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Spatial patterns of sub-tidal seagrasses and their tissue nutrients in the Torres Strait, northern Australia: Implications for management

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Abstract

The distribution and nutritional profiles of sub-tidal seagrasses from the Torres Strait were surveyed and mapped across an area of 31,000 km^2. Benthic sediment composition, water depth, seagrass species type and nutrients were sampled at 168 points selected in a stratified representative pattern. Eleven species of seagrass were present at 56 (33.3 %) of the sample points. *Halophila spinulosa, Halophila ovalis, Cymodocea serrulata* and *Syringodium isoetifolium* were the most common species and these were nutrient profiled. Sub-tidal seagrass distribution (and associated seagrass nutrient concentrations) was generally confined to northern-central and south-western regions of the survey area (< longitude 142.60), where mean water depth was relatively shallow (approximately 13 m below MSL) and where sediments were comprised primarily of muddy sand to gravelly sand. Seagrass nitrogen and starch content, the most important nutrients for marine herbivores, were significantly correlated with species and with the plant component (above or below ground). For all seagrass species, the above-ground component (shoots and leaves) possessed greater nitrogen concentrations than the below-ground component (roots and rhizomes), which possessed greater starch concentrations. *S. isoetifolium* had the highest total nitrogen concentrations (1.40 ± 0.05% DW). However, it also had higher fibre concentrations (38.2 ± 0.68% DW) relative to the other four species. *H. ovalis* possessed the highest starch concentrations (2.76 ± 0.12% DW) and highest digestibility (83.24± 0.66 % DW) as well as the lowest fibre (27.2 ± 0.66% DW). The high relative abundance (found at 55 % of the sites that had seagrass) and nutrient quality characteristics of *H. ovalis* make it an important source of energy to marine herbivores that forage sub-tidaly in the Torres Strait. There were two regions in Torres Strait (north-central and south-western) where sub-tidal seagrass meadows were prevalent and of relatively higher nutritional value. This spatial and nutritional information can be used by local agencies to

manage and to protect the ecological, economic and cultural values of the sub-tidal seagrass ecosystems and associated fisheries of the Torres Strait.

Key words

Seagrass; dugong; turtle; benthic; nutrient; biogeography; Torres Strait

1. Introduction

Seagrass meadows are highly productive marine ecosystems (Costanza et al, 1997; Duarte and Chiscano, 1999) and are a key component of coastal trophodynamics, benthic faunal habitat, and biogeochemical cycling (Walker, 1989; Cebrián and Duarte, 1997; Perry and Dennison, 1999). The high primary productivity of seagrass meadows drives the high productivity of valuable commercial fisheries such as penaeid shrimps (Coles et al., 1987; Watson et al., 1993).

Coastal seagrass habitats have come under growing pressure in recent decades from anthropogenic threats associated with agriculture and urban development (Short and Willie-Echeverria, 1996; Duarte 2002). Excessive nitrogen loading from terrestrial sources such as sewerage and agricultural run-off can inhibit seagrass growth and survival through direct physiological response and by stimulating algal growth leading to light reduction (Schaffelke et al., 2005).

Management initiatives designed to conserve ecologically and economically valuable seagrass communities require comprehensive mapping and inventory databases for monitoring changes (natural and anthropogenic) in seagrass communities (Kirkman, 1996; Coles and Fortes, 2001; McKenzie et al., 2001). The first step towards enhancing seagrass meadow management, and the management of fisheries that depend on seagrasses, is the acquisition of baseline data on spatial patterns and relative 'quality' as habitat. This includes identifying optimal foraging sites for marine herbivores based on the nutritional value of the seagrass available.

The Torres Strait region of far north Queensland, Australia, comprises one of the most extensive seagrass communities in Australia and provides critical habitat for commercial and traditional fishery species (Bridges et al., 1982; Pitcher et al., 1992; Long and Poiner, 1997; Coles et al., 2003). However, regional variation in the nutritional value of these seagrass meadows has not been studied or mapped. The seagrass meadows are regionally important habitat and food resources for threatened green turtle (*Chelonia mydas*) and dugong (*Dugong dugon*) populations (Marsh et al., 1997; Butler and Jernakoff, 1999; André et al., 2005). Green turtle and dugong populations are fished traditionally and managed as fisheries under the arrangements in Article 22 of the Torres Strait Treaty and Torres Strait Fisheries Act 1984. Fishing for turtle and dugong is an important part of the cultural life of many Torres Strait Islanders and the meat from these animals is an important part of the local island diet.

Despite the considerable ecological and economic value of the Torres Strait marine ecosystem, the sub-tidal benthic communities remain understudied. Regional variation in subtidal seagrass species composition has not been mapped for a decade in Torres Strait (Long and Poiner, 1997), and the south-west region has never been mapped. Large-scale seagrass dieback events in the north-western Torres Strait associated with climatic disturbance (Pitcher et al., 2004) highlight the urgent need for baseline data on seagrass community structure, composition and dynamics. Prediction of the effects of environmental impacts on Torres Strait benthic habitats and the fisheries they sustain requires better understanding of the distribution, status and functioning of the regions' extensive seagrass ecosystems.

We conducted a baseline survey of the sub-tidal seagrass communities of the Torres Strait under the aegis of a CSIRO seabed biodiversity project. The 31,000 km^2 area surveyed included open sea floor, reef flats, and benthic habitat adjacent to continental islands. Seagrass species distribution and nutrient profiles were sampled and compared against environmental parameters such as water depth and sediment type. In this paper we investigate whether abiotic factors (water depth, sediment) influence subtidal seagrass community structure and provide quantitative data on the seagrass meadows of the Torres Strait at spatial scales relevant to regional conservation and management needs. We provide species distributions and examine the nutritional value of subtidal seagrasses for marine herbivores and the distribution of food resource quality in the Torres Strait.

2. Methods

2.1 Study area

The Torres Strait comprises a narrow stretch of water (150 km north-south and 250 km east-west) between Cape York, the northernmost tip of Queensland, Australia and southern Papua New Guinea. It is divided longitudinally by two central ridge lines that are dissected by numerous channels and which often emerge as reefs and islands (Maxwell, 1968; Hopley, 1982; Harris, 1988; Pitcher et al., 2004). The Torres Strait has three main geographic regions: (1) the western region, which extends westward from (but not including) a north-south string of continental islands that extend from Cape York to Papua New Guinea; (2) the central region, which lies between the continental islands and the Warrior Reef complex, and; (3) the eastern region, which lies between the Warrior Reefs to the west and the Ribbon Reefs of the Great Barrier Reef to the east (Figure 1).

2.2 General physiography

There are several large islands in the western region with fringing reefs, and reef platforms and complex channel systems and wetlands. The western region is relatively shallow (< 20 m) and its northern section is characterised by extensive sand waves (Harris, 1991; Long and Poiner, 1997; Heap et al., 2005). The central region is also shallow (< 20 m) with mostly small rocky islands fringed by reef, including the westward island string and Orman Reefs. Mangroves are found on some of the larger reefs (Long and Poiner, 1997). Water depths in the eastern region range from 20 m at the Warrior Reefs to 100 and 4000 m at the western and eastern sides of the Ribbon Reefs respectively (Long and Poiner, 1997; Pitcher *et al.*, 2004).

The physical oceanography of Torres Strait is dominated by the tidal regime, which generates extremely strong currents (Harris, 1991). Large sea level gradients exist across Torres Strait due to the lack of phase between Coral Sea/ Gulf of Papua and Gulf of Carpentaria/ Arafura Sea tidal cycles. The gradients result in alternating east-west currents (> 1 $m^3 s^{-1}$) that keep water vertically well mixed and shape the physical oceanography and biotic assemblages of the region (Harris, 1991; Wolanski 1991; Long and Poiner, 1997; Pitcher *et al.*, 2004). Tidal currents and locally generated surface waves are responsible for re-suspension of sediments, giving rise to a turbidity maximum in the central Torres Strait (Harris, 1991; Harris and Baker, 1991). Benthic sediments range from fine terrestrial muds near rivers to coarse carbonate sands and gravels among coral reefs further from land (Harris, 1991; Harris and Baker, 1991; Pitcher *et al.*, 2004). Previous surveys found that seagrass meadows in the Torres Strait are sparsely distributed over wide areas and are often restricted to intertidal areas leeward of coral reef crests (Long and Poiner, 1997). This is probably due to the erosive effects of the strong currents (up to 18 km/ hour) and high turbidity associated with the region (Long and Skewes, 1997).

2.3 Sampling design and implementation

Sub-tidal seagrass communities in the Torres Strait were sampled in a broad-scale survey conducted between March and April, 2005. 168 sample site locations were selected according to a stratified representative pattern (SRP). The SRP technique based sample site selection on the spatial distribution of environmental correlates (e.g., depth, sediments, current stress) determined from previous habitat studies in the Torres Strait to be significant factors in biophysical analyses. The sampling region was segregated into relatively homogenous strata based on environmental correlates from which sample sites were selected. The intensity of sampling within each strata was optimised to match the expected diversity and variance (Pitcher *et al.*, 2004; Haywood *et al.*, this issue).

At each sample site a video camera was deployed along a 500 m transect to detect the presence of seagrass. Where seagrass was detected, a 1.5 m wide epibenthic sled with a 10 mm (mesh size) net backing was towed along the video transect path for approximately 200 m to collect plant specimens. Sediment at each site was described using Folk's (1954) classification system. Water depth at each sample site was recorded relative to mean sea level (MSL). The research vessel used to conduct the survey was the RV *James Kirby*, owned by James Cook University. This steel hulled vessel is 19.6 m long with a draft of 2.15 m The size of the survey vessel prevented shallow water and intertidal seagrasses (< 3 m) from being sampled.

Seagrass collected was washed in seawater to remove sediment and epiphytes, sorted into species, then frozen for transportation to the laboratory. Prior to nutritional analysis samples were thawed and separated into above ground (stem and leaf) and below ground (root and rhizome) components and dried to constant weight for at least 48 hours at 40ºC. For each site, the above and below-ground dry weights were recorded for each species prior to being finely ground for nutrient profile analysis.

2.4 Near infra-red reflectance spectroscopy

Samples taken from 45 sites were analysed for a range of chemical constituents. Near infrared reflectance spectroscopy (NIRS) was used to analyse the nutrient content of seagrass samples following methods described by Lawler et al. (2006). This technique was chosen for its ability to identify the composition of organic samples in a rapid, cost-effective and repeatable manner (Shenk and Westerhaus, 1993; 1994). Calibration equations were developed to describe the relationships between NIRS spectra and their matching nutrient values (Shenk and Westerhaus, 1991), derived from the following laboratory methods: (1) total nitrogen (N) colorimetrically by the salicylate-hypochlorite method of Baethgen and Alley (1989); (2) total starch using the thermostable a-amylase and amyloglucosidase method of McCleary et al., (1997); (3) *in-vitro* dry matter digestibility (IVDMD) using Pepsin-Cellulase *In-Vitro* digestibility; (4) neutral detergent fibre (NDF), acid detergent fibre (ADF) and lignin using the Foss fibre cap system Fibretec 2023 (18 place); (5) total organic matter (OM) by straight ashing, and (6) water-soluble carbohydrate (WSC) by ethanol extraction.

2.5 Analyses

Analysis of relationships between seagrass characteristics and abiotic factors was conducted using Statistica (v6, StatSoft, Inc. 2001) and S-PLUS (Insightful Corp). All error estimates are given as ± standard error. Maps of seagrass species and nutrient distribution were generated from the benthic sled and NIRS data using ArcMap (Environmental Systems Research Institute, Inc., Redlands, CA). Analysis of variance was used to test the effects of environmental treatments on subtidal seagrass nutrient characteristics. Restricted maximum likelihood (REML) analysis was used to compensate for the lack of balance in some treatment combinations.

3. Results

3.1 Seagrass species distribution

Seagrass was found at 56 (33.3 %) of the 168 sample sites. Eleven species were encountered (Figure 2). Only the four most commonly occurring species (*C. serrulata, H. spinulosa, H. ovalis and S. isoetifolium)*, yielded enough dry-weight biomass (> 2 g DW) per sample site to conduct nutrient analyses (n = 45 sites). These four dominant species typically occurred in large (> 100 m^2) multispecific patches, separated by large gaps of bare sediment.

Sub-tidal seagrass distribution in the Torres Strait displayed a clear east-west partitioning at a regional scale >15 000 km^2 (Figure 3). Sub-tidal seagrasses were common west of the Warrior Reefs (<143°E) and generally absent within eastern sites (>143°E) which coincided with deeper water (mean = 25.1 ± 1.2 m below MSL) and sandy sediments. Sub-tidal seagrasses in central Torres Strait displayed clear north-south partitioning, with seagrasses common north of the Orman Reefs (>10.0°S). Seagrasses were only found in the southern part of the western region as few samples were collected in the north-west.

Seagrass was found most often in sites with sediments classified as muddy sand, gravelly sand and gravel (Figure 4). No seagrass was found growing at sites where the sediment was slightly gravelly sandy mud or gravelly mud. *H. spinulosa*, *H. ovalis* and *C. serrulata* were found growing in the broadest range of sediment types (7 of the 10 sediment categories recorded on this cruise). *S. isoetifolium* was generally restricted to medium sediments (gravelly muddy sand to sandy gravel) and was present in 5 of the 10 sediment categories.

Subtidal seagrasses in the Torres Strait were found at a maximum depth of 33.5m below MSL (*S. isoetifolium* and *C. serrulata*) (Figure 3, Site 2). Although the maximum depths recorded for seven of the 11 seagrass species were greater than 20 m, presence at this depth was rare (Figure 5). The mean combined depth of all subtidal seagrass was 12.6 ±0.8 m below MSL. With the exception of *C. rotundata*, the mean depth each species was found at was less than 15m. *C. serrulata* and *S. isoetifolium* had the broadest depth range of the eleven species found in the Strait (30.3 m). Seagrass species number (8 species) was highest in shallow water <5 m (Figure 5).

3.2 Seagrass nutrients

There were no significant effects of individual sample site or the latitude of individual sample sites on the nutrient concentrations of any seagrass species (all REML analysis p-values > 0.05). The only species which had a significant relationship between seagrass tissue nutrients and depth was *S. isoetifolium*, where starch concentration decreased with depth ($r^2 = 0.58$, p = 0.0002) (Figure 6).

3.2.1. Within plants

For all species, total nitrogen was higher in the above-ground tissue components than in the below-ground components. Conversely, total starch was higher in below-ground tissue components than in above-ground components for *H. ovalis* and *S. isoetifolium* (Table 1,

Figure 7). Neutral detergent fibre was higher in above-ground plant tissue than in below-ground tissue for all species except *H. spinulosa*.

3.2.2. Between species

The four seagrass species (whole plant) differed significantly from each other for total starch (df = 3, F = 21.86, p <0.001), water-soluble carbohydrates (df = 3, F = 14.78, p <0.001), *in-vitro* dry matter digestibility (df = 3, F = 131.04, p <0.001), organic matter (df = 3, F = 74.0, p <0.001), acid detergent fibre (df = 3, F = 47.52, p <0.001), neutral detergent fibre (df = 3, F = 41.69, p <0.001), and lignin (df = 3, F = 12.11, p <0.001). However, nitrogen concentration was not significantly different between seagrass species (df = 3, F = 2.46, p = 0.07) (Table 1, Figure 7).

The greatest inter-species nutrient variation was for starch concentration. Total starch content (whole plant) was highest in *H. ovalis* and lowest in *S. isoetifolium* (Tukey HSD post hoc test mean difference = 1.35, se = 0.23, p <0.001). *H. ovalis* had the highest seagrass *in-vitro* dry matter digestibility (mean = 83.2 ±0.66%), with the greatest significant interspecies difference in IVDMD occurring between *H. ovalis* and *C. serrulata* (mean difference = 16.8 ±1.11 %, p <0.001).

4. Discussion

This survey provides a valuable snapshot of the species distribution and nutritional value of sub-tidal Torres Strait seagrasses. The Torres Strait seagrass communities we sampled had high diversity, with eleven species recorded. Subtidal seagrass communities were primarily restricted to the central and western regions of the Torres Strait. The eastern region, comprising nearly half the Torres Strait, was mostly devoid of seagrass. Our findings support previous surveys of Torres Strait seagrass distribution and species diversity (Pitcher et al., 1992, 2004; Long and Poiner, 1997), indicating this distribution has remained constant for over a decade. Management to protect sub-tidal seagrass resources that are important for large marine herbivores such as dugongs and turtles should be focused on the extensive sub-tidal seagrass communities of the central and western regions. Long and Poiner (1997) found the eastward decrease of sub-tidal seagrass in Torres Strait correlates with increased water turbidities. In the Torres Strait, it is likely that the high current flows, close proximity of land masses, and regions with high rainfall lead to generally more turbid waters than those found in adjacent waters such as the Great Barrier Reef lagoon.

The physical variables that we examined explain relatively little of the spatial patterns in sub-tidal seagrass, other than an absence of seagrass in waters deeper than 33.5 m and an absence of seagrass in fine, muddy sediments. Seagrasses have been found at depths of up to 60 m in the Great Barrier Reef (Coles et al., 2000). *T. hemprichii, C. rotundata, H. uninervis* and *S. isoetifolium* were recorded at depths of more than 25 m. This is considerably deeper than the 5 – 15 m range these species have been found in previous studies of seagrass meadows along the north eastern coast of Australia (Lee Long et al., 1996; Coles et al., 2000). Environmental conditions specific to the Torres Strait (e.g., constant nutrient availability, high water clarity, high water temperatures) may allow these species to grow at depths beyond their usual limits. Exploiting deeper than usual habitats may not be without metabolic cost to the plant. The starch content of *S. isoetifolium*, a species that typically occurs in intertidal/shallow sub-tidal waters 5 – 12 m (Coles et al., 2000), decreased significantly with increased depth; presumably making it less nutritious to subtidally foraging herbivores.

This study is the first nutritional analysis of sub-tidal seagrasses in Torres Strait, and the first study to provide a map comparing the nutritional value of sub-tidal meadows in the Torres Strait region (Figure 8). The nutritional profiles of the four tropical seagrasses we sampled were generally consistent with previous studies of the same species (see Lanyon, 1991; de Iongh et al., 1995; Aragones, 1996; Udy and Dennison, 1997; Mellors, 2003; Yamamuro et al., 2004; Yamamuro and Chirapart, 2005; Sheppard et al., *in press*). The nitrogen content of the leaves of all species of seagrass studied here was within the range previously reported for tropical seagrasses (1.8% N DW, cf. Duarte, 1990). The preponderance of starch in the below-ground component of these tropical species confirms previous findings that seagrass rhizomes provide a rich source of starch (Birch, 1975; Masini, 1983; Lanyon, 1991; Mellors, 2003; Aragones et al., 2006; Sheppard et al., *in press*).

The 4.1 % (± 0.3 se) whole-plant mean lignin concentration for *H. ovalis* sampled in the Torres Strait was considerably lower than the 9 – 10 % range recorded by Aragones et al. (2006) for *H. ovalis* in tropical north Queensland, and lower than the 15 % (± 0.96 se) recorded for *H. ovalis* in sub-tropical Queensland by Sheppard et al. (*in press*) and by Bité, J. (*pers. comm.*). These previous three studies on seagrass nutrient content were conducted using the same methodology as ours. Therefore, this decrease in seagrass lignin concentration with latitude may reflect regional differences driven by environmental factors specific to each study area. Also, the previous studies collected primarily intertidal *H. ovalis*; the deep water seagrasses we collected may have invested more energy into compensating for reduced photosynthesis in light-limited depths instead of accumulating lignin. Reduced wave action in deep water may reduce the need for plant structural carbohydrates.

The selection of food resources by dugongs is believed to be determined by the availability of seagrass species of high nutrient quality (Heinsohn and Birch, 1972; Marsh et al., 1982; Lanyon et al., 1989; Preen, 1995; Aragones et al., 2006; Sheppard et al., *in press*). Availability of starch and nitrogen determine population fitness in herbivores, and these are the most cited indicators of habitat nutritional quality in large terrestrial grazers (e.g., Illius and Gordon, 1993; Van Wieren, 1996; Prins and Olff, 1998; Augustine and Frank, 2001; Mutanga *et al.*, 2004). To provide the metabolic reserves required to sustain reproduction dugongs must consume plants high in nitrogen and starch (Kwan, 2002; Sheppard et al., *in press*). *H. ovalis* was the most nutritious of the four most commonly encountered sub-tidal seagrass species in the Torres Strait, with high nitrogen, starch and digestibility and low fibre levels. Whole-plant *H. ovalis* possessed nearly twice as much starch as *S. isoetifolium*. However, the below-ground starch content of *H. ovalis* was >20 % higher than the above-ground component. Consequently, sub-tidal nitrogen and starch distributions in the Torres Strait were concentrated where *H. ovalis* was prevalent, particularly around the south-west and north-central regions. The nutritional superiority of *H. ovalis* coupled with its broad geographic and depth distribution likely make it an important seagrass species for dugong foraging subtidally in the Torres Strait. *H. ovalis* is consistently present in dugong stomach content samples and in the seagrass meadows dugongs target (Marsh et al., 1982; de Iongh et al., 1995; Preen, 1995; Aragones and Marsh, 2000; Masini et al., 2001; André and Lawler, 2003).

Although *S. isoetifolium* had considerably less starch content (particularly with increasing depth) and digestibility than *H. ovalis*, it had slightly higher nitrogen content and lower fibre and lignin levels. Given its similar geographic range to *H. ovalis*, *S. isoetifolium* may also constitute an important food resource. André et al. (2005) found a high proportion of *S. isoetifolium* amongst the seagrasses sampled from the stomachs of dugongs from the Torres Strait, in contrast to low levels of *H. ovalis*. *S. isoetifolium* is generally a larger plant than *H.*

ovalis. *S. isoetifolium* also forms denser meadows and has higher total biomass in the Torres Strait than *H. ovalis* (Long and Poiner, 1997). Food seagrasses that occur in concentrated patches will presumably increase the foraging efficiency of a grazing herbivore by reducing search costs and maximising intake rates for grazing effort. *S. isoetifolium* provides less nutritional energy than *H. ovalis* when compared on an individual plant basis; however the large morphology, dense patch characteristics and high prevalence (total availability) of *S. isoetifolium* may enhance its dietary value to a foraging dugong. Variability in seagrass palatability, although not tested in this study, may also play a role in dugong diet selection (André et al., 2005). For instance, seagrass tannin concentrations were not tested.

Green turtles appear to be more flexible and opportunistic foragers than dugongs. In the Torres Strait, the green turtle populations are dominated by immature animals that are predominantly seagrass feeders in seagrass areas or algal-feeders in areas with abundant algae (Garnett et al., 1985; Lanyon et al., 1989; Read, 1991; Forbes, 1996; Brand-Gardner et al., 1999; Andre et al., 2005). When feeding on seagrass, green turtles graze at the base of the shoots, where they obtain the younger leaves, without disturbing the below ground plant parts (Lanyon et al, 1989; Aragones and Marsh, 2000).

Similar to dugongs, immature green turtles generally select food on the basis of high nitrogen and low fibre levels (Ross, 1985; Jupp et al., 1996; Brand-Gardner et al., 1999; Andre et al, 2005). In the Torres Strait, immature green turtles are reported to feed predominately on *T. hemprichii* and *E. acoroides*, but also ingest other species to a less degree including *T. ciliatum, Cymodocea* spp, *H. uninervis, S. isoetifolium, H. ovalis* and *H. spinulosa* (Garnett et al., 1985; Andre et al., 2005).

Although green turtles generally spend 90% of their time feeding in waters shallower than 4 m (Hays et al., 2002), this appears predominately a consequence of greater seagrass abundance at these depths. Feeding at depths to 20m is considered no more exhaustive for green turtles than feeding shallower than 4m, as at deeper depths individuals can still attain near-neutral buoyancy after diving with full lungs (Hays et al., 2000, 2001, 2002). Subtidal seagrass resources therefore provide a suitable alternative for green turtles in the event of shallow water seagrass loss caused by impacts at both localised (e.g., land use and development) or regional (e.g., climate change) scales.

The sampling methods used in this study enabled a large geographic region to be surveyed in a relatively short time period, albeit with some compromises. Use of a sled for collecting samples may have over-represented shallow-rooted species such as *H. ovalis* at the expense of deep-rooted species such as *T. hemprichii*. Other seagrass species which contribute significantly to the diets of marine herbivores, such as *T. hemprichii, E. acoroides* and *H. uninervis,* are commonly found on reefs and in shallow intertidal waters around continental islands in Torres Strait (Long and Poiner, 1997); areas that we were unable to sample because of the size of our survey vessel Nevertheless, given that we encountered eleven of the twelve seagrass species recorded by previous studies, we believe that our sampling regime was intense enough to capture a realistic broad-scale representation of sub-tidal seagrass species distribution in the Torres Strait.

Although dugongs have been observed in deep waters (> 30 m) they are generally restricted to foraging in less than 20-30 m depths due to physiological and energetic constraints (Marsh et al., 1978; Chilvers et al., 2004; Sheppard et al., 2006). Consequently, dugong population fitness is likely determined by the availability of seagrass meadows of high nutritional quality in water

< 20 m deep. We identify two optimal subtidal sites for dugongs foraging in the Torres Strait, based on high concentrations of seagrass starch located in comparatively low water depths (< 20 m); (1) a south-western site, and (2) the north-central site (Figure 8). Both sites are at a distance of more than 20 km from inhabited islands and areas of disturbance and high boat traffic. The north-central site is also situated in a zone permanently closed to prawn trawling. It has been previously recognized as an area important to dugong based on the large populations of dugongs consistently observed during aerial surveys in 1987, 1991, 1996 and 2001 (Marsh et al., 2004a, 2004b). While trawling is permitted south of 10°28 in the south-western site (Torres Strait Prawn Fishery Working Group, 1999) the area was identified as a site important for dugong and established in 1985 as a management zone within which dugong fishing is not permitted (Commonwealth of Australia, 2003).

Dugongs and green turtles are fished in the Torres Strait by Papua New Guinea and Australian traditional fishers for food and ceremony. Fishing for dugong in Torres Strait at the present level is considered unsustainable in the Torres Strait (Heinsohn et al., 2004; Marsh et al., 2004b). However, providing appropriate management advice is difficult when the dugong fishery is not simply a fishery but part of the rich cultural and traditional ceremonial life in Torres Strait, involves two countries with differing needs and approaches, and where data is limited on dugong density and catches from all locations where dugongs are found (e.g. Marsh et al., 1997, 2004a). Our approach has been to map, using quantitative metrics, areas of quality food at depths accessible for feeding. This adds to the knowledge available for fisheries managers and Torres Strait Islander fishers and will assist in providing an understanding of the habitat issues important for sustainable management of the dugong fishery.

5. Conclusions

1. The Torres Strait has eleven species of tropical seagrasses in sub-tidal waters. There are large spatial discontinuities in the meadows with almost no seagrass east of the Warrior Reef complex. In this study seagrass was prevalent in the north-central and south-west, a distribution pattern that is likely to be a consistent feature of the region.

2. The seagrass meadows in the Torres Strait are habitat for juvenile penaeid prawns and food for green turtle and dugong. Turtle and dugong populations in the Torres Strait are fished and managed as traditional fisheries as part of the Torres Strait Treaty agreement between Australia and Papua New Guinea. Present fishing levels are likely to be unsustainable and understanding the relationship between the animals and their food sources will assist in providing effective management advice.

3. For all seagrass species, the above-ground component (shoots and leaves) possessed greater nitrogen concentration than the below-ground component (roots and rhizomes), which possessed greater starch concentration. *H. ovalis* possessed the highest total starch and highest digestibility, as well as the lowest fibre. The high relative abundance and quality nutrient characteristics of *H. ovalis* make it an important source of energy to marine herbivores that forage sub-tidally in the Torres Strait.

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Table and Figure Captions

Table 1. Mean % nutrient concentrations for above and below-ground plant fractions of the four dominant species of sub-tidal seagrass sampled in the Torres Straits.

Figure 1. Map of Torres Strait showing the jurisdictional boundaries and spatial zones of the study area (adapted from Long and Poiner, 1997; Pitcher et al., 2004).

Figure 2. Frequencies of seagrass species encountered from 168 sub-tidal sample sites in the Torres Strait.

Figure 3. Seagrass species distribution from 168 sample points across the Torres Straits. (HO = *H. ovalis,* SI = *S. isoetifolium,* CS = *C. serrulata*, HS = *H. spinulosa*, HU = *H. uninervis (wide),* TH = *T. hemprichii*, EA = *E. acoroides,* HD = *H. decipiens,* HC = *H. capricorni*, CR = *C. rotundata*, TC = *T. ciliatum*).

Figure 4. Percentage of sites with seagrass present (all species pooled) for each sediment category. Sediment is classified from fine (slightly gravelly sandy mud) to coarse (gravel).

Figure 5. Mean depth and range (below msl) for 11 species of seagrass present in Torres Strait subtidal waters.

Figure 6. Negative linear relationship between water depth and starch content for *S. isoetifolium*.

Figure 7. Plots of (A.) mean seagrass nitrogen and starch concentrations, and; (B.) mean *in-vitro* dry matter digestibility (IVDMD) and acid detergent fibre (ADF) (HO = *H. ovalis,* SI = *S.*

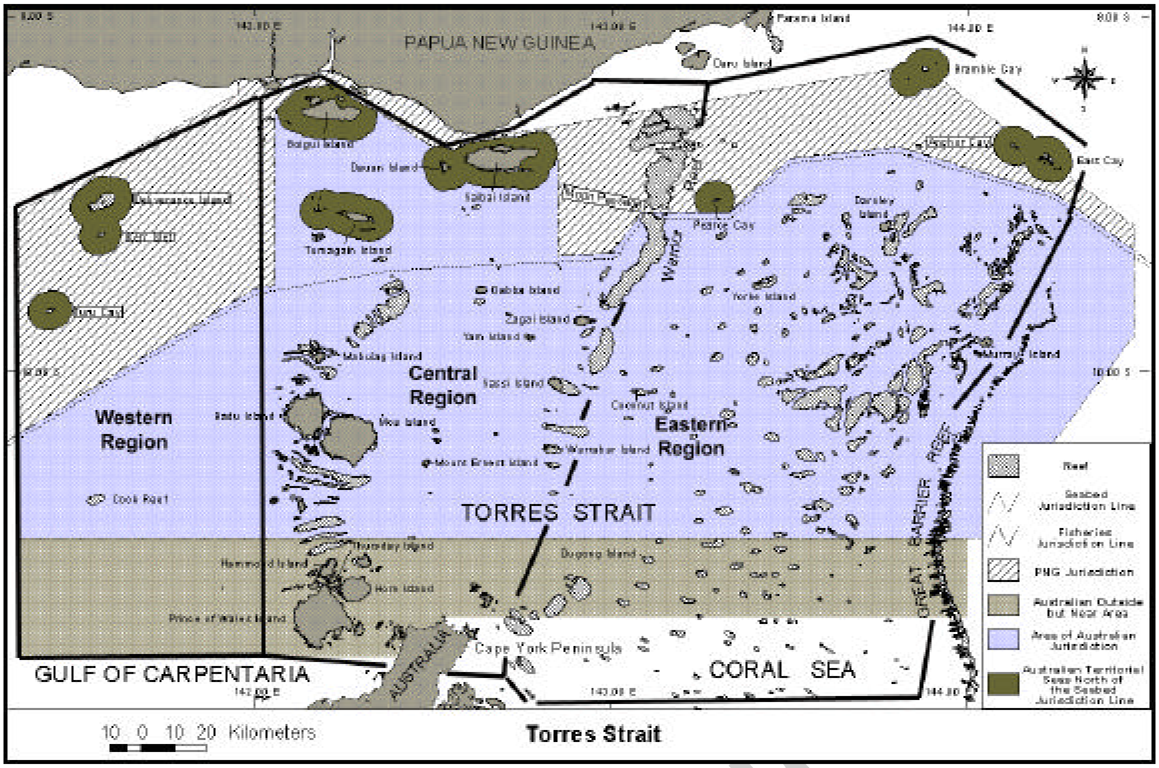
isoetifolium, CS = *C. serrulata* and HS = *H. spinulosa*). L = leaves, stems and shoots (above ground), R = roots and rhizomes (below ground).

Figure 8. The north-central and south-west sites are optimal dugong foraging sites in the Torres Strait with high seagrass starch concentrations and shallow water (3-20 metres). The diagonal lines represent a dugong sanctuary that was established in 1985 as a management zone within which dugong fishing is banned (Commonwealth of Australia, 2003). Black stippled areas represent a 20 km buffer of potential anthropogenic disturbance around inhabited islands.

Species[1]	Plant component	N Mean	se	Starch Mean	se	WSC Mean	se	IVDMD Mean	se	OM Mean	se	ADF Mean	se	NDF Mean	se	Lignin Mean	se
HO	Above-ground	1.65	0.03	2.50	0.10	2.68	0.20	81.72	0.48	28.51	0.75	24.55	0.60	43.59	0.72	4.13	0.37
	Below-ground	0.74	0.03	3.03	0.12	2.41	0.25	87.11	0.58	33.74	0.91	30.75	0.73	38.18	0.88	4.50	0.38
	Whole plant	1.32	0.05	2.76	0.12	2.80	0.29	83.24	0.66	29.78	1.26	27.15	0.66	41.31	1.06	4.10	0.28
CS	Above-ground	1.86	0.02	2.28	0.08	1.66	0.16	67.03	0.37	39.29	0.58	34.88	0.46	56.48	0.55	6.99	0.21
	Below-ground	0.66	0.02	2.39	0.08	2.44	0.16	64.96	0.39	70.11	0.61	33.16	0.48	37.84	0.58	7.46	0.23
	Whole plant	1.35	0.04	2.30	0.10	1.84	0.24	66.41	0.56	52.45	1.05	34.13	0.55	48.70	0.89	7.16	0.17
HS	Above-ground	1.39	0.02	1.99	0.07	2.06	0.14	72.24	0.32	36.31	0.50	33.18	0.40	47.07	0.48	4.48	0.20
	Below-ground	0.85	0.02	1.87	0.09	3.86	0.18	83.42	0.42	45.65	0.65	35.65	0.52	49.06	0.62	4.86	0.26
	Whole plant	1.22	0.04	1.92	0.09	2.43	0.24	75.51	0.55	38.71	1.04	34.00	0.54	48.17	0.87	4.56	0.15
SI	Above-ground	1.75	0.03	1.19	0.11	5.59	0.21	78.72	0.51	30.24	0.79	42.19	0.63	40.07	0.76	NA[2]	NA
	Below-ground	1.11	0.03	1.73	0.10	3.22	0.21	74.95	0.49	39.56	0.76	33.55	0.61	31.09	0.73	6.48	0.28
	Whole plant	1.40	0.05	1.42	0.12	4.30	0.29	75.84	0.68	35.01	1.29	38.21	0.68	35.05	1.09	NA	NA

Table 1. Mean % nutrient concentrations for above and below-ground plant fractions of the four dominant species of sub-tidal seagrass sampled in the Torres Straits.

[1] (HO = *H. ovalis,* SI = *S. isoetifolium,* CS = *C. serrulata* and HS = *H. spinulosa*).
[2] There was not enough plant material collected to conduct an accurate test for above-ground and whole-plant lignin on *S. isoetifolium*



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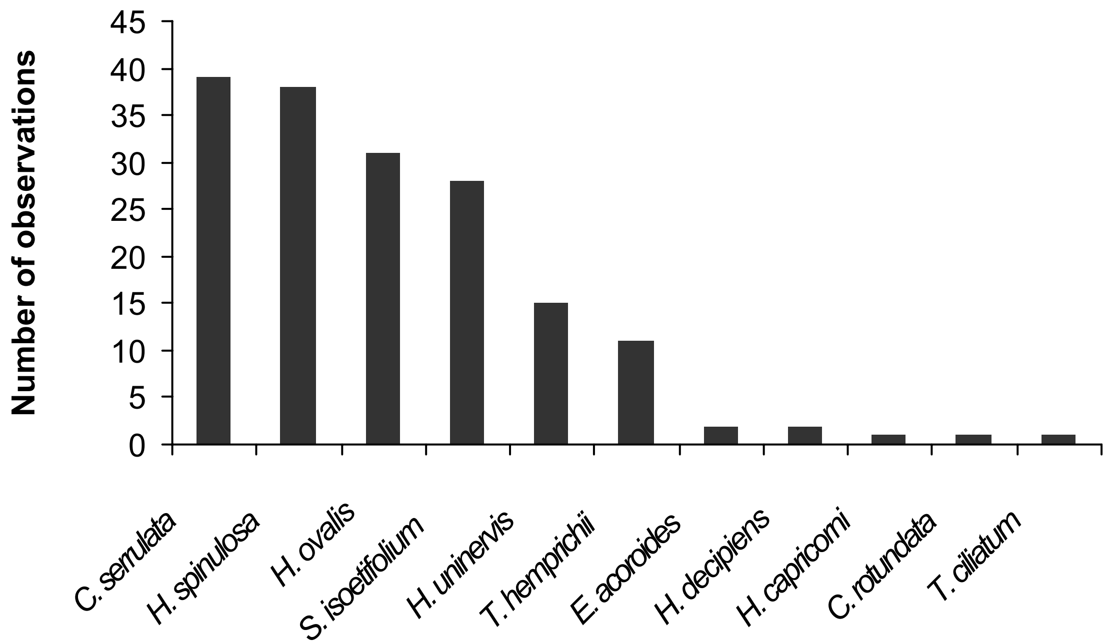
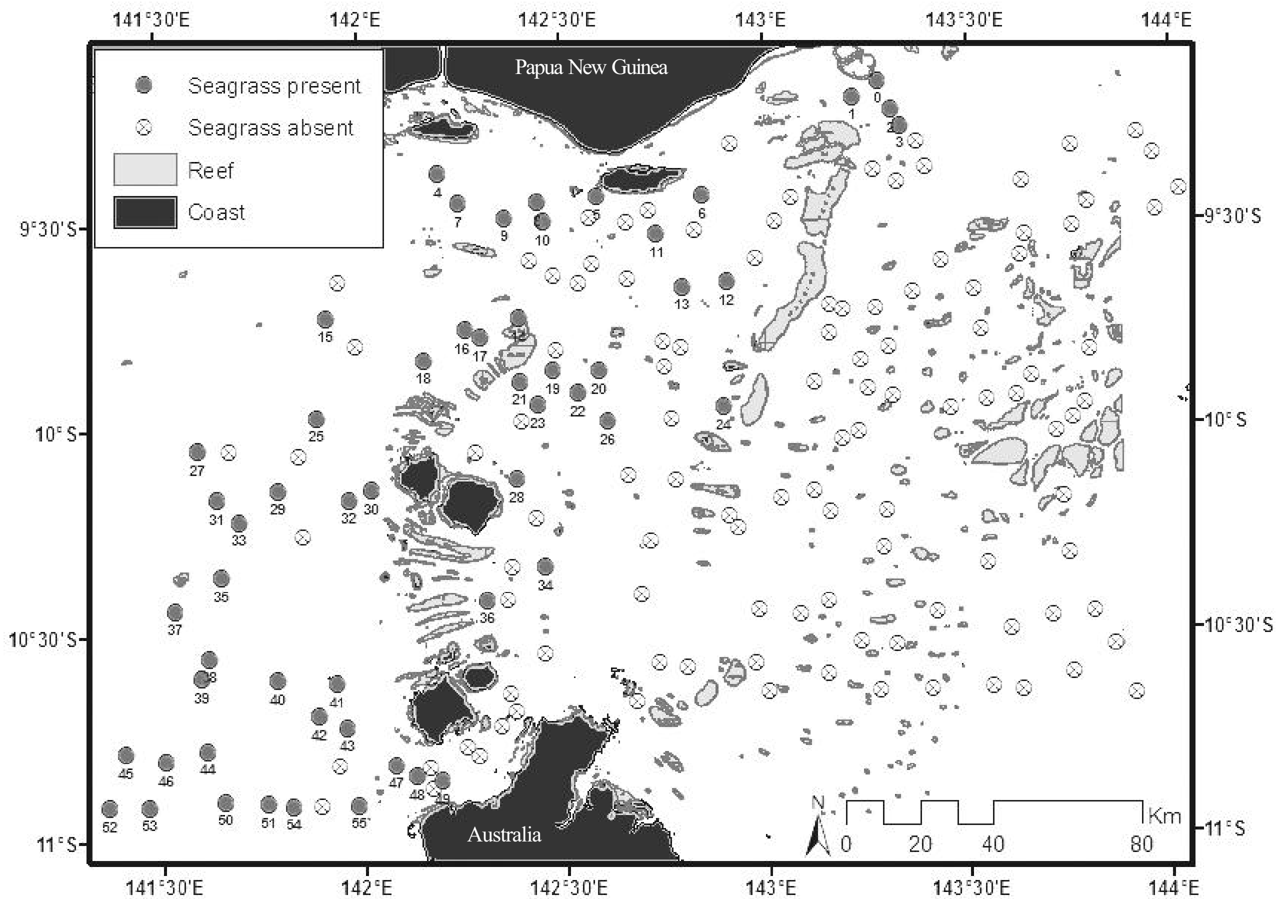
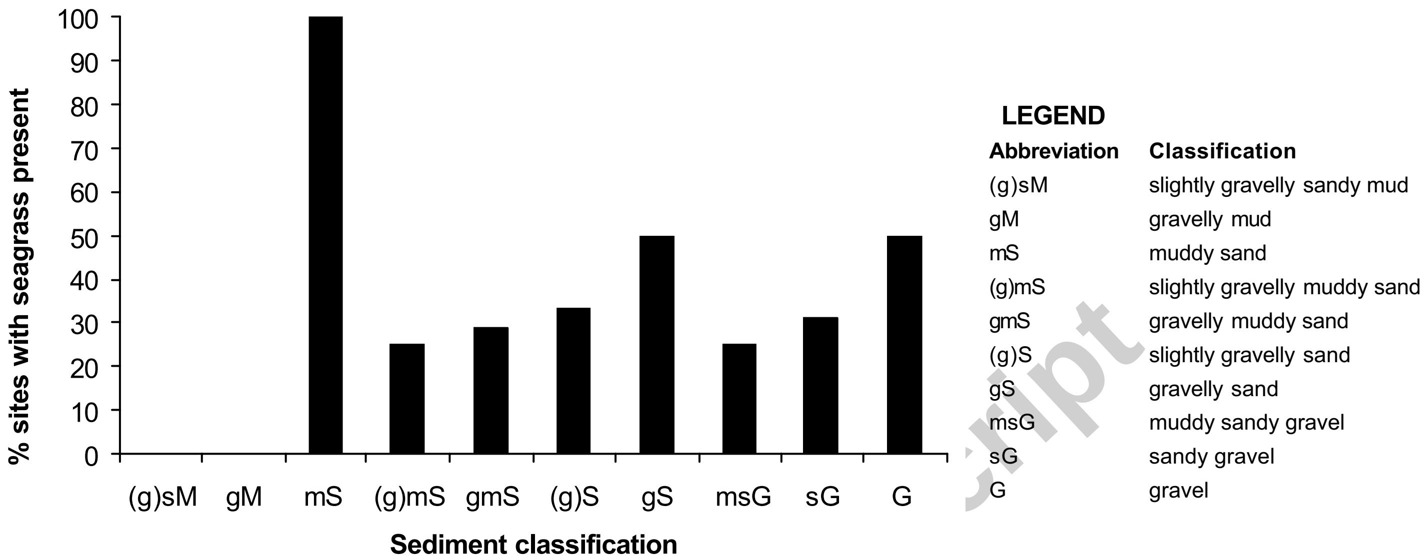


Figure 2. Frequencies of seagrass species encountered from 168 sub-tidal sample sites in the Torres Strait.



Site #	Species present	Site #	Species present	Site #	Species present
0	CS	19	HO HS CS	38	HO HU HS CS SI
1	TH	20	HS	39	HO HU HS CS SI
2	CS SI	21	HO HS CS SI	40	HU CS SI
3	HU CS SI CR	22	HO HU CS	41	HS CS SI
4	HO HD HU HS CS SI TH	23	HS CS	42	HO HU HS CS SI
5	CS EA TH	24	HU HS	43	HO HS CS
6	TH	25	TH	44	HO HS CS SI
7	HO HS CS SI	26	HO HS CS	45	HO HS CS SI
8	HO SI	27	HO HS CS SI	46	HO HS CS SI
9	CS	28	HU CS	47	HS CS SI
10	HS TH	29	CS	48	SI EA
11	HD TH	30	HO HU HS CS SI TH TC	49	HS SI
12	HS TH	31	HO HS CS SI	50	HO HS
13	HO HU HS	32	HO HU CS SI	51	HO HS CS SI
14	HS CS	33	HO HS CS	52	HO HS
15	HU HS CS SI	34	HO HS CS SI	53	HO HS CS
16	HO HS SI TH	35	HO HS CS	54	CS
17	HO HU HS SI	36	HO	55	HS CS
18	HC HO HU HS CS SI	37	HO HS CS SI		

Figure 3. Seagrass species distribution from 168 sample points across the Torres Straits. (HO = *H. ovalis,* SI = *S. isoetifolium,* CS = *C. serrulata*, HS = *H. spinulosa*, HU = *H. uninervis (wide),* TH = *T. hemprichii*, EA = *E. acoroides,* HD = *H. decipiens,* HC = *H. capricorni*, CR = *C. rotundata*, TC = *T. ciliatum*).



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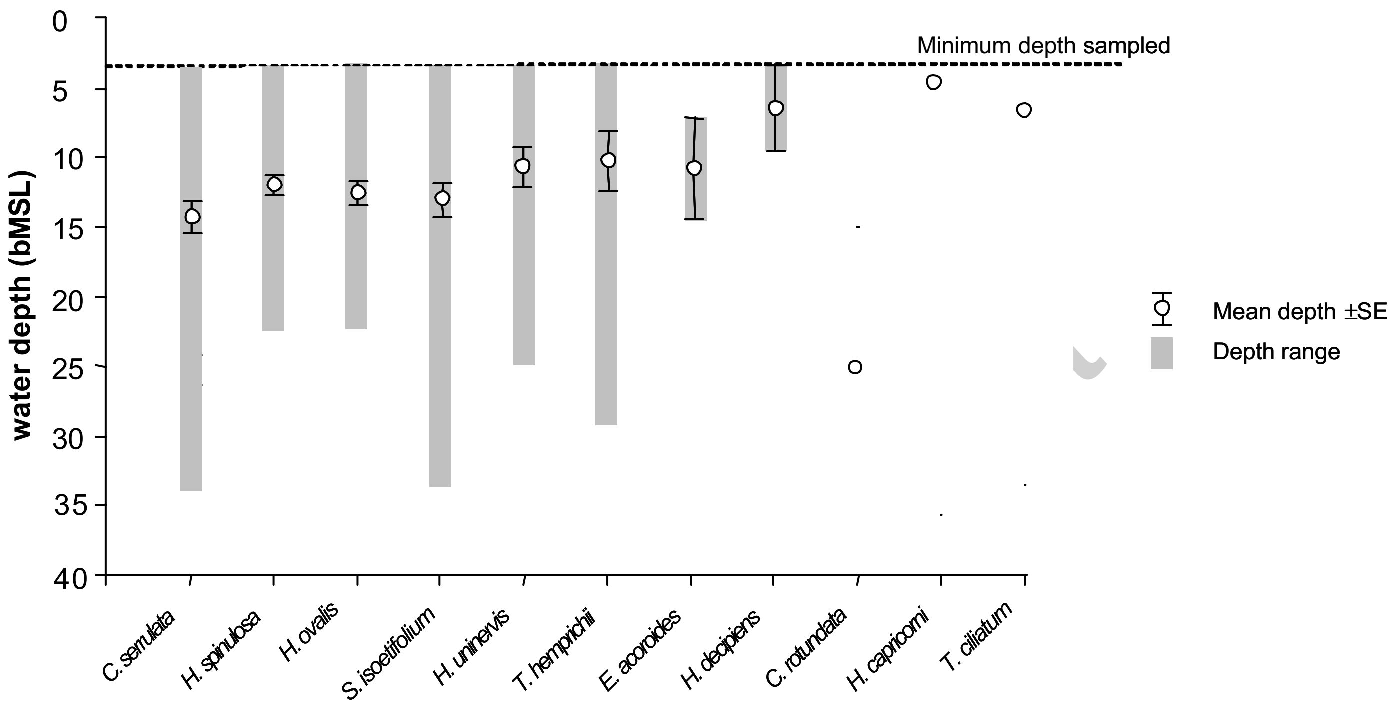

Figure 5. Mean depth and range (below msl) for 11 species of seagrass present in Torres Strait subtidal waters.

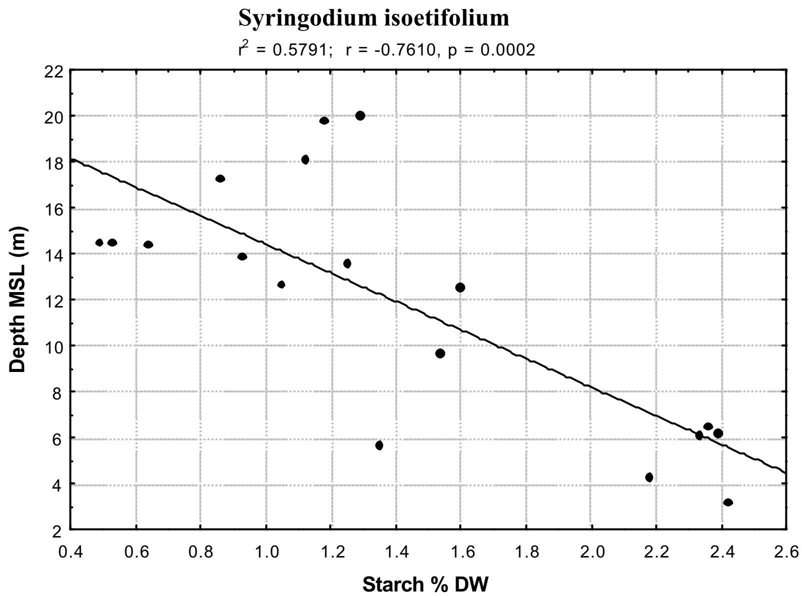

Figure 6. Negative linear relationship between water depth and starch content for *S. isoetifolium*.

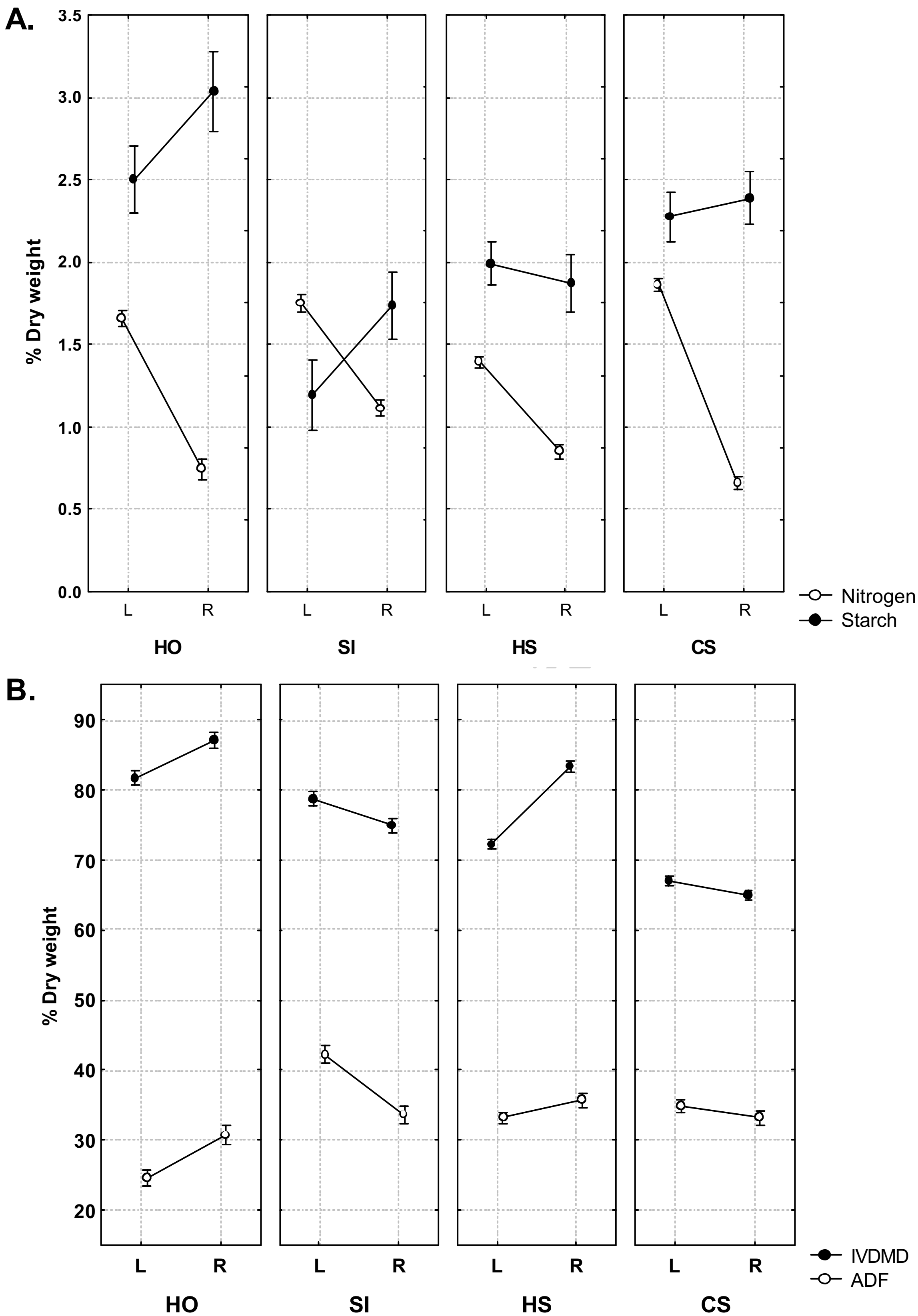

Figure 7. Plots of (A.) mean seagrass nitrogen and starch concentrations, and; (B.) mean *in-vitro* dry matter digestibility (IVDMD) and acid detergent fibre (ADF) (HO = *H. ovalis,* SI = *S. isoetifolium,* CS = *C. serrulata* and HS = *H. spinulosa*). L = leaves, stems and shoots (above ground), R = roots and rhizomes (below ground).

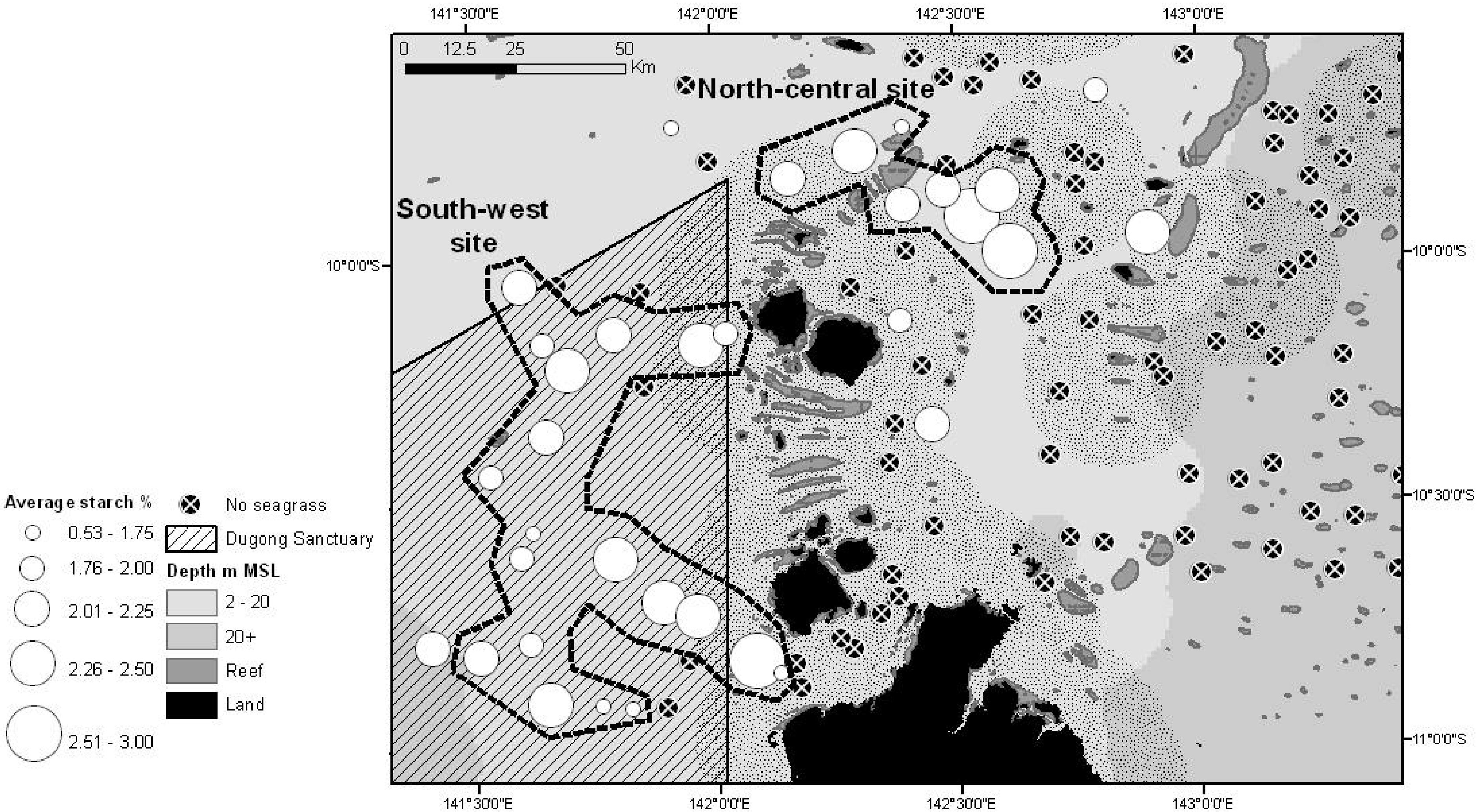

Figure 8. The north-central and south-west sites are optimal dugong foraging sites in the Torres Strait with high seagrass starch concentrations and shallow water (3-20 metres). The diagonal lines represent a dugong sanctuary that was established in 1985 as a management zone within which dugong fishing is banned (Commonwealth of Australia, 2003). Black stippled areas represent a 20 km buffer of potential anthropogenic disturbance around inhabited islands.