Assessment of the effects of foreshore nourishment and mitigation projects on seagrass ecosystems (SRMP-004)

GCWA Scientific Research and Management Program

December 2016

Rod Connolly
Ryan Dunn
Mogens Flindt
Emma Jackson
Erik Kristensen
Skye McKenna
Andrew Olds
Michael Rasheed
Thomas Schlacher
Paul York

<table>
<tr><td rowspan="4">GRIFFITH UNIVERSITY

Gold Coast Campus
QLD 4222

Telephone (07) 55528614

www.griffith.edu.au/environment-planning-architecture/australian-rivers-institute</td><td>Document: Assessment of the effects of foreshore nourishment and mitigation projects on seagrass ecosystems (SRMP-004)</td></tr>
<tr><td>Project: GCWA SRMP-004</td></tr>
<tr><td>Title: Assessment of the effects of foreshore nourishment and mitigation projects on seagrass ecosystems
Project Leader: Professor Rod Connolly
Author(s): Rod Connolly, Ryan Dunn, Mogens Flindt, Emma Jackson, Erik Kristensen, Skye McKenna, Andrew Olds, Michael Rasheed, Thomas Schlacher, Paul York</td></tr>
<tr><td>Sponsoring Organisation: Gold Coast Waterways Authority
Contact: Jessica Bourner</td></tr>
<tr><td colspan="2">Synopsis: This report reviews previous sand nourishment and seagrass translocation projects in Gold Coast waterways to determine factors influencing colonisation and transplant success. Additionally, the report presents findings from seagrass field surveys in the Broadwater at sites of foreshore nourishment and transplant projects. It also provides guidelines for seagrass restoration and rehabilitation as a guide for future work in Gold Coast waterways. The broader ecological benefits that flow from restoring seagrass habitats are also described.</td></tr>
<tr><td colspan="2">Keywords: Gold Coast waterways, restoration, rehabilitation, seagrass transplants, ecosystem services</td></tr>
</table>

REVISION/CHECKING HISTORY

REVISION NUMBER	REPORT DATE	CHECKED BY	ISSUED BY
0	1 March 2016	Rod Connolly	
1	11 April 2016	Ryan Dunn	Rod Connolly
2	22 December 2016	Ryan Pearson	Rod Connolly

Citation

Connolly RM, Dunn RJK, Flindt MR, Jackson, EL, Kristensen E, McKenna S, Olds AD, Rasheed MA, Schlacher TA, York PH, (2016) Assessment of the effects of foreshore nourishment and mitigation projects on seagrass ecosystems (SRMP-004). Report to Gold Coast Waterways Authority, Griffith University, Gold Coast, Australia, December 2016.

Contents

List of Figures

List of Tables

1. Background

This project was initiated by the Gold Coast Waterways Authority (GCWA). The GCWA has created a Scientific Advisory Committee, which is in part responsible for the GCWA Scientific Research and Management Strategy and the accompanying Scientific Research and Management Program (SRMP). This project is part of that program and is intended to enhance understanding of Gold Coast waterways (GCWs) and contribute to improved management outcomes.

2. Introduction

Gold Coast waterways (GCWs) are extensive and iconic features of the wider cityscape. The dominant geographic feature is the Gold Coast Broadwater, a large shallow estuarine waterbody forming part of southern Moreton Bay. It plays an important role in the region's tourism industry, recreational pursuits, and fisheries (Warnken et al. 2004, URBIS 2012, Dunn et al. 2014). Furthermore, the environmental values of the Broadwater are considerable, with critical wetland habitats (seagrass, mangroves, saltmarsh) supporting essential feeding, spawning and nursery sites for aquatic fauna. These wetland habitats, and associated sandbanks, are also important feeding and roosting grounds for birds (Dunn et al. 2014).

The Broadwater's position in one of the fastest growing regions in Australia, and the diversity of interests among its user groups, have resulted in dramatic changes in recent decades. Construction of canal estates and marina facilities, foreshore redevelopments, and the creation (and maintenance) of anchorages and navigable channels, have combined to change the environmental state of the Broadwater (and other GCWs); each change potentially exerts pressure on the ecological condition of GCWs (e.g. Dunn et al. (2003), Warnken et al. (2004)).

Dredging is undertaken in portions of the waterways, typically in locations prone to shoaling, to provide navigation access (GHD 2006). There have also been several larger dredging projects, the largest being the creation of the Seaway (in 1985), with other major events associated with beach nourishment projects (in 1975 and 2000). Dredged sand has also been used for foreshore nourishment within the Broadwater, typically adjacent to dredging project sites, as well as for reclamation (including most recently for the Broadwater Parklands Phase 3 project, discussed below).

Seagrass habitats are widely recognised to provide numerous ecosystem services. Re-purposing of dredge material may improve the quality and extent of seagrass habitats on foreshores, potentially creating positive outcomes for both the community and the environment; it may also reduce costs by limiting the distance that dredged sand has to be transported (DSDIP 2016).

Environmental offsets associated with dredge works can be achieved by restoring or creating new habitat for seagrass. Restoration can be accomplished by improving habitat conditions that promote seagrass growth, or by transplanting seagrasses. Such transplants can occur in areas where seagrass has historically existed or in newly-created habitats (e.g. those created by sand nourishment).

Seagrass rehabilitation refers to projects that seek to improve, augment or enhance degraded areas. Restoration, on the other hand, generally refers to projects aimed at returning an ecosystem approximately to the condition before an impact occurred (Lord et al. 1999). It is important to note that in instances where the factors that caused a decline in seagrass are known (e.g. elevated nutrients, contaminants or suspended sediments (Connolly et al. 2016a)), these stressors must be reduced, or ideally removed, before seagrass is likely to respond positively to rehabilitation or restoration efforts (Lord et al. 1999).

Transplanting, as a means of seagrass rehabilitation and restoration, became established as a method from the late 1980s onwards, both internationally (e.g. Fonseca (1992)) and nationally (e.g. Paling (1995), Kirkman (1999), Meehan and West (2002), van Keulen et al. (2003)). Since then, the feasibility of transplanting, methods, and outcomes have been assessed in numerous studies (Gordon 1996, Lord et al. 1999, Wear 2006). Within GCWs, transplanting (or translocation) projects have mostly been done as part of marine plant offsets, stipulated as a condition of foreshore development approval (Australian Wetlands 2009, Element Ecology 2014a).

This report first presents recommended guidelines for seagrass restoration projects, and summarises a global review of factors recorded as influencing the success of restoration projects. Previous seagrass transplanting projects in GCWs are assessed against the guidelines. Findings are presented from seagrass surveys of areas of the Broadwater associated with transplanting and foreshore nourishment projects. We also assess the broader ecological benefits that flow from restoring seagrass habitats. Future works aimed at enhancing and restoring seagrass should include several complementary strategies that a) improve environmental conditions for growth and survival (e.g. increased water clarity), b) optimise techniques for the local situation, and c) potentially create suitable habitats.

3. Seagrass Restoration Guidelines and Factors Influencing Restoration Success

3.1 Recommended restoration guidelines

This section describes recommended restoration (and rehabilitation) guidelines for seagrass based on ten key steps applicable to GCWs (Fig. 1). These steps were developed through comprehensive global reviews and syntheses of findings from the following sources: Gordon (1996), Campbell (2002), Paling et al. (2009), van Katwijk et al. (2009), Fonseca (2011), Cunha et al. (2012), Statton et al. (2012) and van Katwijk et al. (2012).

These guidelines represent a best-practice approach for the successful design, implementation and completion of seagrass restoration (and rehabilitation) projects in order to deliver successful outcomes. They are intended as a generic guide to, firstly, assess previous restoration projects in GCWs, and secondly, to provide a framework for future restoration projects.

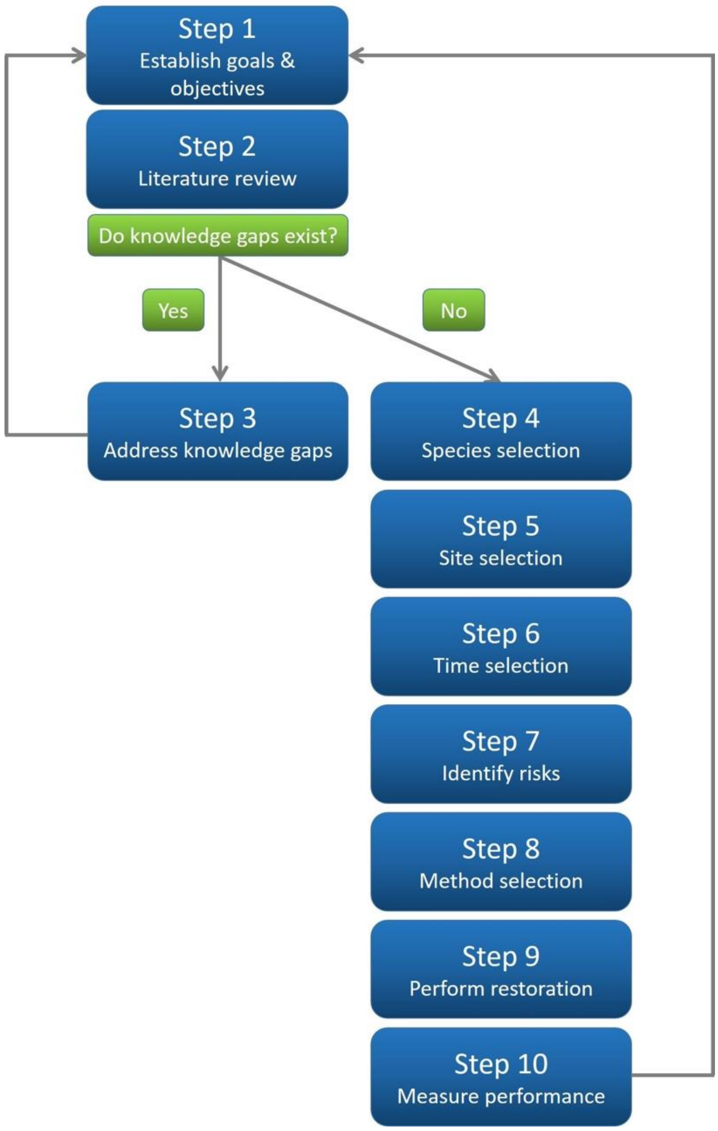

Fig. 1. Ten step recommended approach for the successful design, implementation and completion of seagrass restoration and rehabilitation projects.

Step 1: Establish Clear Goals and Set Objectives

Identifying clear goals early is critical to properly design the works, operate within budget, meet community expectations, and deliver outcomes against performance criteria.

Campbell (2002) outlines several aspects when defining goals:

- Ecological target(s)
- Stakeholders & community expectations,
- Legal responsibilities;
- Budget & costs;
- Criteria to judge performance (both short- and long-term).

For example, goals may include: i) "*create new seagrass habitat*"; ii) "*restore an area to pre-disturbance conditions*", or iii) "*offset seagrass loss through reintroduction of seagrass meadows*"

Step 2: Literature Review

Review the regional literature to address:

- Seagrass distribution;
- Causes of seagrass loss, and future risks;
- Likelihood of natural recovery;
- Potential seagrass donor and transplant sites;
- Habitat suitability model
  (predicts where seagrass could potentially grow based on shear bed stress, slope, depth, hydrodynamic connectivity data (e.g. identification of propagule sinks), photosynthetically active radiation (PAR), and sedimentation/erosion rates).
- Likely potential for persistent (versus transitory) seagrass meadows;
- Genetic diversity (and rates of dispersal between seagrass in different areas within the region)
  (If collection of quantitative genetic data is outside the budget, transplants should come from a wide variety of sites and be interspersed at the restoration site).
- The status of existing nearby meadows (e.g. species, form and dynamics), which represent potential donor sites, and models of potential natural dispersal of propagules (seeds and plant fragments; e.g. Erftemeijer et al. (2008), Grech and Coles (2010), Renton et al. (2011), Weatherall et al. (2016));
- Connectivity with other habitats.

Step 3: Address Knowledge Gaps

Where knowledge gaps remain, attempts should be made to build the knowledge base through a combination of field observations and surveys, experiments, and modelling (Fig. 2). For example, if elevated levels of turbidity are suspected to cause seagrass failure, laboratory experiments can be useful to test the sensitivity of local species to various light and turbidity levels. Results from such experiments can then be used to model the probability of particular field sites sustaining seagrass and to validate potential restoration sites.

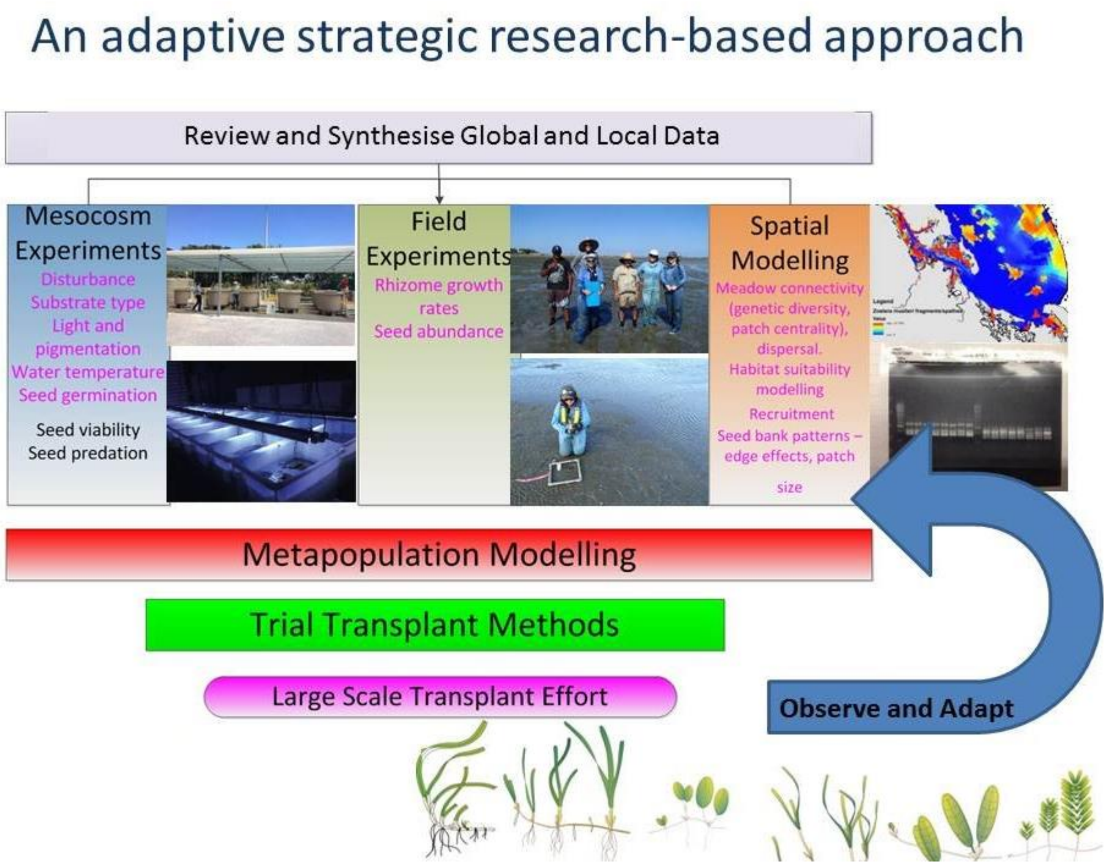

Fig. 2. Illustration of approaches that can inform the improvement of methods to restore seagrass. Experiments in tanks (mesocosms) can be used to test the influence of specific factors (e.g. light) on biological processes (e.g. seed viability and germination). Field experiments and surveys are useful to assess how seagrass performs at sites similar to restoration candidate sites. Modelling is useful to predict the likely success of sites; it draws on data from both laboratory and field experiments (source: original figure produced for this report).

Step 4: Species Selection

Select seagrass species according to project objectives and environmental, biological, and physical conditions typical at potential restoration site(s):

- Consider habitat-forming traits and life forms, such as pioneer species (e.g. *Halophila* spp.) or climax species (e.g. *Zostera muelleri*);

- Match physiological tolerances of species with conditions at potential transplant sites.

Step 5: Site Selection

Selecting appropriate sites is critically important in restoration (van Katwijk et al. 2009). In practice, potential sites are often broadly identified in the planning phase, providing general indications of possible locations. Ideally, this process should draw on principles outlined in steps 1 to 4 above. This step then is about defining the precise locations and extent of sites, considering the following factors:

- Donor sites:
  Identification of location and suitability, drawing on criteria listed under Step 4 above ('Species Selection)';

- Transplant sites.
  Identification of location and suitability. Multiple criteria are employed in this step, the cardinal question to be addressed being: *"Why does seagrass not grow at the site?"* Several sets of factors need to be considered, including water quality (e.g. light availability and nutrient regime), hydrodynamics, sediment geochemistry, sediment stability and slope;

- Seagrass survival and persistence:
  The likelihood of persistent seagrass meadows developing should be considered (Fig. 3). It is best assessed at nearby sites that match the proposed restoration site as closely as possible.

- Consider costs:
  Where possible, reduce project costs by planting in intertidal and shallow subtidal areas in the first instance; seagrass can subsequently grow deeper into the subtidal zone; and

- Reference meadows
  Identify control sites against which performance of restored areas can be gauged.

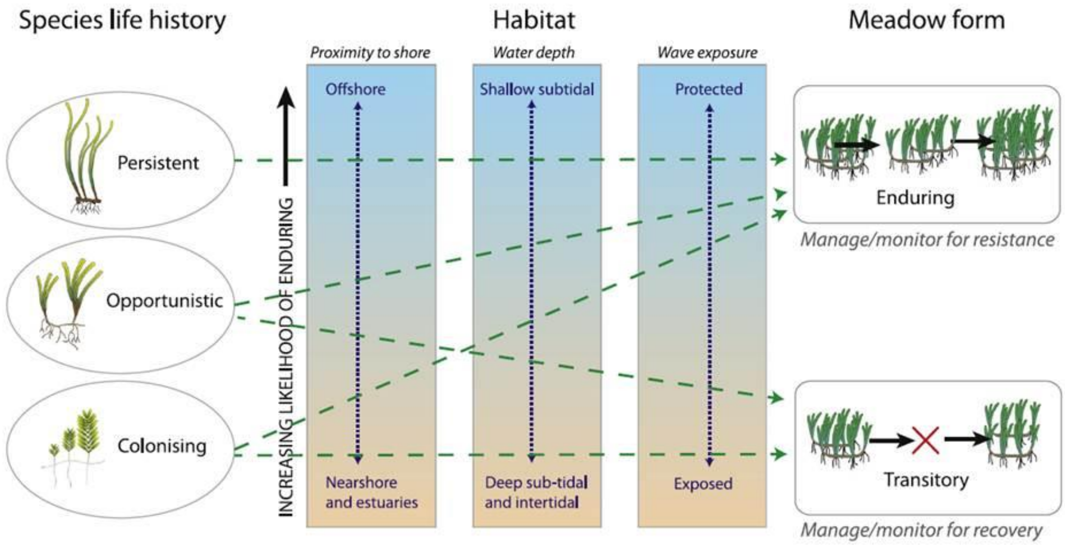

Fig. 3. Habitat characteristics and seagrass life history type dictate the likely form of the meadow. Meadows that exist at, or near, their capacity to cope with physiological or anthropogenic influences are more likely to be transitory (source: Kilminster et al. (2015)).

Step 6: Time Selection

The timing of the transplant works should consider:

- Maximising light availability
- Avoiding seasonal pulses in turbidity, and freshwater run-off
- Avoiding peak times of human disturbance and interference
- Matching natural growth cycles, occurrence of fruit and flowers
- Taking advantage of any predictable longer-term climate patterns (e.g. El Niño events).

Step 7: Identifying Risks and Planning for Mitigation

Identify and assess options for reducing risks of failure. For example, although sites subject to active dredging are likely to be avoided, unexpected intense vessel activity could occur. Mitigation of potential disturbances can be encouraged through, for example, the use of physical buffers in the sea to protect newly restored seagrass habitat.

Step 8: Method Selection

The most suitable method will be different for each location and species. However, understanding the advantages and disadvantages of each method that can *potentially* be used, enables practitioners to select the method likely to best fit the specific project needs in a local setting. Table 1 outlines the key advantages and disadvantages of common methods.

Table 1. Common methods of seagrass restoration and their advantages and disadvantages. Listed in order of their prevalence in Australian projects.

Method*	Advantages	Disadvantages
Transplanting plugs/cores **27%**	• Maintains root and rhizome integrity • Maintains associated fauna	• Damages donor meadow • Larger cores increase survival but also the difficulty in extracting and replanting
Seedlings **14%**	• Very little damage to donor meadow • Management of genetic diversity relatively easy	• Requires aquaculture facilities • Seedling stage more vulnerable to damage and disturbance once planted
Bare root sprigs **9%**	• Collection and temporary storage relatively easy • Removal of any potential parasites, disease or bioturbation	• Potential damage to roots and rhizomes during transfer • Loss of associated fauna • Loss of rhizosphere biochemistry
Turf/mats **6%**	• Maintains root and rhizome integrity • Maintains associated fauna • Maintains chemistry of sediment and porewater	• Larger translocation units can be difficult to extract, handle and replant, and might need specialised equipment.
Enhancement through shoreline alteration only **5%**	• No damage to donor meadows • No need for direct manipulation of seagrass; costs can be low.	• Can disrupt natural hydrodynamics
Seeds **4%**	• Very little damage to donor meadow • Management of genetic diversity relatively easy	• Potentially high rates of loss due to seed herbivory • Dormancy/germination issues • Collection difficulties (availability can be problematic in subtropical waters for many species)

*Percentages represent the proportion in Australian studies (note: 35% of studies did not report method)

When selecting a method, the following should be considered:

- Cost, potential risks, and seagrass species;
- Evaluation of previous successes in similar environments and for similar species; and
- The results of small-scale feasibility trials.

Step 9: Perform Restoration Works

Restoration work should begin after steps 1–9 have been investigated and completed adequately.

Step 10: Measure Performance

Measure performance against agreed, and transparently communicated, criteria, using:

- Initial, frequent monitoring using indicators of short-term seagrass responses (e.g. shoot counts, biomass);
- Longer-term monitoring based on seagrass area cover, density and possibly ecological function (e.g. provision of habitat for juvenile fish); and
- Comparisons against patterns of change at reference sites.

In most cases monitoring should also be done at donor sites to determine any effects on meadows following harvesting of plants intended as transplants.

Based on the evaluation of performance, consideration should now turn to repeating Step 1 – 9 to close the adaptive management loop.

3.2 Factors influencing the success of restoration projects

We have reviewed the global literature to identify factors influencing the likelihood of seagrass establishment, survival and growth, conventionally grouped into three categories:

- Abiotic;
- Biotic; and
- Socio-economic (including methodological).

Abiotic factors

The most common abiotic influences on seagrass establishment comprise hydrodynamic conditions, sediment characteristics, and water quality.

Hydrodynamic conditions

Hydrodynamic conditions (e.g. tidal range, current velocity and wave action) are important factors influencing the success of restoration projects (e.g. Inglis (2001), Bos and Van Katwijk (2007)). Strong currents and wave turbulence cause erosion that can uproot or damage seagrass (Schanz & Asmus 2003). Turbulence can also increase turbidity, reducing light (Fonseca et al. 1983, Koch 2001, Wear et al. 2010).

Sediment Characteristics

The physical, chemical, and biological characteristics of the seafloor can influence seagrass germination, survival and growth (Phillips 1974, Valiela 1984, Short 1987, Barko et al. 1991, Halun et al. 2002). Sediment grain size, in particular, influences oxygen diffusion, rhizome elongation, concentrations of nutrient and chemicals toxic to seagrass (e.g. sulfides), and root and rhizome establishment (Chambers et al. 1994, Townsend & Fonseca 1998). Ideally, the sediment characteristics of the donor and transplant sites should match as closely as possible, because strong differences in sediment types between the two sites are likely to inhibit success.

Water Quality

Water quality parameters such as nutrients, contaminants, organic matter and total suspended solids strongly influence the success of restoration projects. Poor water quality resulting from seasonal rainfall can reduce transplant survivorship in the same way that it impedes growth in established meadows (see *Gold Coast Seagrass Sensitivities and Resilience (SRMP-003)* (Connolly et al. 2016a)).

Biotic factors

Biotic factors important to the success of seagrass restoration and rehabilitation projects include: i) activities of burrowing animals (i.e. 'bioturbating fauna' that tunnels and/or digs into the seafloor), ii) grazing, iii) seagrass density, iv) genetic diversity, and v) growth of algae on seagrass (epiphytic algae).

Bioturbation and Direct Grazing

Within GCWs, bioturbating and grazing faunal groups include fish, crabs, shrimp, amphipods, worms and stingrays (Dunn et al. 2014). Bioturbating animals (i.e. those that disturb sediments) have been reported to negatively impact seagrass establishment, survivorship and meadow size/distribution (e.g. Townsend and Fonseca (1998), Valdemarsen et al. (2011)).

Fauna may influence meadows through:

- Burial and manipulation of shoots and seeds;
- Undermining roots;
- Damaging roots or rhizomes;
- Shading through increased suspended sediments; and
- Changing biogeochemical conditions and processes.

Additionally, grazing (i.e. consumption of partial or entire planting units) by fish, dugong and turtles can also diminish restoration success. Paling and van Keulen (2002) suggest that grazing associated with transplants is important for two reasons. Firstly, as transplants are removed from donor meadows and replanted in transplant areas they may become a 'beacon' because they are then the sole food source in an otherwise bare area and are at greater risk of being consumed (Virnstein & Curran (1986), Connolly pers. obs.). Secondly, the lack of mobile epiphytic grazing animals occurring in established meadows, but not accompanying the transplanted units, may allow epiphytes to proliferate. Such an event may increase shading or leaf weight, which may cause leaves to 'settle' and make them more susceptible to burial (Paling & van Keulen 2002).

Bioturbating and grazing fauna can potentially be managed in restoration projects using preventative measures (e.g. caging and matting techniques; Nojima and Aratake (1997), Townsend and Fonseca (1998)) to provide protection from biotic disturbances.

Positive Density Dependence or Positive Feedback

Both the density of seagrass and the size of the meadow can influence the performance of restoration projects (van Katwijk et al. 2016). With increasing densities of planted individuals, and greater total areas planted, the survival percentage increases and population growth rates increase. This is believed to be driven by a 'spreading of risk' to overcome spatial variability, in combination with positive feedback mechanisms (Fig. 4).

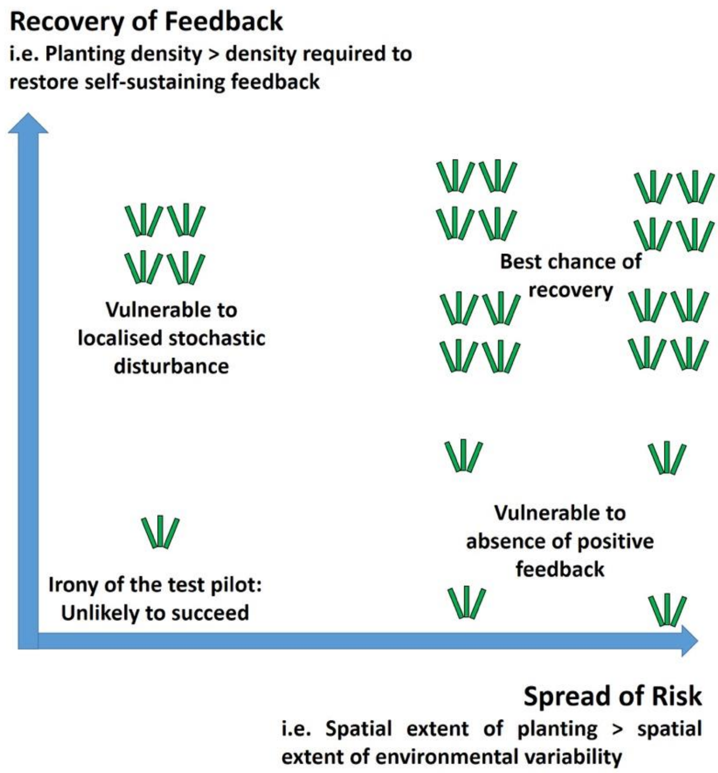

Fig. 4. Conceptual model of how planting density and the size of the meadow influence the likelihood of seagrass establishment (modified from van Katwijk et al. (2016)). Note that whilst small-scale pilot studies have a poorer success rate, they can nevertheless be important to optimise methods for the local situation and hence increase success in larger-scale projects subsequently.

Genetic Diversity

Best practice for seagrass rehabilitation currently recognises the importance of understanding and applying genetic principles (Kettenring et al. 2014). To date, restoration has commonly focused on transplanting seagrass into degraded areas from healthy donor meadows. Where adult transplants are taken from a relatively small area, there is concern that genetic diversity will be low (Reynolds et al. 2011). High genetic diversity has been recognised to convey fitness, stability, and resilience (Montalvo et al. 1997, Reynolds et al. 2012). There is also experimental evidence demonstrating the benefits of genetic diversity in influencing the capacity of seagrass populations to resist stressors such as disease and physical disturbance (Williams 2001).

Understanding the genetic diversity of a population also provides opportunities to match the genotypes of transplants that are likely to be adapted to local site conditions (Dattolo et al. 2013, Sinclair et al. 2014).

Socio-economic (including Methodological) factors

Statton et al. (2012) lists the following social and economic factors:

- Differences in expectations and aspirations among sections of the community;
- Financial constraints on project scope and capability;
- Inadequate site and method selection; and
- Failure to engage with science and scientists. Approaches and technologies that are not science-based or proven in application may lead to costly losses or inefficiencies in planting success.

Financial Obligation/Constraints (project funding)

Seagrass transplantation projects often use labour-intensive and time-consuming manual planting methods, making restoration costly (Paling et al. (2009). Paling and van Keulen (2002) suggest that any seagrass restoration program in Australia should be based on the acceptance that success can only be achieved in sizable programmes that should last five years or more. Such a duration is seen as necessary to develop optimal techniques for local conditions and to measure performance adequately. Logically, this requires matched financial and logistical support.

Method Selection

The method employed can be critical in determining success or failure (Uhrin et al. 2009, Wear et al. 2010, van Katwijk et al. 2016). Decisions need to be made about the donor species, core size, planting method (mechanical versus manual), use of sprigs, plugs or turfs, depth of transplanted seagrass establishment and density of transplants; Gordon (1996), provides a detailed technical treatment of methods.

For example, in a study examining the effects of burial on tropical seagrasses, Ooi et al. (2011) identified that treatments where rhizomes of *Cymodocea serrulata* and *Syringodium isoetifolium* had been severed (as occurs during transplant coring) were less able to cope with burial than those with clonal integration (intact rhizomes). Also, larger planting units have been shown to increase restoration success (e.g. for *Amphibolis griffithii* in Australia (van Keulen et al. (2003), and for *Zostera marina* in Denmark (Olesen & Sand-Jensen 1994)) This is most likely due to improved anchoring capability and physical integration between shoots.

Measuring performance

Performance can be defined in a number of ways, including: i) survival (e.g. per unit, per shoot), ii) area covered, iii) shoot growth, iv) spread rate, and v) provision of an ecological function such as providing habitat for juvenile fish (Paling & van Keulen 2002, Bell et al. 2008, Li et al. 2010). Because there is no single 'correct' measure by which to judge success in restoration projects, it is important to define criteria at the outset and establish agreed goals. Examples of possible goals in transplant projects include (Paling et al. 2009, Lefcheck et al. 2015):

- Returning the site to pre-existing conditions
    - Success should be based on cover, and possibly ecological function, returning to pre-disturbance levels

- Creating a seagrass meadow (of a specific area) at a new site to offset loss elsewhere
    - Success should be measured in meeting targets for the survival and growth of a specific area of seagrass

- Creating a seagrass meadow to perform a specific ecosystem function, such as the promotion of biodiversity
    - Success should be measured in terms of the delivery of the ecosystem services of interest.

4. Assessment of Gold Coast Seagrass Transplant Projects

This section presents a summary of three GCWs seagrass transplant projects performed within the Broadwater between 1997 and 2014:

- Wave Break Island (1997);
- Southport Broadwater Parklands Stage 1 (2009); and
- Southport Broadwater Parklands Stage 3 (2014).

We first describe each project and summarise the key methods, findings, and conclusions. We then evaluate the design and implementation components of these projects against the ten step restoration guidelines proposed in Section 3 of this report. Finally, we discuss the factors that influenced performance of the GCW restoration projects.

4.1 Gold Coast Waterways Transplant Projects

Of the three previous GCWs seagrass translocation projects, Wave Break Island (1997) was primarily an experimental investigation, while the other two were used as environmental offsets associated with foreshore development of the Broadwater Parklands.

Wave Break Island (1997): QLD Department of Fisheries

Project Summary

Seagrass was transplanted on the western foreshore of Wave Break Island in 1997 (27^{o} 56.00' S, 153^{o} 24.50' E) as part of an experimental assessment of the potential for seagrass translocation, in the face of perceived rapid change in seagrass distribution in the southern Broadwater region (McLennan & Sumpton 2005). In August 1997, a suction dredge was used to excavate a hole (1.5 m deep and 30 m x 10 m wide) into which transplants from nearby beds (within 100 m) were to be planted. The excavated hole was left for three months before seagrass transplanting began. Donor seagrass cores were collected from similar depths and transplanted in November 1997. Transplant cores (11 cm diameter; area 95 cm^2) involved 57 mixed cores of *Zostera muelleri* (formerly known as *Z. capricorni)* and *Halophila ovalis,* and 64 cores of pure *H. ovalis* (McLennan & Sumpton 2005). The total area of seagrass transplanted was very small (~ 1 m^2). Cores were planted in a grid pattern with each core being one metre from its nearest neighbour.

Findings from monitoring of transplanted seagrass

Divers measured survival of cores monthly for four months after transplanting, and at eight months made a final assessment of seagrass cover (not of individual cores). Survivorship of cores was initially high, but after four months was < 50%, both for mixed species and pure *H*. *ovalis* cores (Fig. 5). At the final survey (8 months post-transplant), total seagrass cover in the transplanted area was 51%. Most of this seagrass, however, was considered to come from natural colonisation.

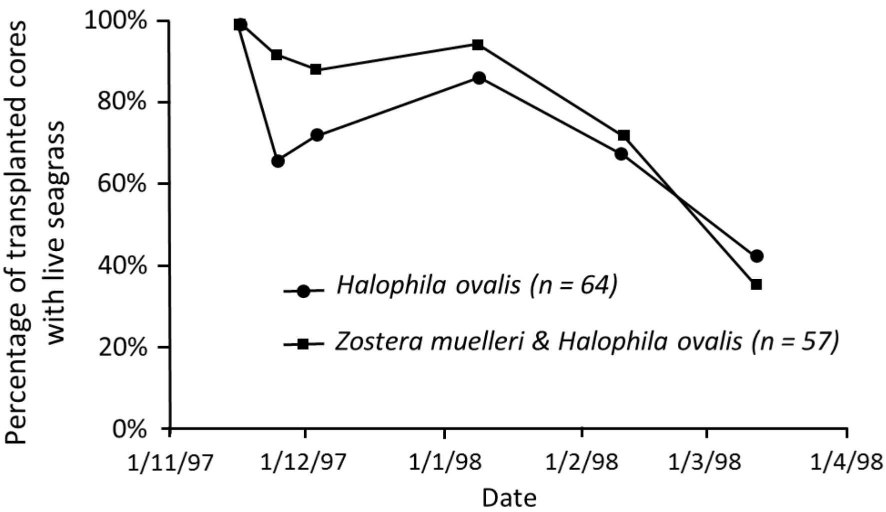

Fig. 5. Changes in the percentage of transplanted cores alive after experimental transplanting at Wavebreak Island (redrawn from McLennan & Sumpton (2005)).

McLennan and Sumpton (2005) report that within two months of transplanting, natural colonisation had occurred at the site, and in some cases seagrass had naturally colonised plots where transplanted seagrass had previously died. The majority of seagrass recorded in the final survey was *H*. *ovalis*, but *H*. *spinulosa*, a species not transplanted to the site, formed the densest single patch. The high rate of natural colonisation and the lack of data on core survival beyond four months limited the conclusions that could be drawn about the longer-term success of transplanted seagrass. It is clear, however, that in GCWs, manipulation of shoreline profiles, including changing the depth of the sea bed, can potentially provide substantial increases in seagrass cover, via natural colonisation.

The concept that transplanting to regions with patchy seagrass distribution might be less likely to succeed, first raised by Fonseca et al. (1994), was mentioned by McLennan and Sumpton (2005). The environmental factors driving patchy distributions can result in cover returning to pre-planting levels regardless of planting effort (Fonseca et al. 1994).

Southport Broadwater Parklands Stage 1 (2009): City of Gold Coast

Project Summary

In 2007, reclamation works planned for the Southport Broadwater Parklands Project were expected to destroy ~ 10,000 m^2 of seagrass (Biome 2007). As one of a number of environmental offsets, it was ultimately decided to transplant a small fraction of this seagrass to another site. In May 2009 Australian Wetlands performed the seagrass transplantations. An area of 833 m^2 of *Zostera muelleri* was removed and replanted into unvegetated areas (between sparse patches of naturally occurring *Z. muelleri and H. ovalis*) at a translocation site, alongside a newly constructed mangrove wetland (Fig. 6). Within the translocation zone, natural seagrass area totalled 1,931 m^2 (Australian Wetlands 2009).

The reported intent of the transplantation project was to assist natural regeneration of seagrass along the western shores of the Broadwater by transplanting small amounts of seagrasses which would have otherwise been destroyed during dredging and reclamation (VDM Consulting 2010). Prior to the transplant works (2009), the transplant area (Fig. 6) was described as being influenced by a number of anthropogenic factors including high turbidity, sedimentation, bioturbation, nutrient loading from runoff, dredging, and boat traffic (VDM Consulting 2010). There was a suggestion that the construction of the mangrove wetland would improve the quality of stormwater inputs at the site, improving nearby conditions for seagrass growth.

It is also worth noting that numerous crab holes were evident in existing intertidal seagrass meadows, and that stingrays were also very common (VDM Consulting 2010). Crabs and rays can both have a potentially significant effect on seagrass through their disturbance of the sea bed while feeding, a factor known to reduce the growth and survivorship of new and establishing seagrass meadows (e.g. Valentine et al. (1994), Fonseca et al. (1996), DeWitt (2009)).

Fig. 6. Constructed mangrove wetland and translocation area, Southport Broadwater Parklands Stage 1. Lower left and lower right images illustrate the general seagrass translocation area (VDM Consulting 2010) before (26 July 2008) and after construction of the mangrove wetland (30 April 2009) (Google Earth 2016).

Findings from monitoring of transplanted seagrass

Seagrass distribution and health was surveyed twice after transplanting. The first survey was in October 2009, five months after planting (Australian Wetlands (2009). Approximately 175 m^2 of the transplant site was observed to contain seagrass transplants. There was some attempt to also quantify density, with 130 m^2 recorded as having 1-2 plugs per m^2, and another 45 m^2 recorded as containing 'denser' seagrass, but without quantification. Overall, this represents a substantial loss of transplanted seagrass, with only ~ 20% of the original transplant area remaining (175 m^2 of an initial 833 m^2). Given the period of five months between transplanting and monitoring, the causes of seagrass loss are necessarily speculative. Australian Wetlands (2009) attributed losses to currents and wave action, and to reduced water clarity caused by significant inflows from the Nerang River immediately after completion of transplant activities (162 mm of rainfall recorded at the nearest weather station 19-24 May 2009). Additionally, a new sandbar formed in the southern part of the transplant zone during the five months, smothering transplanted seagrass (Australian Wetlands 2009).

The transplant site was resurveyed in August 2010 (15 months post-transplant) to assess seagrass distribution and abundance (VDM Consulting 2010). This survey reported a *total* of 1,229 m^2 of seagrass, with no distinction made between transplanted seagrasses and natural seagrass that existed prior to transplanting. This total area is less even than the 1,931 m^2 of pre-existing seagrass present at the site prior to transplanting (Biome 2007), and there is therefore no evidence of any benefit from the transplanting project.

Southport Broadwater Parklands Stage 3 (2014): City of Gold Coast

Project Summary

In 2014, a major land reclamation project as part of the Southport Broadwater Parklands Stage 3, meant that ~3,000 m^2 of seagrass habitat was to be permanently removed and converted to terrestrial parkland (Fig. 7 & Fig. 8). Between August and October 2014, approximately 238 m^2 of this seagrass was translocated from six donor sites to the same general area used in the previous restoration attempt (Stage 1) (Element Ecology 2014a). The seagrass was translocated as 13,455 cores (15 cm diameter; area 177 cm^2), into a shallow subtidal patch alongside existing seagrass. Transplanted cores consisted predominantly of *Halophila ovalis*, with some *H*. *spinulosa* and *Zostera muelleri* (Element Ecology 2014b).

Element Ecology (2014) acknowledged a number of factors that may affect the survivorship and success of the transplanted seagrasses. These were: (i) increased light exposure and desiccation due to a differences in water depth between the donor and translocation sites (with the translocation site being shallower); (ii) storm damage, noting the influence that storm associated flooding and wave action was believed to have had on the 2009 translocation efforts in particular; (iii) root and rhizome damage during the translocation process, or from differences in substrate characteristics between the sites (e.g. the donor site was predominantly mud-silt while the translocation site was mostly sandy substrate); (iv) human trampling, and; (v) the presence of marine fauna, such as stingrays.

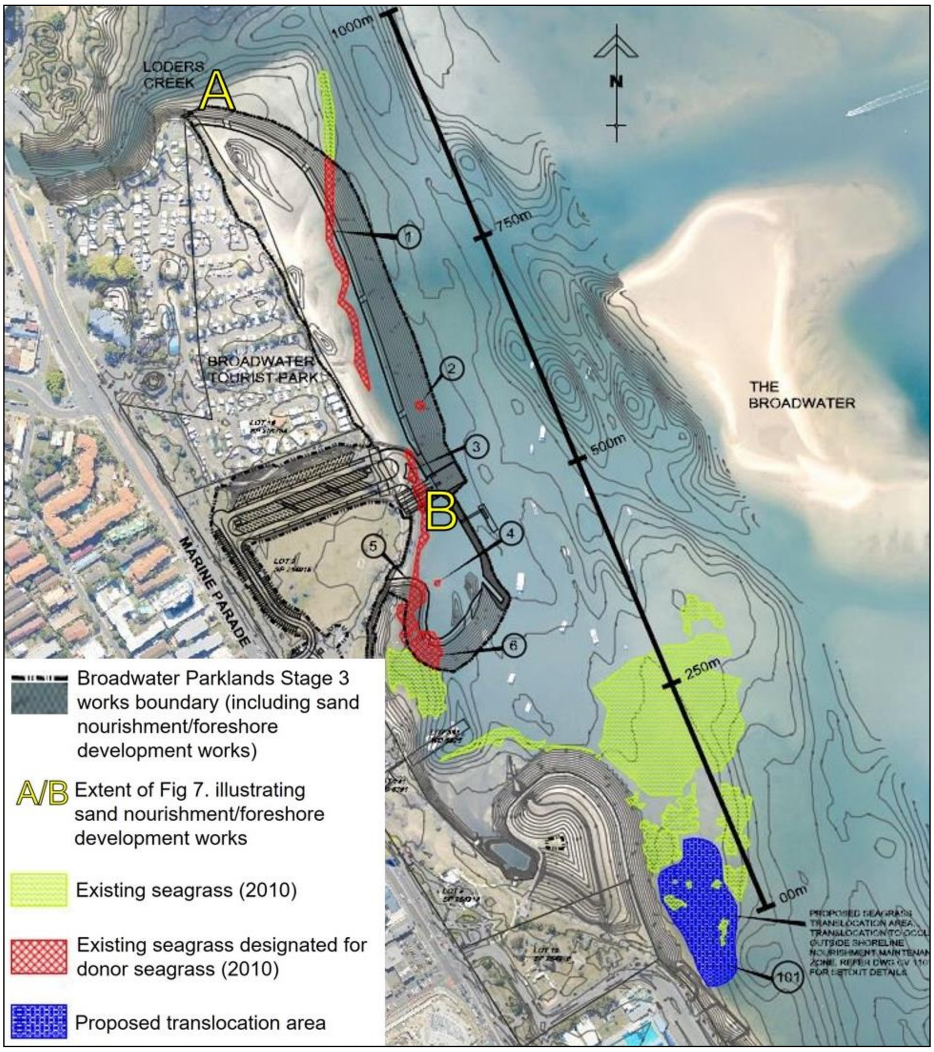

Fig. 7. Southport Broadwater Parklands, Stage 3, showing proposed foreshore development, seagrass to be lost, donor sites (1-6), and translocation area (modified from Element Ecology (2014b)). Letters A & B indicate positions shown in Fig. 8.

Fig. 8. Aerial photograph illustrating progress of the foreshore development area in September 2015 (outlined by yellow boundary) as part of the Southport Broadwater Parklands Stage 3 (photo: R Connolly).

Findings from monitoring of transplanted seagrass

To date, only a single monitoring event has been undertaken, in November 2014, one month after transplanting. This was reported as a preliminary assessment ('baseline photo-monitoring' (Element Ecology 2014a)), and identified new growth and rhizome development in at least some of the transplanted seagrass cores (Element Ecology 2014a). However key metrics of performance, such as changes in seagrass cover, biomass, or proportion of cores alive, were not measured.

At the time of this first survey, it was anticipated that photo-monitoring would also be conducted at about 6 and 12 months after transplanting (i.e. March and October 2015), to assess seagrass cover and biomass (Element Ecology 2014a). It has subsequently been reported that a combination of poor water clarity and the presence nearby of on-going construction works resulted in the abandonment of both of these planned monitoring events (J. Hall, City of Gold Coast, pers. comm.). Further monitoring anticipated for April 2016, representing a 17 month period between the transplant works and monitoring, also did not proceed (J. Hall, City of Gold Coast, pers. comm.). This lack of post-transplant monitoring was one of the reasons we undertook an additional, in-water field survey of the Stage 3 transplanting area in September 2016, as part of the current project, with findings reported below.

4.2 Gold Coast Waterways Transplant Project Assessment

The ten step guide presented in Section 3 represents a best-practice guide for seagrass restoration, against which we have compared the previous GCWs projects (see Table 2). This assessment is designed to detect aspects addressed adequately and any shortcomings with a view to informing future restoration projects.

The principle deficiencies and limitations of these projects are that:

- Although each project demonstrated some level of understanding of the restoration literature, none appeared to include assessments of habitat suitability, light availability or sediment stability, nor of habitat connectivity (e.g. potential for natural recolonisation), dynamics of natural seagrass populations, or of genetic diversity;
- No field, experimental or modelling approaches were used to address knowledge gaps prior to restoration;
- No rationale or justification behind seagrass species selection was evident (i.e. use of pioneer versus climax species, or species characteristics suitable for the site);
- There were no attempts to compare environmental conditions or habitat suitability at donor and transplant sites, which is still important despite these sites being close together;
- There was no explanation or justification of the timing of the transplanting (e.g. to avoid periods of poor water clarity during the wet season, or to take advantage of natural growth cycles or of fruiting and seed production);
- While some risks to project success were investigated (e.g. identification of bioturbating fauna and potential influences from storm damage and human trampling), no countermeasures were discussed or reported (such as exclusion matting or cages to minimise bioturbating and grazing fauna);
- No small scale feasibility trials were reported for Broadwater Parklands projects, despite concerns raised earlier by McLennan and Sumpton (2005) of potential difficulties transplanting seagrass on the western side of the Broadwater;
- The method of translocating seagrass was not justified or discussed in any detail;
- There was insufficient monitoring of short-term indicators to facilitate potential adaptive restoration measures; and
- There was insufficient monitoring of longer-term indicators. Hence, it was not possible to determine rigorously whether the seagrass transplantation was successful or to understand the causes behind a lack of transplant success.

Table 2. Comparison of Gold Coast waterways seagrass restoration projects against the 10 step restoration guidelines.

10 step guidelines		Wave Break Island, Broadwater (1997)	Southport Broadwater Parklands (2009): Stage 1	Southport Broadwater Parklands (2014): Stage 3
Step	***Description***			
1	Establish goals and objectives	Not clearly defined	Reported objective was to offset losses of seagrass associated with reclamation works by assisting natural regeneration through transplant efforts as part of a development approval	Reported objective was to preserve and enhance marine habitats through transplant efforts as part of a required offset
2	Literature review	Not defined	Demonstrated a limited literature review (e.g. acknowledged possible causes of seagrass loss, species present, potential donor site and transplant site attributes) No reported assessment of habitat suitability, light or sediment transport observations/modelling, habitat connectivity, natural population dynamics, or genetic diversity	Demonstrated a limited literature review (e.g. acknowledged species present and potential donor site attributes) No reported assessment of habitat suitability, light or sediment transport observations/modelling, habitat connectivity, natural population dynamics, or genetic diversity
3	Address knowledge gaps	No reported attempt to fill knowledge gaps through field, experimental or modelling approaches	No reported attempt to fill knowledge gaps through field, experimental or modelling approaches	Field surveys assessed site condition for both the donor and transplant sites, including: seagrass distribution, density and species at donor site and identifying areas suitable for planting at the transplant site No reported attempt at experimental or modelling approaches
4	Species selection	No reported justification of suitable species or natural meadow dynamics	No reported justification of most suitable species or natural meadow dynamics	No reported justification of most suitable species or natural meadow dynamics
5	Site selection	Not specified	Commentary on site selection included proximity to constructed mangrove stand (designed to improved water quality) and area re-profiling for suitable transplant site	Commentary on site selection included site inspection but no evaluation of potential alternative locations

10 step guidelines		Wave Break Island, Broadwater (1997)	Southport Broadwater Parklands (2009): Stage 1	Southport Broadwater Parklands (2014): Stage 3
Step	*Description*			
6	Time selection	No reported justification (August [spring])	No reported justification (May [autumn])	No reported justification (August-October [winter–spring])
7	Identify risks	None reported	Some risks reported (e.g. field survey identified bioturbating fauna, observable impacts of reduced light resulting from nutrient loading and suspended sediments, sedimentation, vessel traffic) No discussion of countermeasures	Some risks reported (e.g. decreased exposure to light, desiccation, different substrates between sites, storm damage, trampling and marine fauna) No discussion of countermeasures
8	Method selection	No reported justification. Small scale feasibility trial.	No reported justification.	Commentary provided regarding methodology (e.g. donor core collection from seagrass patches of high density which was expected to result in greater seed material for transplants, and improve likelihood of survival) Methodological improvements and realised benefits discussed No small scale feasibility trials and assessment reported
9	Perform restoration	Work undertaken August 1997	Work undertaken May 2009	Work undertaken August–October 2014
10	Measure performance	Monthly monitoring for four months, followed by a survey eight month post-transplant Success defined as percentage of cores having live seagrass, and area coverage (only at final survey) No long-term monitoring	No short-term monitoring reported Two surveys, 5 and 14 months following transplant efforts. No ongoing monitoring Success defined as density of seagrass within transplant area Monitoring not sufficient to determine success of transplant efforts	Immediate short term monitoring reported (one month post-transplant) No long-term monitoring reported (an event is planned at ~ 17 months post-transplanting) Monitoring not sufficient to determine success of transplant efforts

5. Field Survey of Restoration and Sand Nourishment Sites

The aim of this section is to assess the current status of seagrass in five Broadwater 'reporting zones' associated with previous nourishment or mitigation projects (Table 3). Findings are presented from seagrass surveys completed as part of the 2015 GCWA Scientific Research and Management Program. For a description of survey techniques and mapping methodology readers are referred to those reported in Connolly et al. (2016b).

Table 3. Broadwater reporting zones and their relationship to previous foreshore nourishment and/or mitigation projects.

Reporting zone		Zone history	Associated zone project/s (year)	Reference
1	Wave Break Island	Seagrass transplant	Seagrass transplant trial project (1997)	McLennan and Sumpton (2005)
2	Broadwater Parklands	Sand nourishment/ foreshore development	Broadwater Parklands Stage 1 (2009)	Australian Wetlands (2009), VDM Consulting (2010)
3	Broadwater Parklands	Seagrass transplant and sand nourishment/ mangrove habitat creation	Broadwater Parklands Stage 1 (2009) & Broadwater Parklands Stage 3 (2014)	Australian Wetlands (2009), VDM Consulting (2010) Element Ecology (2014a)
4	Broadwater Parklands	Sand nourishment/ foreshore development	Broadwater Parklands Stage 3 (2014)	Element Ecology (2014a)
5	Southwest Marine Stadium	Sand nourishment/ foreshore development	Nourishment (2013)	Analysis of historical Google Earth imagery (see Appendix)

5.1 Survey Results and Discussion

Seagrass species composition, above-ground biomass, and percent cover were determined for each reporting zone. Adjacent areas were also considered because they may influence (or be influenced by) reporting zones through seed dispersal. Seagrass percentage cover is reported as: sparse = 0.1-25%; moderate = 26 – 50%; moderately dense = 51 – 75% and dense = 76 – 100%. In the field surveys, no distinction could be made between pre-existing and transplanted seagrasses in reporting zones. We have, however, used local knowledge of changes in site profiles and depths to interpret any potential evidence about transplanted or naturally colonising seagrass. We also undertook additional in-water field surveys of Reporting Zones 3 & 4 (Table 3) in August/September 2016, and report those findings below in the relevant subsections.

Seagrass was present in four of the five zones (Table 4; Fig. 9 – Fig. 14) with six seagrass species being identified (*Zostera muelleri*, *Halodule uninervis*, *Cymodocea serrulata*, *Cymodocea rotundata*, *Halophila ovalis* and *Halophila decipiens*). A summary of survey results for each zone is provided below.

Table 4. Characteristics of seagrass within the five Broadwater reporting zones. Area is the total seagrass area within the reporting zone; Meadow ID # is the meadow identification number indicated on figures in this section; % cover and biomass represent the percent cover and above-ground biomass respectively, and Fig. is the relevant figure number in this report.

Reporting zone	Species present	Area (ha)	Meadow ID #	% Cover			Biomass (g DW m^{-2})		Fig.
				Range	Mean ± 1SE	Density	Range	Mean ± 1SE	
Wave Break Island	*C.r, Z.m, C.s, H.u, H.o*	7.31	150	5 - 80	51.3 ± 18.1	Moderately dense	5.2 – 23.0	17.0 ± 4.1	Fig. 9
Broadwater Parklands Stage 1	*Z.m, H.o*	0.17	166	8 - 30	14.3 ± 5.3	Sparse	16.9 – 44.0	30.5 ± 5.7	Fig. 10
Broadwater Parklands Stage 3a	*Z.m, H.o*	0.28	165	8 - 30	19.0 ± 11.0	Sparse	0.3 – 31.6	15.9 ± 15.6	Fig. 11
Broadwater Parklands Stage 3b	*H.u, H.o*	0.12	165	1 - 5	3.0 ± 2.0	Sparse	0.1 – 0.7	0.4 ± 0.2	Fig. 12.
Southwest Marine Stadium	–	–	–	–	–	Absent	–	–	Fig. 14.

Species code: *C.r* = *Cymodocea rotundata*, *C.s* = *Cymodocea serrulata*, *H.o* = *Halophila ovalis*, *H.d* = *Halophila decipiens*, *H.s* = *Halophila spinulosa*, *H.u* = *Halodule uninervis* and *Z.m* = *Zostera muelleri*,

Wave Break Island

The Wave Break Island zone contained four moderately-dense aggregate seagrass patches covering. These were situated in depressions and channels on the sand flat (Table 4; Fig. 9). The meadows were dominated by *C. rotundata* and *Z. muelleri*, with *C. serrulata*, *H. uninervis* and *H. ovalis* also present. Nearly two decades after the 1997 transplant trial, seagrass is distributed widely in the vicinity of the trial location; however no assessment can be made as to whether any of the current seagrass derived from the transplants.

Broadwater Parklands Stage 1

This reporting zone represents the sand nourishment/foreshore development area associated with the Broadwater Parklands Stage 1 development. A thin strip of seagrass adjacent to the shoreline in the low intertidal zone was observed in this zone (Table 4; Fig. 10). This strip (Meadow 166) contained aggregations of sparse patches (14.3 ± 5.3% cover) dominated by *Z. muelleri* with a small percentage of *H. ovalis* also present. This meadow occurs on the foreshore realigned in 2010. Prior to that, this habitat was in deeper water, in a zone known to support *H. ovalis* but not *Z. muelleri* (Cuttriss et al. 2013). Given that the seagrass now occurs in the intertidal and shallow subtidal zones, and is dominated by *Z. muelleri*, we conclude with certainty that seagrass has colonised the realigned foreshore naturally in the intervening five years. Some of this seagrass, but not all, was noted in an inspection of the shoreline by VDM Consulting (2012) in April 2012, and it seems clear, therefore, that some natural colonisation had occurred within 2 years of foreshore realignment.

The seagrass transplanted during Stage 1 was placed near the constructed mangrove wetland, immediately adjacent to the transplant area for Stage 3, and the relevant findings from the survey are reported below under Broadwater Parklands Stage 3a.

Broadwater Parklands Stage 3

Two reporting zones are presented for the Broadwater Parklands Stage 3 footprint area. The first represents a zone associated with seagrass transplant efforts and sand nourishment/mangrove habitat creation and the second zone represents a sand nourishment/foreshore development area. Hereafter for reporting purposes these zones are referred to as Broadwater Parklands Stage 3a and Broadwater Parklands Stage 3b, respectively. The Stage 3 reporting zones include the constructed mangrove wetland and correspond to the seagrass transplantation project area as part of Stage 1.

Broadwater Parklands Stage 3a

This area contained a thin strip of sparse seagrass patches (Meadow 165, Fig. 11) adjacent to the constructed mangrove wetlands. These patches were found in the intertidal and shallow subtidal zones (Table 4; Fig. 11). The meadow was dominated by *Z. muelleri* with some *H. ovalis*, which matches species observed during previous surveys in the same area (Sillars 2011, Ebrahim 2012, Henkelmann 2012, Element Ecology 2014b). However a third species, *H. spinulosa*, previously recorded in the area and which was also transplanted during Stage 3, was not reported at all from this meadow. An additional meadow (164) of sparse seagrass was recorded in deeper water, adjacent to the reporting zone. A meadow in this area has previously been reported (see VDM Consulting (2012), Cuttriss et al. (2013), Element Ecology (2014a)).

At the scale of mapping performed during this broad regional study, we can conclude that seagrass is growing in the general vicinity of transplant sites for both Stage 1 and Stage 3, but it is not possible to determine whether this seagrass derives from the translocated plants of either stage.

Given the larger scale and more recent timing of Stage 3 transplanting, and the lack of post-transplant monitoring of this site, we undertook an additional in-water field survey of the Stage 3 site in August 2016. A comparison of the current seagrass distribution against detailed, fine-scale maps of transplanted areas shows that very little seagrass remains in transplanted areas. Just eight small, individual seagrass plants were found precisely where transplanted shoots were placed (6 of *Z. muelleri* and 2 of *H. ovalis*).

Broadwater Parklands Stage 3b

No seagrass was recorded along the newly aligned foreshore in the central and northern parts of the reporting zone (Fig. 12). This is an area where the foreshore continued to be actively filled with dredge material up until the time of the survey. Seagrass was observed at the southern end of the reporting zone in the form of an extension of Meadow 165 (described above in Broadwater Parklands Stage 3a) (Table 4; Fig. 12), but this is not where the Stage 3 foreshore realignment occurred.

Given that realignment of this foreshore was ultimately completed in late October 2015 (three weeks after the main seagrass survey), we undertook an additional, in-water field survey of seagrass in August 2016, 10 months later (Fig. 13). No seagrass was found on the newly developed shoreline. Three small, sparse patches of seagrass (mixed stands of *Z. muelleri* and *H. ovalis*) were present at the northern end of the survey area, but these are just outside the nourished area and were present prior to the realignment.

In summary, we now have two key pieces of evidence for the potential for natural colonisation of nourished, realigned foreshores in the Broadwater. We infer from past surveys of the Stage 1 nourishment project that seagrass colonisation occurred within 2 years of foreshore realignment. And we conclude from the Stage 3 nourishment site that colonisation did *not* occur within 10 months of works being completed. This points to an approximate expectation of colonisation between 1 – 2 years after nourishment, at least for the two common species *Z. muelleri* and *H. ovalis*.

Southwest Marine Stadium

No seagrass was observed during surveys of the Southwest Marine Stadium reporting zone. This area is a hydrodynamically energetic environment that has been subject to sand nourishment (Table 4; Fig. 14). A thin, moderately dense *H. ovalis* mixed species seagrass meadow (156) was observed near to the reporting zone (i.e. <100 m), but that is within the less hydrodynamically energetic area inside the Marine Stadium. We conclude, therefore, that seagrass has been unable to colonise the nourishment site itself, probably because of the very dynamic sand movement.

Fig. 9. Seagrass meadows located in and adjacent to Wave Break Island (seagrass transplant associated zone). Patches of dark colouration not reported as surveyed seagrass can be areas of, among other things, rock substrate, mud or discoloured sand, or macroalgae either attached or drift.

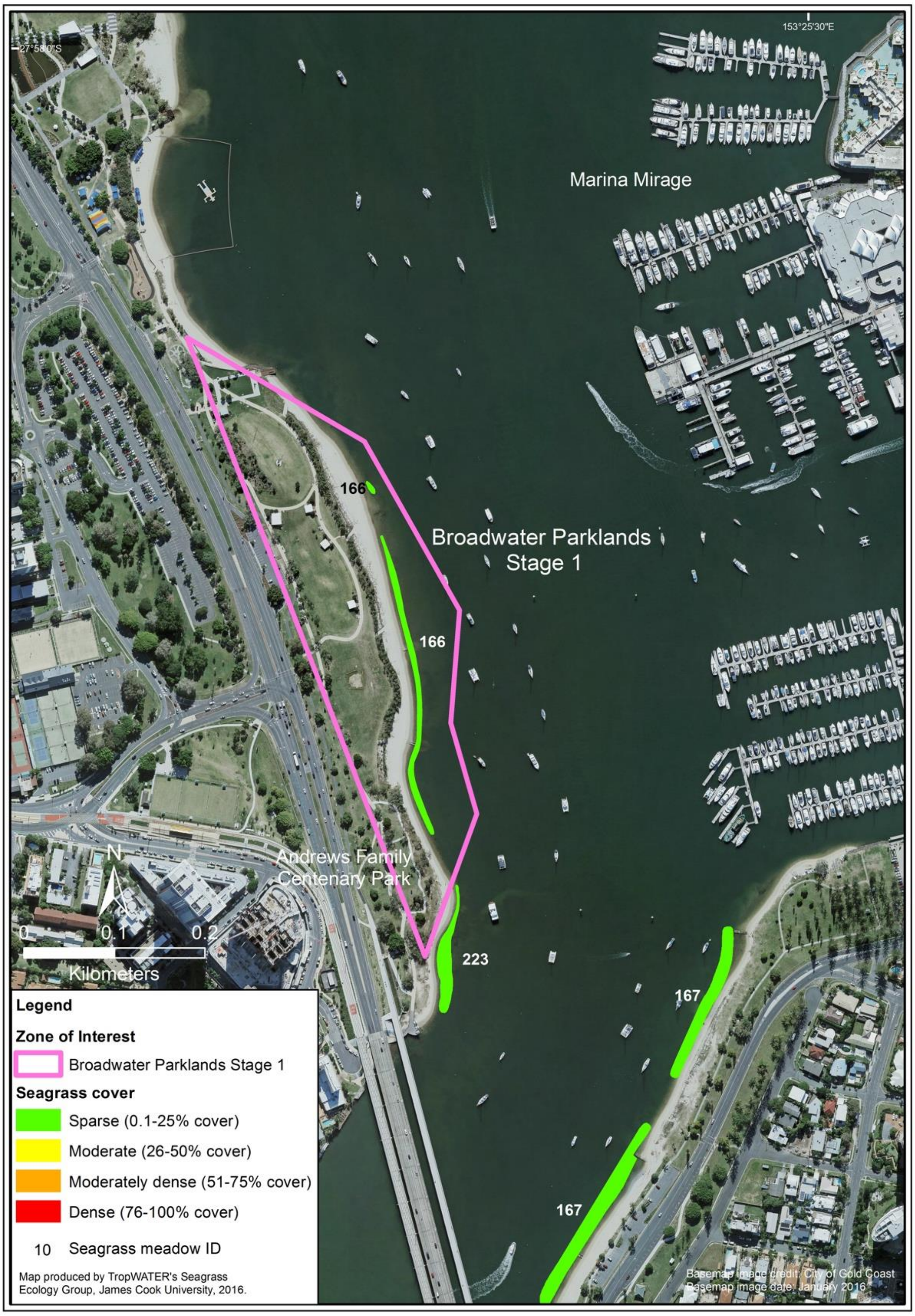

Fig. 10. Seagrass meadows located in and adjacent to Broadwater Parklands Stage 1 (sand nourishment, foreshore development zone). Patches of dark colouration not reported as surveyed seagrass can be areas of, among other things, rock substrate, mud or discoloured sand, or macroalgae either attached or drift.

Fig. 11. Seagrass meadows located in and adjacent to Broadwater Parklands Stage 3a (seagrass transplant, sand nourishment, mangrove habitat creation zone). Patches of dark colouration not reported as surveyed seagrass can be areas of, among other things, rock substrate, mud or discoloured sand, or macroalgae either attached or drift.

Fig. 12. Seagrass meadows located in and adjacent to Broadwater Parklands Stage 3b (sand nourishment, foreshore development zone). Patches of dark colouration not reported as surveyed seagrass can be areas of, among other things, rock substrate, mud or discoloured sand, or macroalgae either attached or drift.

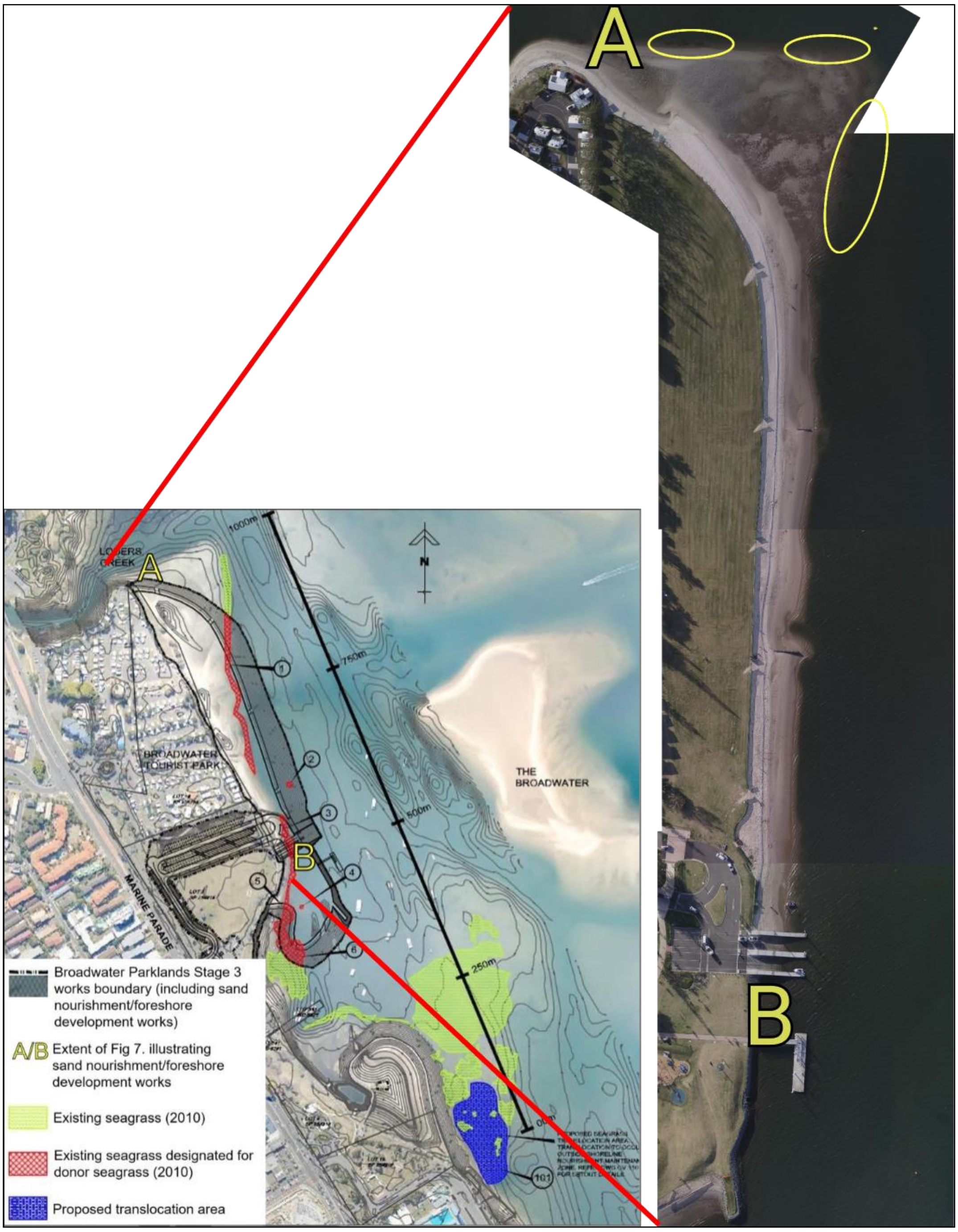

Fig. 13. Findings of additional seagrass survey, Southport Broadwater Parklands, Stage 3. Left side, plan of foreshore development, existing seagrass in green (modified from Element Ecology 2014b). Right side, aerial imagery of Parklands foreshore in August 2016, 10 months after completion of nourishment works. Yellow circles indicate the location of the only seagrass present in August 2016, which are all meadows that existed prior to the realignment and were unaffected by the nourishment work.

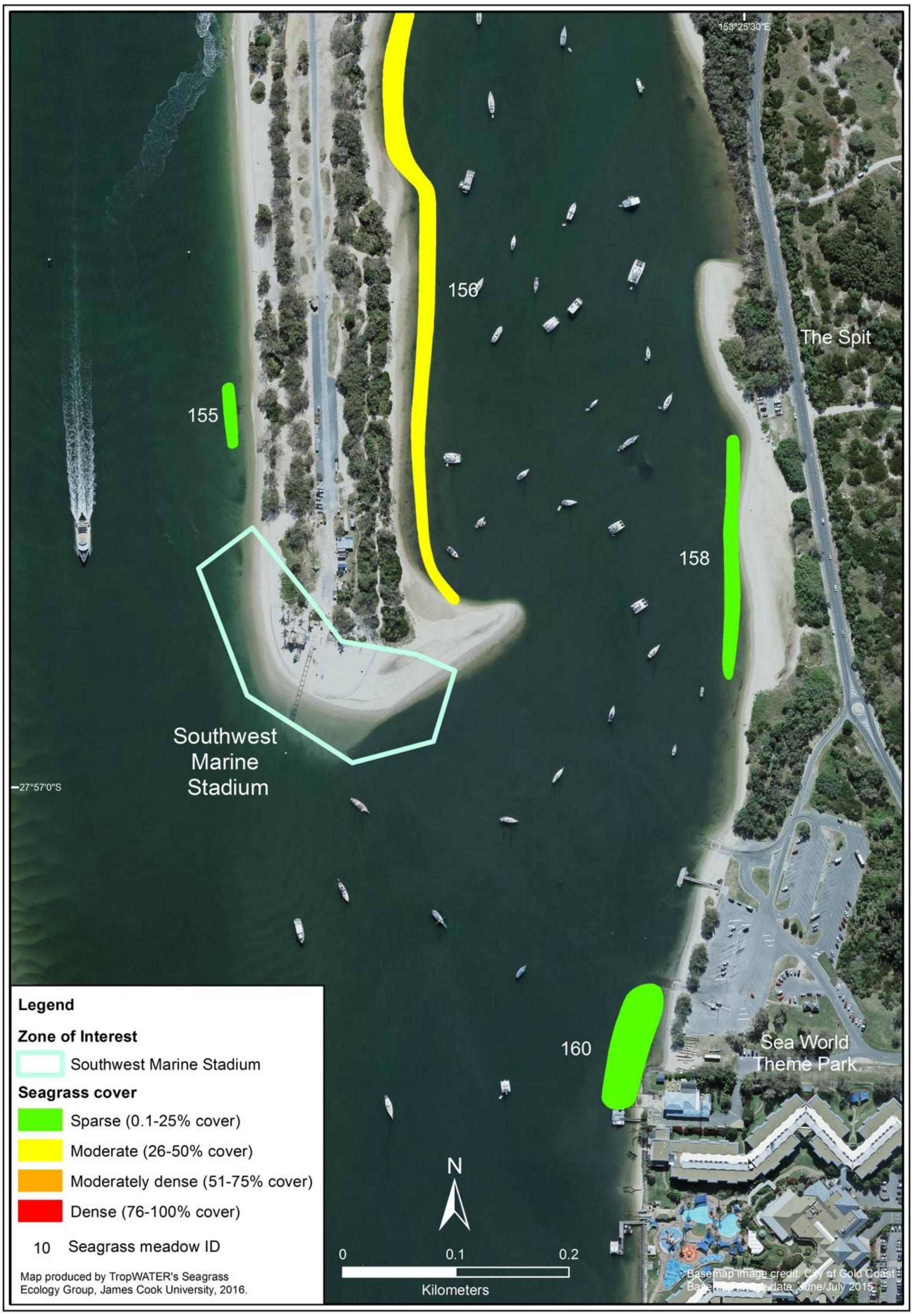

Fig. 14. Seagrass meadows located in and adjacent to Southwest Marine Stadium (sand nourishment zone). Patches of dark colouration not reported as surveyed seagrass can be areas of, among other things, rock substrate, mud or discoloured sand, or macroalgae either attached or drift.

6. Potential Enhancement of Ecosystem Services

This section presents a preliminary assessment of the potential to enhance ecosystem services as part of sand nourishment projects. Here we consider fisheries habitat area values, through proactive management of Broadwater channels, banks, foreshore profiles, and seagrass growth and connectivity with other vegetated habitats.

Although it is recognised that seagrass, mangrove and saltmarsh habitats individually, and collectively, provide important ecosystem services, we specifically address services provided by seagrass (Table 5). The effects of spatial relationships amongst seagrass meadows and patches of mangrove and saltmarsh habitat are also taken into consideration (i.e. habitat connectivity).

Table 5. Ecosystem services provided by seagrass.

Ecosystem services		Key reference
Provisioning services		
	Nursery and habitat for fisheries species	Beck et al. (2001), Jackson et al. (2001)
	Support fisheries and macrofauna diet (e.g. food webs)	Jackson et al. (2001), Jackson et al. (2015)
	Macrofauna food source	De longh et al. (2007), Sheppard et al. (2007)
	Food security	Cullen-Unsworth et al. (2014)
Regulating services		
	Primary production	Costanza et al. (1997), Duarte and Chiscano (1999), Green and Short (2003)
	Carbon sequestration	Macreadie et al. (2014)
	Nutrient cycling	Wood et al. (1969), Bach et al. (1986), Lotze et al. (2006)
	Trapping and stabilising sediment	Koch et al. (2009)
	Protection against wave damage caused by storms, cyclones and tsunamis	Barbier et al. (2008), Barbier et al. (2011)
	Trophic subsidies to near and distant locations	Heck et al. (2008)
Supporting/cultural services		
	Grazing area for charismatic herbivores (e.g. dugong, turtles)	Beck et al. (2001), Unsworth et al. (2007)
	Maintenance of biodiversity and beneficial species	Duarte (2000), Cullen-Unsworth et al. (2014)
	Tourist attraction	Cullen-Unsworth et al. (2014)
	Provide areas important for recreation	Cullen-Unsworth et al. (2014)
	Significance to aboriginal owners	Cullen-Unsworth et al. (2014)

Estuarine areas such as the Broadwater and coastal rivers of the Gold Coast are dynamic systems forced by tidal currents, freshwater flow and wave action. These hydrodynamic factors influence sediment transport processes and bathymetry (i.e. depth) across the system. The location and persistence of channels, shoals, sandbanks, foreshore profiles and intertidal water depths may also be transformed through human intervention, especially in attempts to maintain navigable waterways or develop foreshore facilities. Such channels and sandbanks provide important settings for the establishment of marine plants and provide habitat for associated fauna.

Channel features are important for two reasons. Firstly, channels allow for tidal exchange of relatively clear seawater through ocean entrances such as Jumpinpin Bar and the Gold Coast Seaway. This frequent inundation of relatively clear and low nutrient seawater increases seagrass health within the Broadwater. Secondly, channels provide ease of passage for fish into and through the system, particularly at low tide.

Sand banks are fundamentally important features for seagrass habitat because GCWs are generally at the poor end of seagrass water clarity tolerances. Thus, the vertical distribution of seagrass is quite narrow, making the presence of shallow banks within the Broadwater necessary for seagrass growth. Results from the *Marine Plant Habitat Survey & Monitoring Program SRMP-002* project (Connolly et al. 2016b) indicated that the deepest seagrass species within GCWs was *H. ovalis*, occurring 4.27 m below AHD (Australian Height Datum).

The upper limit of seagrass habitat is primarily regulated by seagrass tolerance to desiccation at low tide (Koch & Beer 1996). The lower limit, however, is regulated by available incident radiation and light attenuation in the water column (Kilminster et al. 2015). The horizontal distance between these upper and lower growth limits governs the amount of suitable substrate. For example, where the upper and lower growth limits are separated by large horizontal distances (e.g. in a gently sloping intertidal zone), large areas are available for seagrass habitat. On the other hand, small distances between vertical limits (e.g. in a sharply sloping foreshore) compress the available area suitable for seagrass growth (Fig. 15). As such, foreshore slope is influential in dictating the area of suitable habitat but not the presence of seagrass. This is because all foreshore slopes on soft-sediment substrates have the potential to provide opportunity for seagrass growth, irrespective of the degree of slope[1], were water, sediment and hydrodynamic conditions are favourable (Silberstein et al. 1986, Fourqurean et al. 1992, Koch 2001).

[1] The degree of slope relevant to sandy substrates. Note: a vertical profile can only persist in hard substrates (e.g. rock or concrete). Such hard structures do not permit seagrass growth and are therefore not relevant in this relationship.

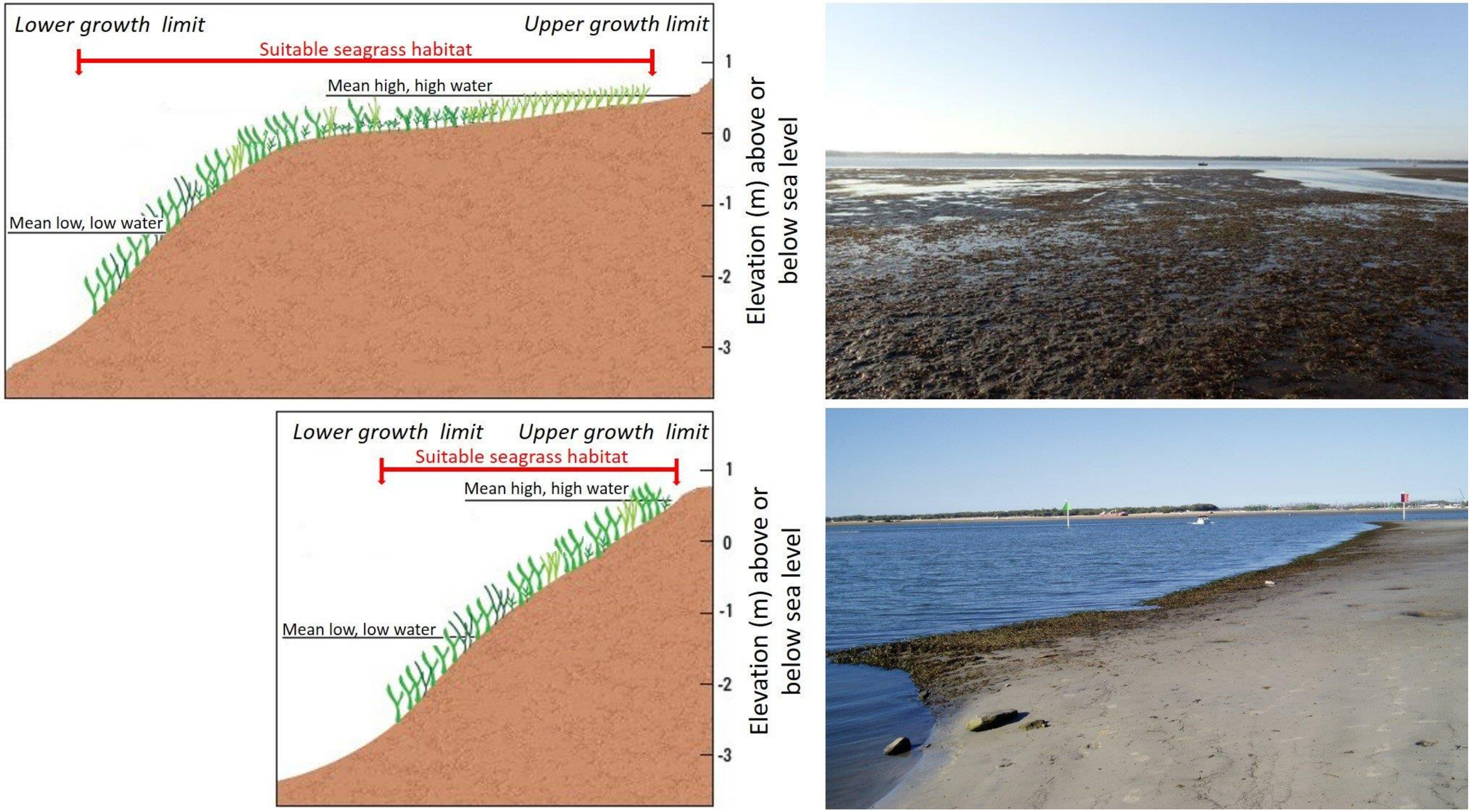

Fig. 15. The relationship between sand slope and total seagrass area with reference to the upper and lower growth limits. Upper images represent an area with a gentle slope that results in a large area of seagrass. The lower images represent areas with steep slopes, and a corresponding smaller total seagrass area. Photographs on right show Gold Coast examples of each situation. Upper: northern side of Loders Creek, central Broadwater (photo: S McKenna) and lower: southern side of Loders Creek (photo: R Connolly).

The occurrence of seagrass itself is fundamentally important for the presence of several important fisheries species within GCWs, supporting much higher abundances of juveniles than in adjacent unvegetated areas (Young & Wadley 1979).

Connectivity between seagrass and mangrove/saltmarsh habitat is also an important consideration for the GCWs. The expected maximum benefit to recreational and commercial fisheries (through provision of ecosystem services) comes from having a mosaic of connected habitats involving seagrass and mangroves/saltmarsh situated as near as possible to one another, as well as to nearby channels. Having seagrass in close proximity to mangroves has been demonstrated to be important for both fish and prawn species (Skilleter et al. 2005, Jelbart et al. 2007). For example, Skilleter et al. (2005) demonstrated that, within Moreton Bay, the abundances of two major prawn species (*Penaeus plebejus* and *Metapenaeus bennettae*) were consistently higher in seagrass near to mangroves than in seagrass further away. Even sparse seagrass close to mangroves supported more of these species than dense seagrass farther away, indicating that the role of spatial arrangement of habitats is more important than the effects of within-meadow structural complexity alone. Elsewhere in Australia, Jelbart et al. (2007) reported higher densities of fish that utilise mangrove forests at high tide in seagrass areas near to mangroves than in those further away.

Examples of recreational and commercial species in GCWs benefiting from the services provided by, and connectivity between, seagrass and mangrove/saltmarsh habitats include; mud crab (*Scylla serrata*) and blue swimmer crab (*Portunus armatus*), and fish species such as flathead (*Platycephalus spp*.), whiting (*Sillago* spp.) and bream (*Acanthopagrus australis*) that rely largely on benthic fauna for food.

Guidelines for nourishment and future monitoring requirements

Our understanding of the patterns and processes of natural seagrass colonisation of nourished foreshore areas in GCWs is still rather weak. Historically, little effort has gone into post-nourishment monitoring of seagrass, and of physical parameters likely to be important for seagrass colonisation and growth. Improved monitoring of future nourishment projects, however, can be used to test the importance of physical factors in seagrass colonisation. Those findings will support a better informed plan targeting seagrass outcomes in future nourishment projects in GCWs.

Based on the findings in this report we conclude that the hydrodynamic environment is critically important. In low energy areas, relatively stable sand at a suitable water depth is generally capable of supporting seagrass. High-energy nourishment sites are unlikely to have favourable outcomes for seagrass. At the single high-energy site inspected (Southwest Marine Stadium), no seagrass was recorded, presumably because of the visibly unstable sand environment and frequent re-working of the seabed. High energy sites will need modifications to slow water movement, such as through construction of adjacent protective banks. The threshold in hydrodynamics at which energy is low enough for successful seagrass outcomes is at this stage unknown. **Determining this hydrodynamic threshold for GCWs should be one of the goals of future monitoring and experiments.** Note that the particle size distribution (PSD) of sediments is also largely determined by hydrodynamics. PSD can therefore be used as an indicator of hydrodynamics; however it does not itself cause seagrass distribution and therefore does not need to be a priority focus for studies in the immediate future.

Foreshore slope appears not to be important in determining seagrass presence. Any slope can support seagrass (other than vertical surfaces, which in any case cannot usually be maintained with unstructured sediments). **Foreshore slope is, however, fundamentally important in determining the *extent* of seagrass distribution** (see Fig. 15). Foreshore slope will therefore be an important design element in nourishment projects, able to be optimised to realise specific amounts of seagrass cover to achieve local goals.

The role of water quality, in particular turbidity and the light environment, is generally well established for seagrass (Connolly et al. 2016a). The specific relationships between water quality parameters and seagrass growth in GCWs are, however, not properly described. Some indication of the light requirements of local species can be discerned from the maximum recorded depths for different species in Table 6 in Connolly et al. 2016b); e.g. two *Halophila* species (*H. ovalis* and *H. spinulosa*) occur substantially deeper than other species and can be considered less sensitive to low ambient light levels. A more explicit understanding of light requirements is needed, however, to support decisions about nourishment site selection in relation to water quality. Initially this would involve local 'ground-truthing' of the known, generalised light requirements (daily dose calculations) for different seagrass species in GCWs (see recommendations in Table 5, Connolly et al. 2016a). **The first step towards achieving this would be through regular measurements of turbidity and light at locations that currently do, and do not, support seagrass.**

7. References

Australian Wetlands (2009) Southport Parklands redevelopment seagrass establishment report. Report for ABIGROUP Constructions Pty Ltd. Australian Wetlands Pty Ltd, Byron Bay

Bach SD, Thayer GW, LaCroix MW (1986) Export of detritus from eelgrass (*Zostera marina*) beds near Beaufort, North Carolina, USA. Mar Ecol Prog Ser 28:265-278

Barbier EB, Hacker SD, Kennedy CJ, Koch EW, Stier AC, Silliman BR (2011) The value of estuarine and coastal ecosystem services. Ecol Monogr 81:169-193

Barbier EB, Koch EW, Silliman BR, Hacker SD, Wolanski E, Primavera J, Granek EF, Polasky S, Aswani S, Cramer LA (2008) Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319:321-323

Barko JW, Gunnison D, Carpenter SR (1991) Sediment interactions with submersed macrophyte growth and community dynamics. Aquat Bot 41:41-65

Bastyan GR, Cambridge ML (2008) Transplantation as a method for restoring the seagrass *Posidonia australis*. Estuar Coast Shelf S 79:289-299

Beck MW, Heck KL, Able KW, Childers DL, Eggleston DB, Gillanders BM, Halpern BS, Hays CG, Hoshino K, Minello TJ, Orth RJ, Sheridan PF, Weinstein MP (2001) The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. BioScience 51:633-641

Bell SS, Fonseca MS, Motten LB (1997) Linking restoration and landscape ecology. Restor Ecol 5:318-323

Bell SS, Tewfik A, Hall MO, Fonseca MS (2008) Evaluation of seagrass planting and monitoring techniques: implications for assessing restoration success and habitat equivalency. Restor Ecol 16:407-416

Biome (2007) Seagrass management plan. A report prepared for Gold Coast City Council by Biome - ESP. Biome, Gold Coast

Bos AR, Van Katwijk MM (2007) Planting density, hydrodynamic exposure and mussel beds affect survival of transplanted intertidal eelgrass. Mar Ecol Prog Ser 336:121-129

Campbell ML (2002) Getting the foundation right: a scientifically based management framework to aid in the planning and implementation of seagrass transplant efforts. B Mar Sci 71:1405-1414

Chambers RM, Hollibaugh JT, Vink SM (1994) Sulfate reduction and sediment metabolism in Tomales Bay, CA. Biogeochemistry 25:1-18

Connolly RM, Dunn RJK, Jackson EL, Kristensen E, Maxwell PS, Pearson RM, Rasheed MA, York PH (2016a) Gold Coast seagrass sensitivities and resilience (SRMP-003). Report for Gold Coast Waterways Authority. Griffith University, Gold Coast

Connolly RM, Dunn RJK, Kovacs E, Maxwell PS, McKenna SA, Phinn S, Rasheed MA, Roelfsema C, York PH (2016b) Marine plant habitat and monitoring program (SRMP-002). Report for Gold Coast Waterways Authority. Griffith University, Gold Coast

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253-260

Cullen-Unsworth LC, Nordlund LM, Paddock J, Baker S, McKenzie LJ, Unsworth RK (2014) Seagrass meadows globally as a coupled social–ecological system: implications for human wellbeing. Mar Pollut Bull 83:387-397

Cunha AH, Marbá NN, van Katwijk MM, Pickerell C, Henriques M, Bernard G, Ferreira M, Garcia S, Garmendia JM, Manent P (2012) Changing paradigms in seagrass restoration. Restor Ecol 20:427-430

Cuttriss AK, Prince JB, Castley JG (2013) Seagrass communities in southern Moreton Bay, Australia: coverage and fragmentation trends between 1987 and 2005. Aquat Bot 108:41– 47

Dattolo E, Gu J, Bayer PE, Mazzuca S, Serra IA, Spadafora A, Bernardo L, Natali L, Cavallini A, Procaccini G (2013) Acclimation to different depths by the marine angiosperm *Posidonia oceanica*: transcriptomic and proteomic profiles. Frontiers in Plant Science 4

De Iongh HH, Kiswara W, Kustiawan W, Loth PE (2007) A review of research on the interactions between dugongs (*Dugong dugong* Müller 1776) and intertidal seagrass beds in Indonesia. Hydrobiologia 591:73-83

Department of State Development Infrastructure and Planning (DSDIP) Guideline for preparing a high level sand management plan. Accessed 7 February 2016. http://www.broadwatermarineproject.com.au/documents/8.4/

Derrenbacker J, J., Lewis I, R.R. (1983) Seagrass habitat restoration, Lake Surprise, Florida Keys. In: Webb J, F.J. (ed) Wetlands Restoration and Creation, Book Proceedings of the 9th Annual Conference Wetlands Restoration and Creation, Hillsborough Community College, Tampa, Florida

DeWitt T (2009) The effects of bioturbation and bioirrigation on seagrasses. In: Nelson W (ed) Seagrasses and protective criteria: a review and assessment of research status. Environmental Protection Agency, Newport

Duarte CM (2000) Marine biodiversity and ecosystem services: an elusive link. J Exp Mar Biol Ecol 250:117-131

Duarte CM, Chiscano CL (1999) Seagrass biomass and production: a reassessment. Aquat Bot 65:159-174

Dunn RJK, Teasdale PR, Warnken J, Schleich RR (2003) Evaluation of the diffusive gradient in a thin film technique for monitoring trace metal concentrations in estuarine waters. Environ Sci Technol 37:2794-2800

Dunn RJK, Waltham NJ, Benfer NP, King BA, Lemckert CJ, Zigic S (2014) Gold Coast Broadwater: Southern Moreton Bay, Southeast Queensland (Australia).

In: Wolanski E (ed) Estuaries of Australia in 2050 and beyond. Springer, Netherlands

Ebrahim A (2012) Monitoring the ecological effect of a created mangrove habitat on the environment. Griffith University, Gold Coast

Element Ecology (2014a) As-completed project report - seagrass translocation. Report for City of Gold Coast. Gold Coast

Element Ecology (2014b) Donor and receiving site condition report - seagrass translocation. Report for City of Gold Coast. Gold Coast

Erftemeijer PL, van Beek JK, Ochieng CA, Jager Z, Los HJ (2008) Eelgrass seed dispersal via floating generative shoots in the Dutch Wadden Sea: a model approach. Mar Ecol Prog Ser 358:115

Fonseca MS (1992) Restoring seagrass systems in the United States. In: Thayer GW (ed) Restoring the nation's marine environment. Maryland Sea Grant College, College Park

Fonseca MS (2011) Addy revisited: what has changed with seagrass restoration in 64 Years? Ecological Restoration 29:73-81

Fonseca MS, Kenworthy WJ, Courtney FX, Hall MO (1994) Seagrass planting in the southeastern United Sates: methods for accelerating habitat development. Restor Ecol 2:198-212

Fonseca MS, Meyer DL, Hall MO (1996) Development of planted seagrass beds in Tampa Bay, Florida, USA. II. Faunal components. Mar Ecol Prog Ser 132:141-156

Fonseca MS, Zieman JC, Thayer GW, Fisher JS (1983) The role of current velocity in structuring seagrass meadows. Estuar Coast Shelf S 17:367-380

Fourqurean JW, Zieman JC, Powell GVN (1992) Relationships between porewater nutrients and seagrasses in a subtropical carbonate environment. Mar Biol 114:57-65

GHD (2006) Appendix E dredging strategy. Report for notional seaway project dredge management strategy. GHD Pty Ltd, Brisbane

Google Earth (2016) Gold Coast Broadwater. Google Earth, California

Gordon DM (1996) Status of seagrass restoration: review of international literature. LeProvost Dames and Moore, Perth

Grech A, Coles RG (2010) An ecosystem-scale predictive model of coastal seagrass distribution. Aquat Conserv 20:437-444

Green EP, Short FT (2003) World atlas of seagrasses. University of California Press

Hall LM, Hanisak MD, Virnstein RW (2006) Fragments of the seagrass *Halodule wrightii* and *Halophila johnsonii* as potential recruits in Indian River Lagoon, Florida. Mar Ecol Prog Ser 310:109-117

Halun Z, Terrados J, Borum J, Kamp-Nielsen L, Carlos MD, Mguel DF (2002) Experimental evaluation of the effects of siltation-derived changes in sediment conditions on the Philippine seagrass *Cymodocea rotundata*. J Exp Mar Biol Ecol 279:73-87

Heck KL, Carruthers TJB, Duarte CM, Hughes AR, Kendrick GA, Orth RJ, Williams SW (2008) Trophic transfers from seagrass meadows subsidize diverse marine and terrestrial consumers. Ecosystems 11:1198-1210

Henkelmann M (2012) Monitoring the ecological health of the 'Southport Broadwater Parklands mangrove and seagrass habitat'. Griffith University, Gold Coast

Inglis GJ (2001) Disturbance-related heterogeneity in the seed banks of a marine angiosperm. J Ecol 88:88-99

Jackson EL, Rowden AA, Attrill MJ, Bossey SJ, Jones MB (2001) The importance of seagrass beds as a habitat for fishery species. Oceanogr Mar Biol 39:269-304

Jackson EL, Wilding C, Attrill MJ (2015) Use of a seagrass residency index to apportion commercial fishery landing values and recreation fisheries expenditure to seagrass habitat service. Conserv Biol 29:899-909

Jahnke M, Serra IA, Bernard G, Procaccini G (2015) The importance of genetic make-up in seagrass restoration: a case study of the seagrass *Zostera noltei*. Mar Ecol Prog Ser 532:111-122

Jelbart JE, Ross PM, Connolly RM (2007) Fish assemblages in seagrass beds are influenced by the proximity of mangrove forests. Mar Biol 150:993-1002

Kaldy JE, Dunton KH, Kowalski JL, Lee K-S (2004) Factors controlling seagrass revegetation onto dredge material deposits: a case study in Lower Laguna Madre, Texas. J Coastal Res 20:292-300

Kettenring KM, Mercer KL, Reinhardt Adams C, Hines J (2014) Application of genetic diversity–ecosystem function research to ecological restoration. J Appl Ecol 51:339-348

Kilminster K, McMahon K, Waycott M, Kendrick GA, Scanes P, McKenzie L, O'Brien KR, Lyons M, Ferguson A, Maxwell P, Glasby T, Udy J (2015) Unravelling complexity in seagrass systems for management: Australia as a microcosm. Sci Total Environ 534:97-109

Kirkman H (1999) Pilot experiments on planting seedlings and small seagrass propagules in Western Australia. Mar Pollut Bull 37:8-12

Koch E (2001) Beyond light: physical, geological, and geochemical parameters as possible submersed aquatic vegetation habitat requirements. Estuar Coast 24:1-17

Koch EW, Barbier EB, Silliman BR, Reed DJ, Perillo GM, Hacker SD, Granek EF, Primavera JH, Muthiga N, Polasky S (2009) Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Front Ecol Environ 7:29-37

Koch EW, Beer S (1996) Tides, light and the distribution of *Zostera marina* in Long Island Sound, USA. Aquat Bot 53:97-107

Lefcheck J, Marion SR, Orth RJ (2015) Actively restored ecosystems as a refuge for biological diversity: a case study from eelgrass (*Zostera marina* L.). PeerJ PrePrints:No. e1662

Li WT, Kim JH, Park JI, Lee KS (2010) Assessing establishment success of *Zostera marina* transplants through measurements of shoot morphology and growth. Estuar Coast Shelf S 88:377-384

Lord D, Paling EI, Gordon DM (1999) Review of Australian rehabilitation and restoration programs. In: Butler A, Jernakoff P (eds) Seagrass in Australia. CSIRO Publishing, Collingwood

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JB (2006) Depletion, degradation, and recovery potential of estuaries and coastal seas. Science 312:1806-1809

Macreadie PI, M.E. B, Trevathan-Tackett SM, Larkum AWD, Ralph PJ (2014) Quantifying and modelling the carbon sequestration capacity of seagrass meadows – a critical assessment. Mar Pollut Bull 429:87-91

McLennan M, Sumpton W (2005) The distribution of seagrasses and the viability of seagrass transplanting in the Broadwater, Gold Coast, Queensland. Proc Roy Soc Queensland 112:31-38

Meehan AJ, West RJ (2002) Experimental transplanting of *Posidonia australis* seagrass in Port Hacking, Australia, to asses the feasibility of restoration. Mar Pollut Bull 44:25-31

Montalvo AM, Williams SL, Rice KJ, Buchmann SL, Cory C, Handel SN, Nabhan GP, Primack R, Robichaux RH (1997) Restoration biology: a population biology perspective. Restor Ecol 5:277-290

Nojima S, Aratake H (1997) Estimation of grazing rate of the parrot fish *Calotomus spinidens* (Quay et Gainard) in a monospecific seagrass bed of *Syringodium isoetiffolium*. In: Koike I (ed) Development process and material flow in tropical seagrass beds. Ocean Research Institute, University of Tokyo, Tokyo

Olesen B, Sand-Jensen K (1994) Patch dynamics of eelgrass *Zostera marina*. Mar Ecol Prog Ser 106:147-156

Ooi JLS, Kendrick GA, Van Niel KP (2011) Effects of sediment burial on tropical ruderal seagrasses are moderated by clonal integration. Cont Shelf Res 31:1945-1954

Paling EI (1995) Seagrass meadow regrowth, transplantation and recovery after disturbance in Western Australia: a review. Shellsand Dredging, Environmental Management Programme, Project S2, Phase 1. Marine and Freshwater Research Laboratory, Western Australia

Paling EI, Fonseca M, van Katwijk MM, van Keulen M (2009) Seagrass restoration. In: Perillo GME, Wolanski E, Cahoon DR, Brinson MM (eds) Coastal wetlands: an integrated ecosystem approach. Elsevier, Netherlands

Paling EI, van Keulen M (2002) Seagrass restoration in Australia. Proceedings of the seagrass restoration workshop for Gulf St Vincent, Adelaide, Australia

Phillips RC (1974) Temperate grass flats. In: Odum HT, Copeland BJ, McMahan EA (eds) Coastal ecological systems of the United States: a source book for estuarine planning. Conservation Foundation, Washington, DC

Renton M, Airey M, Cambridge ML, Kendrick GA (2011) Modelling seagrass growth and development to evaluate transplanting strategies for restoration. Ann Bot-London 108:1213-1223

Reynolds LK, McGlathery KJ, Waycott M (2012) Genetic diversity enhances restoration success by augmenting ecosystem services. PloS one 7:1-7

Reynolds LK, Waycott M, McGlathery KJ, Orth RJ, Zieman JC (2011) Eelgrass restoration by seed maintains genetic diversity: case study from a coastal bay system. Mar Ecol Prog Ser 448:223-233

Schanz A, Asmus H (2003) Impact of hydrodynamics on development and morphology of intertidal seagrasses in the Wadden Sea. Mar Ecol Prog Ser 261:123-134

Sheppard JK, Lawler IR, Marsh H (2007) Seagrass as pasture for seacows: landscape-level dugon habitat evaluation. Estuar Coast Shelf S 71:117-132

Short FT (1987) Effects of sediment nutrients on seagrasses: literature review and mesocosm experiment. Aquat Bot 27:41-57

Silberstein K, Chiffings AW, McComb AJ (1986) The loss of seagrass in Cockburn Sound, Western Australia. III. The effects of ephytes on productivity of *Posidonia australis* Hook. F. Aquat Bot 24:355-371

Sillars A (2011) Monitoring the condition of sediment and associated fauna within a created mangrove wetland. Griffith University, Gold Coast

Sinclair EA, Krauss SL, Anthony J, Hovey R, Kendrick GA (2014) The interaction of environment and genetic diversity within meadows of the seagrass *Posidonia australis* (Posidoniaceae). Mar Ecol Prog Ser 506:87-98

Skilleter GA, Olds A, Loneragan NR, Zharikov Y (2005) The value of patches of intertidal seagrass to prawns depends on their proximity to mangroves. Mar Biol 147:353-365

Statton J, Dixon KW, Hovey RK, Kendrick GA (2012) A comparative assessment of approaches and outcomes for seagrass revegetation in Shark Bay and Florida Bay. Mar Freshwater Res 63:984-993

Townsend EC, Fonseca MS (1998) Bioturbation as a potential machanism influencing spatial heterogeneity of North Carolina seagrass beds. Mar Ecol Prog Ser 169:123-132

Uhrin AV, Hall MO, Merello MF, Fonseca MS (2009) Survival and expansion of mechanically transplanted seagrass sods. Restor Ecol 17:359-368

Unsworth RK, Taylor JD, Powell A, Bell JJ, Smith DJ (2007) The contribution of scarid herbivory to seagrass ecosystem dynamics in the Indo-Pacific. Estuar Coast Shelf S 74:53-62

URBIS (2012) Gold Coast Broadwater economic assessment and monitoring. Baseline report - Gold Coast City Council. Brisbane

Valdemarsen T, Wendelboe K, Egelund JT, Kristensen E, Flindt MR (2011) Burial of seeds and seedlings by the lugworm *Arenicola marina* hampers eelgrass (*Zostera marina*) recovery. J Exp Mar Biol Ecol 410:45–52

Valentine JF, Heck Jr. KL, Harper P, Beck M (1994) Effects of bioturbation in controlling turtlegrass (*Thalussicz tesrudinum* Banks ex Konig) abundance: evidence from field enclosures and observations in the Northern Gulf of Mexico. J Exp Mar Biol Ecol 178:18l-192

Valiela I (1984) Marine Ecological Processes. Springer-Verlag, New York

van Katwijk MM, Bos AR, de Jonge VN, Hanssen LSAM, Hermus DCR, de Jong DJ (2009) Guidelines for seagrass restoration: importance of habitat selection and donor population, spreading of risks, and ecosystem engineering effects. Mar Pollut Bull 58:179-188

van Katwijk MM, Hermus DCR (2000) Effects of water dynamics on *Zostera marina*: transplnatation experiments in the intertidal Ducth Wadden Sea. Mar Ecol Prog Ser 208:107-118

van Katwijk MM, Thorhaug A, Marbà N, Orth RJ, Duarte CM, Kendrick GA, Althuizen IHJ, Balestri E, Bernard G, Cambridge ML, Cunha A, Durance C, Giesen W, Han Q, Hosokawa S, Kiswara W, Komatsu T, Lardicci C, Lee K-S, Meinesz A, Nakaoka M, O'Brien KR, Paling EI, Pickerell C, Ransijn AMA, Verduin JJ (2016) Global analysis of seagrass restoration: the importance of large-scale planting. J Appl Ecol 53:567-578

van Katwijk MM, Thorhaug A, Marbà N, Pickerell C, Althuizen I, Balestri E, Bernard G, Cambridge ML, Cunha AH, Duarte CM, Durance C, Gadoullet C, Giesen W, Han Q, Hosokawa S, Kendrick G, Kiswara W, Komatsu T, Lardicci C, Lee KS, Meinesz A, Nakaoka M, Orth RJ, Paling EI, Ransijn A, Verduin JJ Revegetation of seagrass beds worldwide: a review of actions and possible keys to success. In: Creed JC, Oigman-Pszczol SS (eds). Proc 10th International Seagrass Biology Workshop. Instituto Biodiversidade Marinha, Rio de Janeiro, Brazil

van Keulen M, Paling EI, Walker CJ (2003) Effect of planting unit size and sediment stabilization on seagrass transplants in Western Australia. Restor Ecol 11:50-55

VDM Consulting (2010) Southport Broadwater Parklands seagrass monitoring Issue No. 1. Report for Gold Coast City Council. VDM Consulting, Southport, Australia

VDM Consulting (2012) Ecological investigations to support the Broadwater masterplan. Report for Gold Coast City Council. VDM Consulting, Southport, Australia

Virnstein RW, Curran MC (1986) Colonization of artificial seagrass versus time and distance from source. Mar Ecol Prog Ser 29:279-288

Warnken J, Dunn RJK, Teasdale PR (2004) Investigation of recreational boats as a source of copper at anchorage sites using time-integrated diffusive gradients in thin film and sediment measurements. Mar Pollut Bull 49:833-843

Wear RJ (2006) Recent advances in research into seagrass restoration. South Australian Research and Development Institute (SARDI) Aquatic Sciences, Adelaide

Wear RJ, Tanner JE, Hoare SL (2010) Facilitating recruitment of *Amphibolis* as novel approach to seagrass rehabilitation in hydrodynamically active waters. Mar Freshwater Res 61:1123-1133

Weatherall EJ, Jackson EL, Hendry RA, Campbell ML (2016) Quantifying the dispersal potential of seagrass vegetative fragments: a comparison of multiple subtropical species. Estuar Coast Shelf S 169:207-215

Williams SL (2001) Reduced genetic diversity in eelgrass transplantations affects both population growth and individual fitness. Ecol Appl 11:1472-1488

Wood E, Odum W, Zieman J (1969) Influence of seagrasses on the productivity of coastal lagoons. Universidad Nacional Autonoma De Mexico, Mexico

Young PC, Wadley VA (1979) Distribution of shallow-water epibenthic macrofauna in Moreton Bay, Queensland, Australia. Mar Biol 53:83-97

Appendix

Established Catalogue of Dredge and Sand Nourishment Works within Gold Coast Waterways

A summary map of dredge and sand nourishment works identified as occurring within the GCWs between 2003-2015 (including planned for 2015) is presented in Fig. A1. This information is drawn from four sources (asterisks on map show from which source):

1. (*) Analysis of historical Google Earth images
2. (**) Maritime Safety Queensland (MSQ) notices to mariners (2010 - 2015 only).
3. (***) Local knowledge from Griffith University project members
4. (****) GCWA provided dredge area ESRI shapefiles in conjunction with dredge works timeline

Caveats:

1. Google Earth images have considerable gaps in image availability - e.g., between 2004 and 2008 there are no images available. Therefore, many works identified through Google Earth have occurred between the dates listed, but likely did not occur for the entire duration.

2. The MSQ reports provided only text descriptions. Therefore, information derived from these is designed to display an approximate area of coverage only, and not exact dredging locations. E.g. on the map, the 'Main Channel North' works, was listed as occurring "... in the main channel between Jacobs Well and Tulleen Island...".

3. Lastly, the ">" on some works (e.g. >Jun 2012) is there because at best we can say that the work was ongoing at that time, and no end date has been identified.

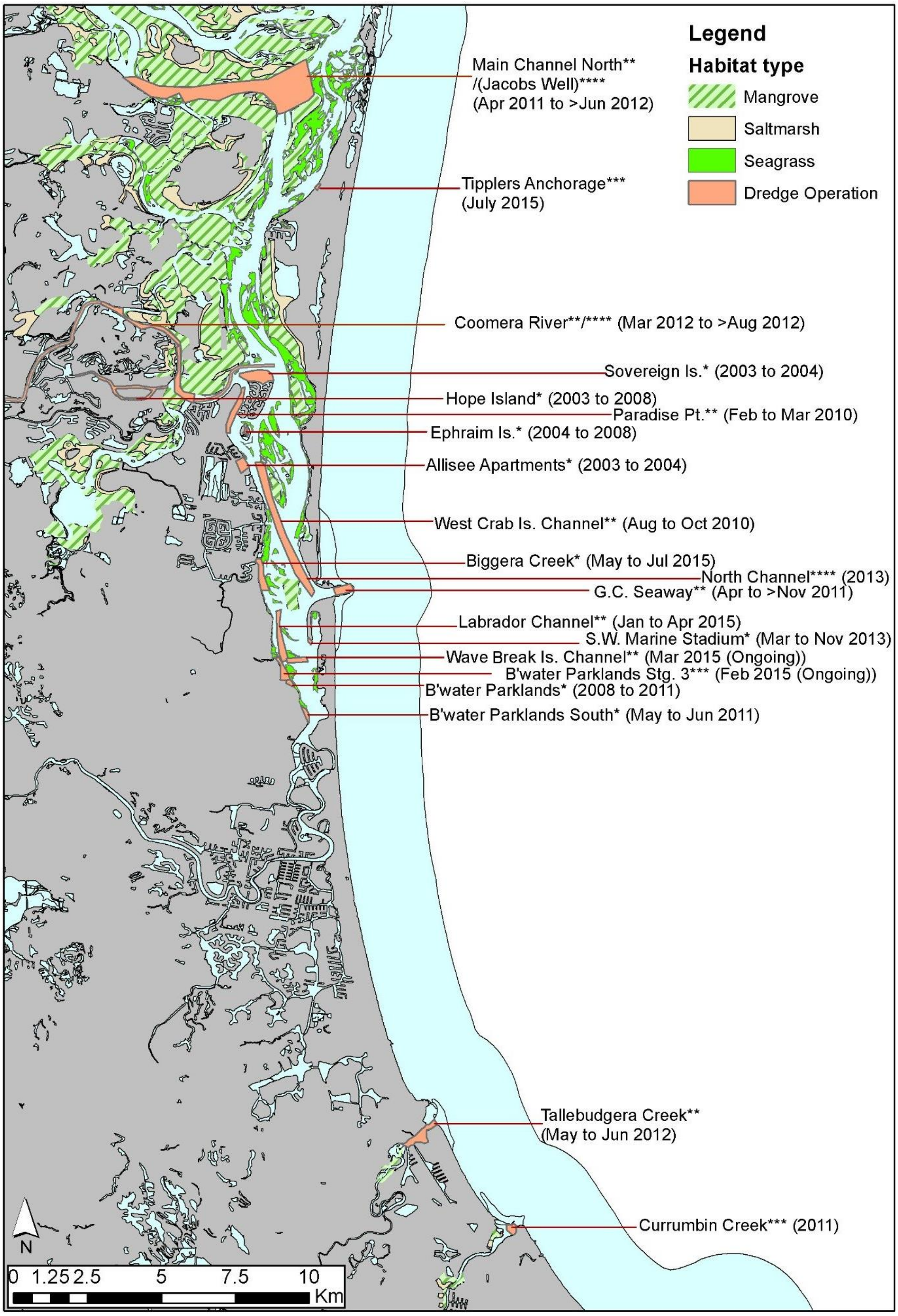

Fig. A1. Identified dedge and sand placement works identified as occurring within the Gold Coast waterways between 2003–2015 (including planned projects for 2015/6).