reference sites and shoot density had reached the level of natural meadows in the eight year old transplanted beds (Oceanica Consulting, 2006). Similar studies in the same area on *Posidonia* spp. transplanted in 2002 found a slower rate of return of ecological function over three years. It seems likely that the rate of return of ecological function in transplanted beds in estuaries is variable and seems to depend on the environmental conditions in the first few years after planting (Oceanica Consulting, 2006).

Recovery of donor seagrass beds

In any seagrass transplanting attempt, it is important to consider the impact of the activity on the donor bed. Experiments have been conducted in Cockburn Sound on the recovery of donor beds of *P. australis* and *P. sinuosa* (Oceanica Consulting, 2006). These studies found that, despite the density at which sprig sections of seagrass were removed from quadrats of seagrass, after one year *P. australis* donor beds showed signs of recovery (i.e., increased number of shoots). Where plugs of seagrass were removed from *P. australis* donor beds, the density and placement of core removal seemed to influence the rate of recovery, and recovery was only reported after one year when five plugs of seagrass were removed in a row. All sprig section and plug treatments in *P. sinuosa* donor beds showed signs of further degradation after one year. In the Albany area, meadows which had rhizomes removed from their edge, indicated a near complete return to normality after 1.5 years, despite the impact from a flood event (Oceanica Consulting, 2006).

3.2.1.2. Seedling methods

Techniques to germinate and grow *P. australis* and *P. coriacea* seedlings from seed in sterile controlled tank conditions have been developed in Western Australia. Researchers at the Kings Park Botanic Gardens (WA) have overcome problems of excessive epiphytic growth reducing the survival of culture-reared seedlings by lowering the light levels but to a level that does not hinder seedling growth (Wear, 2006). This problem of epiphytic growth was also experienced by researchers in South Australia (Wear, 2006). It is hoped that this seedling rearing technology could result in an abundant supply of seagrass seedlings for restoration purposes, but more research is considered necessary to develop a sufficiently high seedling production rate from such tissue culture techniques (Oceanica Consulting, 2006).

In Australia to date, much of the research on tissue culture techniques has focussed on developing successful laboratory techniques. To determine the ultimate use of these techniques for seagrass restoration, some trial studies have investigated the survival and growth of seedlings planted in the ‘wild’. In Western Australia, the planting of both laboratory-reared and natural seedlings of *P. australis* in sheltered natural waters around Albany between 2003 and 2006 found high initial short-term survival rates. In the first trial, 76 laboratory reared seedlings which had formed three leaves and moderate root development, were planted and secured with hair clips, and 60 naturally growing seedlings were collected and planted using longer (70 mm) wire staples. After one year, the survival rate was 60% for seedlings raised from seed and 80% for those obtained from the natural environment (Oceanica Consulting, 2006). In a second trial, 120 seedlings planted with an undescribed, but claimed ‘improved’ attachment method showed 100% survival after six months (Oceanica Consulting, 2006). In early 2006, the trial planting of culture-reared seedlings amongst hessian bags was also conducted in Western Australia (Oceanica Consulting, 2006). The survival of these planting units varied considerably and seemed dependent upon the quality of hessian bag used (Oceanica Consulting, pers. comm., 2007).

In South Australia, the use of culture-reared *Posidonia* spp. seedlings to form a large area of seagrass habitat was deemed impractical due to the difficulty in cultivating seedlings, the highly spatially and temporally variable sexual reproduction of local *Posidonia* species, and the slow growth rate of these species (Seddon *et al.*, 2005). Research found that the growth of *Posidonia* spp. seedlings in culture is possible, but the survival rate of these seedlings was low due to excessive epiphyte growth and the level of shading over the tanks. It was suggested that cultured *Posidonia* spp. seedlings could be useful in accelerating natural succession in areas that are starting to be recolonised by fast-growing seagrass species (Seddon *et al.*, 2005).

Another method of seagrass restoration using *Posidonia* spp. seedlings is being trialled in South Australia. Here *Posidonia* spp. fruits collected from beaches are held in tanks until dehiscence and the resultant seedlings are planted into sand-filled hessian bags that are then placed into the natural environment. The few seedlings that survived planting into the natural environment had very good growth rates over the longer-term (Wear, 2006).

3.2.2. Zostera species

3.2.2.1. Transplantation methods

A total of five attempts at transplanting *Z. capricorni* have been conducted in NSW estuaries since 2000 (Appendix 1). These consisted of small-scale experiments to trial techniques for seagrass habitat restoration (Roberts *et al.*, 2006; Danny Roberts, BIO-ANALYSIS Pty Ltd, pers. comm., 2006), or were attempts at restoring relatively small areas of recently damaged seagrass habitat (EP Consulting Group, 2004; Matt Gordos, NSW DPI, pers. comm., 2006; NSW DPI, 2006). Standard single shoot, clump and core methods were trialled to transplant *Z. capricorni*. Some of these transplanting attempts failed due to sediment movement or flood damage. However, a high percentage of survival (close to 100% after 12 months) was recorded when cores of *Z. capricorni* were transplanted into existing recipient beds of this species in Tuggerah Lakes (Danny Roberts, BIO-ANALYSIS Pty Ltd, pers. comm., 2006). Also, some survival was recorded when clumps, cores and shoots of *Z. capricorni* were transplanted into vegetated and unvegetated habitat in Botany Bay, before being buried by sand which probably originated from an adjacent beach re-nourishment program ten months after transplanting (Roberts *et al.*, 2006).

On the Gold Coast of Queensland, less than 50% of mixed and pure cores of *Z. capricorni* and *H. ovalis* that were transplanted into a human-made depression had survived after six months (McIennan and Sumpton, 2005). Further transplanting in this area was not recommended, due to the cost of transplanting, associated donor bed damage and the observation of natural seagrass colonisation in the area (McIennan and Sumpton, 2005).

Pilot investigations into the transplantation of *Zostera muelleri* in Western Port Victoria in the early 2000s found the transplantation of plugs of this species to be the most appropriate method, in terms of survival, for this location. The planting of high-density units in areas of low rates of desiccation was recommended (Walker, 2003). A cost-analysis of the collection, planting and monitoring of each planting method showed the plug method ($AUD1,308,284/ha) to be the cheapest (Walker, 2003). With the use of a model to select transplant sites, the overall short-term survival rate of the various planting units was 47% (Walker, 2003). However, none of these units appeared to have survived in the longer term, possibly due to being smothered by sediment (Ealey, 2006). The model considered tidal velocity, surface water quality, pore-water quality, and sediment quality (Walker, 2003). Other seagrass transplanting trials that have been subsequently conducted in this area also failed, but the results of transplanting trials conducted in 2006 have not yet been published (Ealey, 2006).

3.2.2.2. Seedling methods

Research conducted in Victoria established viable tissues of *Heterozostera tasmanica*[4] in vitro and developed a method to initially culture this species, without destroying plant viability. A culturing attempt on *Z. muelleri* in Victoria found this species to be highly sensitive to the initial culturing process of in vitro growth, and subsequently further investigations into the culture of this species were not conducted (Walker, 2003).

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[4] There is currently active debate concerning the taxonomy of *Heterozostera* in Australia (Les *et al*., 2002; Kuo, 2005). Where the species name *Heterozostera tasmanica* is used in this review it is because it is the name used in the referenced article. However, this species and *Zostera tasmanica* may be the same.

3.2.2.3. *Re-seeding methods*

In assessing the feasibility of using seeds to restore areas of *Zostera* spp. decline in Victorian estuaries, Parry (2007) concluded that this cannot be determined without additional research on the biology, especially seed ecology, of local *Zostera* species. An investigation into the seed ecology of Victorian *Zostera tasmanica*[5] and *Z. muelleri* found that the collection by hand of *Z. tasmanica* seeds for restoration purposes, as performed on *Zostera marina* in Chesapeake Bay, may be practical (Parry *et al.*, 2005). However, this may not be so for *Z. muelleri* as mature spadices of the seeds of this species are only attached to the parent plant for a short period of time. Further, they are located near the base of the plant which makes them very difficult to detect (Parry *et al.*, 2005). To collect *Z. muelleri* seeds, Parry (2007) suggested the use of techniques to gather seeds from the sediment. In proceeding with the large-scale restoration of previously denuded sites, Parry (2007) stressed the importance of only commencing restoration of these sites once factors that contributed to the seagrass loss had been mitigated.

3.2.3. *Other seagrass species*

3.2.3.1. *Transplantation methods*

Sods of *Amphibolis griffithii* that were mechanically transplanted in an oceanic wave-exposed environment in Western Australia with the ECOSUB machines, exhibited a much lower survival rate than the *Posidonia* spp. that were transplanted with these same machines. The survival of *A. griffithii* sods that were transplanted with ECOSUB I after two years was 44.3%. This lower survival rate appears to relate to the morphological ‘branch-like’ structure of *A. griffithii* (Paling *et al.*, 2001b).

Methods to stabilise sediments around seagrass planting units have been trialled in Western Australia and South Australia. In the Cockburn Sound area of Western Australia, the use of plastic mesh around transplanted plugs of *A. griffithii* resulted in 90% survival of transplant units after 18 months (Van Keulen *et al.*, 2003).

In South Australia the success of the use of biodegradable hessian mats to stabilise sediments around cores and secure sprigs of mature *A. antarctica* and *H. tasmanica* transplants could not be determined (Seddon *et al.*, 2004). The trialled methods were deemed unlikely to be suitable for forming large areas of seagrasses in the study area due to poor trial transplant survival rates, the relatively high amount of labour for these methods, and donor bed damage issues (Seddon *et al.*, 2004). It was suggested that this technique may only be suitable in low wave energy environments (Seddon *et al.*, 2004).

3.2.3.2. *Natural recruitment facilitation methods*

Research in South Australia discovered that the comb-like grappling apparatus on *Amphibolis* seedlings facilitated their entanglement in a range of biodegradable hessian bags, strips or mats. After five weeks, a total of 16,514 seedlings (or 157.2 seedlings / m^2) had recruited onto all experimental units. However, the retention of seedlings on these units declined, and after one year only 31.4% of these seedlings remained (Wear *et al.*, 2006). The method was found to be a non-destructive, cost-effective (i.e., costing $10,000 to rehabilitate one hectare of seagrass) method of *Amphibolis* seagrass restoration that could easily be deployed over large spatial scales (Wear *et al.*,

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[5] Considering the above-mentioned taxonomic debate, where the species name *Zostera tasmanica* is used in this review it is because it is the name used in the referenced article. However, this species and *Heterozostera tasmanica* may be the same.

2006). Hessian bags covered with a coarse weave hessian layer were found to be the most effective recruitment facilitation method. At the end of the experimental period, these bags retained the greatest seedling density and were one of the most cost-effective methods trialled (Wear *et al.*, 2006). The other families of seagrasses found in Australia do not have this grappling hook on their seedlings.

3.3. Summary

Seagrass restoration currently remains a costly somewhat developmental process. Although innovative techniques have been developed, and improvements to the success of restoring some seagrass species have been made, seagrass restoration projects conducted since 2000 have shown large variations in success. Natural variability among sites, the local biology and ecology of the restored species, and environmental conditions during the restoration process all have a strong influence on the success of restoration projects, such that the success of these projects in a given area cannot be guaranteed. The restoration of several hundred hectares of seagrass is still to be realised, and no one-to-one replacement of seagrass habitat using any restoration technique has been documented. Seagrass restoration techniques have still only been documented to successfully replace small areas of seagrasses. Seagrass transplanting and other restoration techniques have still not been developed to the extent that particular methods could be recommended for different species in different habitats.

Poor planning was often identified as a factor that contributed to the failure of seagrass restoration attempts. Consideration of the following factors at the project planning phase may improve the success of seagrass restoration projects:

- the restoration of sites only when factors that contributed to the decline of seagrass in the area have been mitigated;
- the local biology and ecology of the species to be restored in choosing restoration techniques and sites;
- the local environmental factors that can influence the success of restoration projects, such as light, water motion, water quality, depth, sediment deposition, substratum and bioturbation activity, in choosing restoration techniques and sites;
- the damage to existing seagrass beds or seed banks resulting from the restoration process;
- the cost of restoration; and
- the monitoring of seagrass restoration projects over the longer term (preferably over five years).

Some models and frameworks, such as Campbell (2002) and Short *et al.* (2002c), have been developed to ensure that all factors that could influence the success of seagrass restoration projects are considered in the project design and/or site selection stages.

Novel techniques for seagrass habitat restoration developed over the time of this review that when experimentally trialled showed good rates of survival include the:

- application of growth hormones (auxins) to enable *P. oceanica* seedlings and cuttings to establish more quickly;
- germination and growth of *P. australis* and *P. coriacea* from seed in controlled tank conditions;
- planting of laboratory-reared and natural *Posidonia* seedlings into the natural environment;
- reduction of transplanting costs and donor bed damage by planting sprigs of *Posidonia* spp. into a more efficient pattern;
- new methods to transplant existing *Zostera* seagrass, i.e., the horizontal rhizome and single unanchored shoot methods, and the transplantation of *Zostera* into existing recipient beds;

- use of *Z. marina* seeds to restore large areas of seagrass beds in denuded coastal bays;
- transplantation of fast-growing species, such as *H. wrightii*, into propeller scars amongst bird roosting stakes that facilitate the spread of nutrients, recovery rates of transplants and, hopefully, the eventual restoration of slow-growing climax species, such as *T. testudinum*; and
- recruitment of *Amphibolis* seedlings through the entanglement of their comb-like grappling apparatus in biodegradable hessian bags.

Along with the novel methods, more traditional seagrass restoration methods (manual transplantation of cores, plugs, sprigs and rhizome segments) continued to be used over the time of this review. Transplant unit survival, which is mostly reported on a short-term basis, continues to vary widely (0 – 95%), apparently strongly influenced by site specific processes. The factors reported to contribute to the failure of seagrass transplantation attempts were:

- erosion;
- burial with sand;
- heavy swell conditions;
- turbidity;
- flood damage;
- bioturbation;
- high sediment ammonia concentrations;
- epiphyte growth;
- human damage; and
- insufficient anchorage of planting units.

Although survival of transplant units was low in many studies, survival rates >60% are increasingly being reported for both *Posidonia* and *Zostera* species. For example, Oceanica Consulting (2006) reported high transplant unit survival rates of up to 96% for the transplantation of sprigs of *Posidonia* species (including *P. australis*) in sheltered waters in Western Australia when site conditions were favourable. These high survival rates were reported over the long term along with the coalescence of these transplant units into a seagrass bed five years after planting. This is a significant achievement in seagrass transplanting in Australia.

4. CONCLUSIONS

1. Seagrass restoration techniques cannot currently be used with confidence as a habitat compensation measure in NSW because:
    - there is a paucity of information on the growth of seagrasses in NSW;
    - success cannot be guaranteed with the use of any current seagrass restoration technique;
    - large-scale seagrass habitat restoration is yet to be achieved with the use of any current technique on any seagrass species;
    - many seagrass restoration techniques are still at a developmental stage; and
    - most seagrass restoration attempts conducted in NSW have failed.

2. To increase the confidence of using seagrass restoration techniques to successfully compensate for habitat losses in NSW, an adaptive strategic research-based approach is required. Some major aims of this would be to fill in information gaps concerning both the growth parameters of local seagrass species in NSW and the environmental parameters of NSW estuaries, and to develop cost effective techniques that are suitable to local species and conditions. Many of the traditional and novel techniques described in this review could be further developed for this purpose. The research projects should have rigorous scientific analysis to allow for natural variation, document the prevailing environmental conditions at the site, and give recommendations to allow for an adaptive approach to achieving strategic objectives. There is the potential to use seagrass restoration techniques to restore small areas of seagrass habitat in NSW. It is worth noting that seagrass restoration attempts are costly.

3. Further research into the biological and ecological aspects of NSW seagrass species would help determine the most appropriate cost-effective restoration technique for local species under various environmental conditions and assist in choosing appropriate restoration sites. This includes information on the local habitat preference, light requirements, substratum preference, other general growth requirements, rhizome growth rates, seedling establishment, reproductive capacity, and seed production, viability and establishment potential of local seagrass species. This information on NSW seagrasses is sparse.

4. Any future seagrass restoration attempts in NSW should place importance on the project planning and site selection stages, as poor consideration in these areas often leads to the failure of these projects. The local factors to be considered at these stages include sediment type, wave exposure, water quality, water movement, turbidity, depth, light availability, sediment movement and bioturbation activity. This would assist in choosing an appropriate site and restoration method for the restored species. The largely unknown influence of such factors on the growth of seagrass species in NSW underlines the need to determine growth parameters for NSW seagrass species. It is also important to consider the survival and growth of trials of the chosen technique at the chosen site to test suitability, and to ensure that the cause of seagrass loss has been mitigated before restoration.

5. Another area of research which will assist in planning seagrass restoration attempts and the conservation of seagrass habitat in NSW is to investigate the cause of seagrass decline in NSW and the method and rate of recolonisation of local seagrass species after disturbance. The need to restore the long-lived, slow recruiting *P. australis* that cannot readily recover after disturbances have been mitigated is far greater than the need to restore the other more rapidly growing and recruiting seagrass species in NSW.

6. In conclusion, seagrass restoration techniques cannot currently be depended upon to achieve the 2:1 habitat compensation policy in NSW, and a review of the current use of seagrass restoration techniques for this purpose is warranted. The protection of existing seagrass beds remains the most important, efficient and effective priority to sustain seagrass resources.

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APPENDICES

Appendix 1: A summary of seagrass transplanting projects conducted in NSW from 1999 to 2006.

(NB. Seagrass transplanting projects conducted prior to 1999 in NSW are similarly summarised in Lord *et al.* 1999).

A) Port Hacking, 1999

Objective of project:	To assess the feasibility of small-scale transplanting as a means of seagrass habitat restoration.
Seagrass species used:	*Posidonia australis*
Planting method:	20 – 30 cm rhizome sections with 1 – 2 plagiotropic and 2 – 4 orthotropic shoots were transplanted. Rhizomes were randomly chosen over a large area, in which 0.5% of the total number of shoots were used. Rhizomes were attached to mesh quadrats using plastic electrical ties. Quadrats were fixed onto bare substrate and shoots were orientated so they could spread into surrounding substrate.
Plant spacing and density:	6 – 8 rhizomes were attached to 0.5 m x 0.5 m quadrats. Five quadrats were set at five sites. 575 shoots were transplanted.
Project duration:	+ 16 months.
Assessment of relative success or failure:	Transplants failed at two sites because of erosion and large scale sand movement. Transplanting using this method can be successful in increasing seagrass habitat, but candidate sites for rehabilitation should be subject to a feasibility study prior to transplanting.
Date and other comments:	Transplanting occurred in July 1999. Negligible impact on donor seagrass bed.
Site characteristics:	Shallow water; sand substrate.
Physical protection/alteration of site:	No
Monitoring:	
• what attributes, how frequently, and for how long	Survival rates of transplanted shoots were monitored in-situ bi-monthly for 16 months and, at the end of the experiment, rhizome growth, shoot growth, shoot production and growth architecture were assessed.
• findings	650 shoots present at end of study. Of the five sites, four exhibited high survival rates in the short term (<6 months) and three exhibited high survival in the long term (>12 months). At one transplant site, growth dynamics of transplants were similar to those of naturally growing plants. Substantial colonisation of surrounding substrate at two sites.
Performance criteria (details of the relevant requirements that were established and needed to be met) :	Experimental trial to test feasibility of technique for seagrass restoration.
References:	Meehan and West, 2002.

B) St. Georges Basin, 1999

Objective of project:	To trial seagrass transplanting techniques and test the influence of shelter and sediment type on transplant success.
Seagrass species used:	*Posidonia australis*
Planting method:	Rhizome sections were attached to a plastic mesh base material which was anchored with pegs into sediment.
Plant spacing and density:	Transplants were planted at different densities from the established seagrass bed.
Project duration:	Approximately two months due to failure of experiment.
Assessment of relative success or failure:	Transplant mortality of greater than 90% in less than two months, due to an inadequate anchoring system, commercial hauling across the transplant site, and heavy swell conditions which buried the transplants with sand.
Date and other comments:	1999
Site characteristics:	Transplants planted at depths of 1m around remnant *Posidonia* beds in the northern section of the estuary.
Physical protection/alteration of site:	No
Performance criteria (details of the relevant requirements that were established and needed to be met):	Transplanting conducted as a trial experiment.
References:	Alex Meehan, pers comm., 2006.

C) Tuggerah Lakes, 2000

Objective of project:	A pilot experiment as part of future investigations into the effects of mine subsidence on seagrass habitats.
Seagrass species used:	*Zostera capricorni*
Planting method:	Cores of seagrass (15 cm in diameter) from the donor seagrass bed were transplanted either within an existing seagrass bed or onto bare sediments.
Plant spacing and density:	Cores were planted randomly.
Project duration:	12 months.
Assessment of relative success or failure:	Seagrasses successfully trans-located using whole plugs with close to 100% survival after 12 months. The key to success in this case was that the seagrass plugs were transplanted with their sediment from a “healthy” donor bed to a “healthy” recipient bed.
Date and other comments:	2000
Site characteristics:	Sand substrate.
Physical protection/alteration of site:	No
Monitoring:	
• what attributes, how frequently, and for how long	Survival and growth monitored over 12 months.
• findings	Close to 100% survival after 12 months observed.
Performance criteria (details of the relevant requirements that were established and needed to be met):	Conducted as a pilot experiment.
References:	Danny Roberts, BIO-ANALYSIS Pty Ltd, pers. comm., 2006.

D) Wagonga Inlet, Narooma, 2001

Objective of project:	To investigate the feasibility of seagrass transplantation in the Wagonga Inlet.
Seagrass species used:	*Posidonia australis*
Planting method:	15 cm diameter plugs extracted from a continuous seagrass bed using 200 mm lengths of PVC piping were planted into excavated holes at the transplant site.
Plant spacing and density:	12 plugs planted into bare sand 10 m from donor bed. Plugs spaced approximately 0.5 m apart in a loose grid formation.
Project duration:	14 – 15 months.
Assessment of relative success or failure:	High survival rate showed that seagrass transplantation may be a viable method to increase seagrass meadow area in Wagonga Inlet.
Date and other comments:	Transplanting occurred in December 2001.
Site characteristics:	Sand substrate.
Physical protection/alteration of site:	No
Monitoring: • what attributes, how frequently, and for how long • findings	Survival and general health monitored monthly for 14 months. At end of monitoring period, 92% of transplants survived. Also some natural seedling and seagrass fragment colonisation within and around the transplant area was reported. One transplant unit was eventually lost after being hit by a boat propeller six months into the monitoring period.
Performance criteria (details of the relevant requirements that were established and needed to be met):	This was a pilot experiment. A properly executed and monitored exercise would be needed to convince regulatory authorities, the public and wider community that success is achievable.
References:	Paling and van Kuelen, 2003.

E) Lady Robinsons Beach, Botany Bay, 2004

Objective of project:	To assess if transplant success is affected by: a) characteristics of donor seagrass material; and, b) plot sizes at recipient locations.
Seagrass species used:	*Zostera capricorni*
Planting method:	Plugs of seagrass (0.8 m x 1.6 m) harvested and transported on trays. In all 305 m^2, from 292 seagrass 'trays' were transplanted.
Plant spacing and density:	a) eight (14 m x 14 m) plots from two locations were transplanted. b) eight (5 m x 5 m plots, and eight 14 m x 14 m plots were transplanted.
Project duration:	Three years after transplanting.
Assessment of relative success or failure:	The experiment appears to have been a failure, the reasons for which have not yet been determined.
Date and other comments:	Transplanting occurred in 2004.
Site characteristics:	Sand substrate. Transplant sites were located in between groynes that were situated in a high wave energy environment.
Physical protection/alteration of site:	No
Monitoring:	
• what attributes, how frequently, and for how long	Change in plot size and seagrass density and leaf length monitored for three years after transplanting. Measurements taken at time 0 and month 1, 2, 4, 6, 8, 10, 12 in the first year after transplanting and on a 6 monthly basis during years 2 and 3.
• findings	a) By December 2005, 17 months after transplanting, 0.6 m^2 of seagrass material remained. In December 2006, no transplanted seagrass was located in recipient plots. b) By December 2005, 15 months after transplanting, 19 m^2 of seagrass material remained. By June 2006, transplanted seagrass survived 21 months at 4 out of 16 recipient plots and the total area covered by seagrass was 1 m^2. This area then decreased in the December 2006 survey.
Performance criteria (details of the relevant requirements that were established and needed to be met):	An attempt at seagrass transplanting for habitat restoration purposes.
References:	EP Consulting Group 2004, 2007.

F) Foreshore Beach, Botany Bay, 2004

Objective of project:	To examine whether transplanting *Zostera capricorni* into different habitat types would result in different success rates for different transplanting techniques. The success of transplanting 'robust' *Zost\era* plants as opposed to 'spindly' *Zostera* plants was also examined.
Seagrass species used:	*Zostera capricorni*
Planting method:	Seagrass extracted by hand or with a core on SCUBA. Seagrass planted into 0.25 m^2 plots as separate single shoots, single shoots planted into a clump, clumps of seagrass and rhizomes with the sediment washed off, and as a plug (10 x 10 cm core), which included sediment, rhizomes and shoots. The plots were planted into three habitat types – original seagrass bed, bare patches within the seagrass bed and unvegetated habitat.
Plant spacing and density:	In all, 228 plots were planted into and adjacent to the existing seagrass meadow. Four plots of the various planting techniques and an untouched control were established at three sites spaced 100 m apart.
Project duration:	23 months.
Assessment of relative success or failure:	The *Zostera capricorni* meadows along Foreshore Beach progressively declined in terms of their density, cover and leaf-length over two years after the transplanting experiment. Major cause of this was burial from sand that most probably originated from the erosion of Foreshore Beach. *Halophila ovalis* colonised some locations in the Foreshore Beach area over these two years. Prior to burial by sand, some success in the transplanting experiment was found. It was also found that transplanting or harvesting this seagrass did not affect its growth.
Date and other comments:	Transplanting occurred in April 2004.
Site characteristics:	Sand substrate.
Physical protection/alteration of site:	No
Monitoring: • what attributes, how frequently, and for how long • findings	 Seagrass density, cover and leaf-length were measured at 4, 10, 23 months after transplanting. The plots were buried by sand after the 10 month sampling period. The findings at 10 months showed that clump and plug techniques could be recommended for the growth of robust *Zostera* in unvegetated habitats, and all four assessed techniques appeared suitable for robust *Zostera* planted into bare patches. The single shoot technique was found to be the most successful method for transplanting spindly *Zostera capricorni* into unvegetated habitat, whilst the single clump method was more suitable for spindly *Zostera* planted within the bare patches in seagrass meadows.
Performance criteria (details of the relevant requirements that were established and needed to be met):	An experimental trial for habitat restoration purposes.
References:	Roberts *et al.*, 2006.

G) Yamba Bay, Clarence River, 2005

Objective of project:	To commence the rehabilitation of an area of seagrass that was denuded as a result of human error. To trial coring transplantation procedures on a small scale to provide management recommendations for future perturbations.
Seagrass species used:	*Zostera capricorni*
Planting method:	Cores of seagrass 100 mm in diameter x 150 mm and were extracted from the adjacent seagrass bed using a PVC pipe and immediately transplanted into bare sand on the damaged site.
Plant spacing and density:	Cores were planted in varying densities within designated 1 m^2 plots that were aligned into a quadrat formation and spaced 1 m^2 apart.
Project duration:	12 months.
Assessment of relative success or failure:	It was proven that coring can be an effective means of seagrass transplanting. The failure of this method in the transplant site was due to site specific processes, mainly sediment movement.
Date and other comments:	Seagrass was denuded at this site two years before transplantation in January 2005. Donor beds exhibited short-term effects from core removal.
Site characteristics:	Sand substrate.
Physical protection/alteration of site:	No
Monitoring:	
• what attributes, how frequently, and for how long	Leaf length and the number of cores and mean shoot density per plot monitored at 0, 1, 3, 6, 9, and 12 months after transplantation.
• findings	Overall the trial was unsuccessful and there was a complete loss of cores from the transplant area six months after transplantation. This loss was primarily attributed to the deposition of 150 – 300 mm of sandy sediment of uncertain origin, over the cores.
Performance criteria (details of the relevant requirements that were established and needed to be met):	An experimental trial of seagrass transplanting for seagrass habitat rehabilitation purposes.
References:	NSW Department of Primary Industries, 2005.

H) Brunswick River, 2005

Objective of project:	To use seagrass transplanting to create 350 m^2 of seagrass habitat in the Brunswick River.
Seagrass species used:	*Zostera capricorni*
Planting method:	Cores of seagrass extracted using a 150 mm diameter PVC pipe were placed through a hessian bag which was buried into sediment.
Plant spacing and density:	Bags were spaced 0.5 m apart and planted into a quadrat formation. Seagrass was transplanted 100 m downstream from donor site.
Project duration:	Project abandoned due to flood damage.
Assessment of relative success or failure:	Transplant units did not survive as they were buried by approximately 1 m of sediment from a flood that occurred before the transplanting phase of the project was complete.
Date and other comments:	June 2005. It was thought that the hessian bags would degrade a few weeks after planting, but this did not occur, probably due to anoxic conditions in sediments.
Site characteristics:	
Physical protection/alteration of site:	Hessian bags were used to prevent erosion around seagrass cores and allow roots to establish.
Monitoring: • what attributes, how frequently, and for how long • findings	Flood destruction prevented any specific monitoring of transplant units. Approximately three months after the flood, only small reduced patches of the original seagrass beds remained.
Performance criteria (details of the relevant requirements that were established and needed to be met):	Project was conducted to replace 100 m^2 of seagrass bed damaged during bridge construction as part of the 2:1 habitat replacement policy in NSW.
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