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PORT OF ABBOT POINT LONG-TERM SEAGRASS MONITORING:

ANNUAL REPORT 2013 - 2014

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Report No. 15/12

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A Report for North Queensland Bulk Ports Corporation (NQBP)

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KEY FINDINGS

This report presents the latest findings of the long-term seagrass monitoring program for the Port of Abbot Point that has been conducting quarterly assessments of seagrass since 2008.

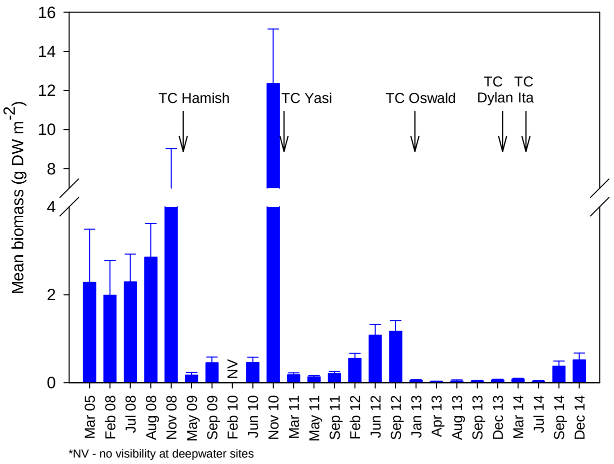
1. After 19 months of declines following Tropical Cyclone Oswald and associated rainfall, high winds and flooding, offshore seagrasses (*Halophila* species) showed significant increases in biomass in September and December 2014;
2. Inshore monitoring meadows have yet to show substantial recovery, however the presence of *Halodule uninervis* and *Zostera muelleri* at some of the inshore meadows are positive signs of initial re-establishment and recovery;
3. The first ever recorded occurrence of *Halophila tricostata* in the Abbot Point/Bowen area was made in the September 2013 survey. *Halophila tricostata* was again present in the September 2014 survey.
4. Light and climate conditions were favourable for seagrass growth and the delay in recovery observed is likely a reflection of previous large scale declines limiting the availability of propagules from which recovery could be initiated and sustained;
5. Initial light requirement thresholds were developed for *Halophila* species and *Halodule uninervis* derived by a review of the literature, ongoing studies and analysis of *in situ* data on light and seagrass change collected at Abbot Point between 2013 and 2014;
6. Future plans for incorporating light based triggers for seagrass management at Abbot Point should remain flexible to allow additional information from ongoing data collection on site, or any additional new studies to be incorporated in refining the initial threshold;
7. Assessments of seagrass seed banks and their viability will be a key addition to the monitoring program to understand their resilience to impacts and potential for recovery;
8. The declines in Abbot Point seagrasses over recent years mean that they likely have a reduced resilience to further impacts and stressors. The cumulative impacts of natural stressors need to be considered in conjunction with future developments associated with port expansions in formulating management strategies to protect seagrasses and allow for their continued recovery.

IN BRIEF

Seagrasses have been monitored quarterly in the Port of Abbot Point since 2008. Each quarter seagrass monitoring meadows representing the range of different seagrass community types found in the Abbot Point area are mapped and assessed for changes in area (inshore meadows only), biomass and species composition. Significant losses of biomass and distribution of seagrasses at Abbot Point were observed after the La Niña events of 2010/11 and severe Tropical Cyclone Yasi, and also after TC Oswald (Figure 1). Similar declines to seagrasses were also seen in other areas of tropical eastern Queensland including Cairns, Mourilyan Harbour, Townsville and Gladstone.

Despite encouraging signs of deep water seagrass recovery after TC Yasi, deep water seagrass declined in density again through 2013 following Tropical Cyclone Oswald and associated rainfall, high winds and flooding (Figure 1). Since TC Ita however, there has been significant recovery of deep water *Halophila* species at Abbot Point (Figure 1). Inshore monitoring meadows have yet to show substantial recovery, however the presence of *Halodule uninervis* and *Zostera muelleri* at some of the inshore meadows are positive signs of initial re-establishment.

The amount of light (PAR) available to seagrasses in the Abbot Point area is similar and comparable to the light environments at other areas of deep water seagrass where PAR is monitored including Green Island off Cairns and Lizard Island in the northern Great Barrier Reef.



*NV - no visibility at deepwater sites

Figure 1. Mean biomass (g DW m^{-2}) of Abbot Point offshore seagrass monitoring sites from 2005 to 2014.

A review of the literature, analysis of ongoing studies by the JCU seagrass group, and analysis of the Abbot Point light and seagrass biomass data has shown that for deep water *Halophila* species at Abbot Point, 1.5 mol photons m^{-2} d^{-1} for at least 7 days best described the light conditions at which seagrass biomass was maintained. For the inshore *H. uninervis* meadows, it was found that 3.5 mol photons m^{-2} d^{-1} over a 14 day rolling average best described the light conditions at which seagrass biomass was maintained. From these results we can say that at the very least, the last two growing seasons (approximately July to January), there has been enough light to support and maintain seagrass at Abbot Point.

While the monitoring program provided a sound basis for developing local light thresholds for *Halophila* spp. and *H. uninervis*, these values are initial thresholds only and refining them into values for use in management/compliance during dredge operations would need further investigations to strengthen those relationships including;

- *Increase the seagrass sampling frequency to monthly between July and December 2015*
- *In situ shading studies;*
- *Laboratory studies;*
- *Investigate the effects of changes in the spectral quality of light associated with dredge plumes*.

The threshold values for the species derived in this report were heavily informed by the *in situ* light and seagrass monitoring at Abbot Point. This monitoring has provided critical information on the light environment associated with the maintenance or increase in seagrass at the sites and emphasises the value of keeping these loggers and seagrass monitoring in place. In addition, given the large changes that have occurred in Abbot Point seagrass biomass and distribution as a result of climatic events, it will be important to maintain monitoring as multiple years of climate induced seagrass decline are likely to have left a legacy of reduced resilience to further impacts. Continued monitoring throughout future dredging programs and as part of an ongoing ambient seagrass program will also help assist in separating out port related versus regional causes of seagrass change detected in the monitoring program.

The Abbot Point seagrass monitoring program forms part of a broader Queensland program that examines condition of seagrasses in the majority of Queensland commercial ports and is a component of James Cook University's (JCU) broader seagrass assessment and research program. Other Queensland seagrass monitoring locations such as Cairns, Townsville and Gladstone have also recorded increases in biomass and distribution at monitoring sites since major declines. For full details of the Queensland ports seagrass monitoring program see www.jcu.edu.au/portseagrassqld.

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1 INTRODUCTION

Seagrasses provide a range of critically important and economically valuable ecosystem services including coastal protection, support of fisheries production, nutrient cycling and particle trapping (Costanza et al. 1997; Hemminga and Duarte 2000). With globally developing carbon markets, the role that seagrasses play in sequestering carbon is also becoming more widely recognised (McLeod et al. 2011; Fourqurean et al. 2012; Macreadie et al. 2013). Seagrass meadows show measurable responses to changes in water quality, making them ideal candidates for monitoring the long-term health of marine environments (Dennison et al. 1993; Abal and Dennison 1996; Orth et al. 2006).

1.1 Queensland Ports Seagrass Monitoring Program

A long-term seagrass monitoring and assessment program has been established in the majority of Queensland commercial ports. The program was developed by the Seagrass Ecology Group at James Cook University's Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER) in partnership with the various Queensland port authorities. While each location is funded separately and they have a range of requirements for use of the information, a common methodology and rationale is utilised to provide a network of seagrass monitoring locations throughout the state (Figure 2).

A strategic long term assessment and monitoring program for seagrasses provides port managers and regulators with the key information to ensure effective management of seagrass resources. It is useful information for planning and implementing port development and maintenance programs so they have a minimal impact on seagrasses. The program also provides an ongoing assessment of many of the most threatened seagrass communities in the state.

Figure 2 Location of Queensland Port Seagrass assessment sites

The program not only delivers key information for the management of port activities to minimise impacts on seagrasses but has also resulted in significant advances in the science and knowledge of tropical seagrass ecology. It has been instrumental in developing tools, indicators and thresholds for the protection and management of seagrasses and an understanding of the drivers of tropical seagrass change. It provides local information for individual ports as well as feeding into regional assessments of the status of seagrasses.

For more information on the program and reports from the other monitoring locations see www.jcu.edu.au/portseagrassqld

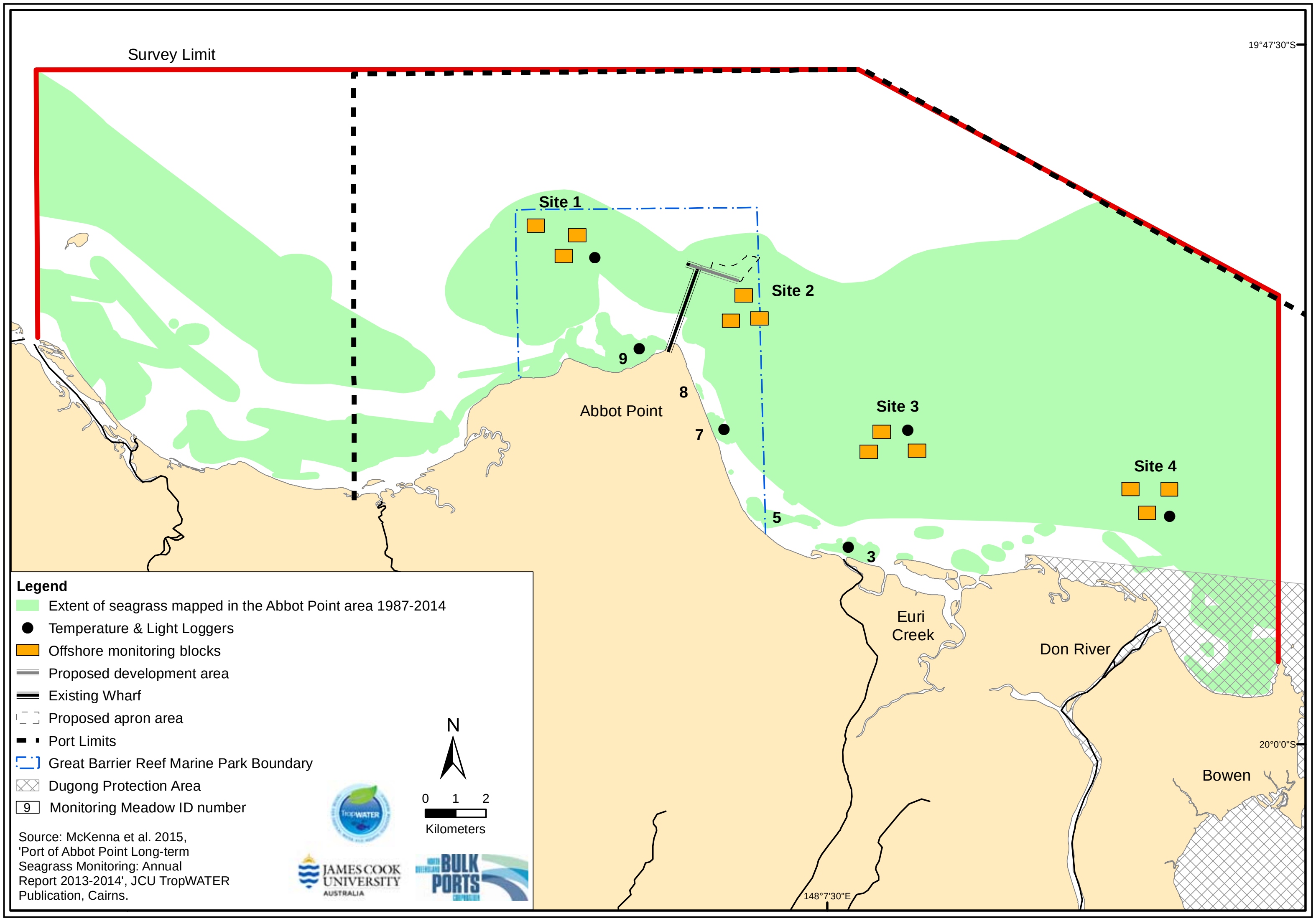
1.2 Abbot Point Seagrass Monitoring Program

North Queensland Bulk Ports Corporation (NQBP) in partnership with the Seagrass Ecology Group at TropWATER have been engaged in a seagrass assessment and monitoring program at Abbot Point since 2008. This program has involved four baseline surveys (two each in 2008 & 2013) of the marine habitat within the port limits, manipulative experimental research of the seagrass at the port, long-term monitoring of representative seagrass meadows at inshore and offshore areas, and light (Photosynthetically Active Radiation (PAR)) and temperature assessments at the seabed (McKenna et al. 2008; Unsworth et al. 2010; Mckenna & Rasheed 2013; McKenna & Rasheed 2014a; Rasheed et al. 2014) (Figure 3). The long-term monitoring areas represent the range of seagrass communities within the port and include meadows considered most likely to be impacted by port activity and development, as well as areas unlikely to be impacted by port development, to assist in separating out port related versus regional causes of seagrass change detected in the monitoring program (Figure 3).

The program was developed to aid in the management of planned port expansions and to minimise potential impacts of port activities on seagrass habitats, and to assess the long-term condition and trend of this important fisheries habitat. Seagrass monitoring surveys satisfy environmental monitoring requirements as part of the port's long-term dredge management plan and are used by management agencies to assess the status and condition of seagrass resources in the region. The monitoring program also forms part of Queensland's network of long-term monitoring sites of important fish habitats in high risk areas.

This report updates the results of long-term seagrass monitoring for assessments between January 2014 and December 2014. The objectives of the long-term seagrass monitoring program of the Port of Abbot Point are to:

1. Compare results with baseline and quarterly monitoring events to assess any changes in seagrass distribution and abundance in relation to natural events or anthropogenic activities;
2. Relate changes measured in seagrass meadows to light and temperature data collected;
3. Discuss the implications of monitoring results for overall health of the Port of Abbot Point's marine environment and provide advice to relevant management agencies.



Source: McKenna et al. 2015, 'Port of Abbot Point Long-term Seagrass Monitoring: Annual Report 2013-2014', JCU TropWATER Publication, Cairns.

Figure 3. Location of coastal monitoring meadows, offshore monitoring sites and light (PAR) and temperature loggers

2 SAMPLING APPROACH AND METHODS

There were two components to the Abbot Point seagrass program in 2014:

1. Quarterly assessments of established monitoring meadows;
2. Light (PAR) and temperature assessments at the seabed.

2.1 Quarterly assessment of established monitoring meadows

From the results of the baseline surveys in 2008 (McKenna et al. 2008), five coastal meadows and four offshore areas were identified as suitable for long-term seagrass monitoring (Figure 3). Monitoring meadows selected were representative of the range of seagrass communities identified in the 2008 baseline surveys and were also located in areas considered ideal sensitive receptor sites for assessing seagrass condition during and after port activity and development.

Seagrass monitoring in the Abbot Point area has been conducted quarterly (weather dependent) since March 2008. Quarterly assessments were established to determine seasonal and year to year variation in seagrass metrics prior to, during and after planned port development and capital dredging.

In addition to the quarterly monitoring surveys, two major surveys of coastal and offshore seagrass habitat within the broader port limits were conducted in 2013, updating the previous 2008 baseline surveys. The 2008 and 2013 baseline surveys were conducted in the wet season (March) and dry season (September) in order to capture seagrasses at their likely seasonal extremes of distribution and abundance.

Methods for assessing inshore and offshore seagrasses in the monitoring and the baseline surveys followed those established for the Abbot Point seagrass program since 2008 (see McKenna et al. 2008; Unsworth et al. 2010 and McKenna & Rasheed 2011). The application of standardised methods at Abbot Point and throughout Queensland allows for direct comparison of local seagrass dynamics with the broader region. Free-diving and deep water sled tows using an underwater CCTV camera system were used to survey inshore and offshore areas for seagrass (Figure 4) (see McKenna et al. 2008 for full description). At each survey site, seagrass habitat observations included seagrass species composition, above-ground biomass, percent algal cover, depth below mean sea level (MSL), sediment type, time and position (GPS). The percent cover of other major benthos at each site was also recorded. At sites where seagrass presence was noted seagrass above-ground biomass was determined. Above-ground seagrass biomass was estimated using a “visual estimates of biomass” technique (Kirkman 1978; Mellors 1991). At free diving sites this technique involved an observer ranking seagrass biomass within three randomly placed 0.25m^2 quadrats at each site (Figure 4). At CCTV camera sled tow sites this technique involved an observer ranking seagrass at 10 random time frames allocated within the 100m of footage for each site. The video was paused at each of the ten time frames then advanced to the nearest point on the tape where the bottom was visible and sled was stable on the bottom. From this frame an observer recorded an estimated rank of seagrass biomass and species composition. A 0.25m^2 quadrat, scaled to the video camera lens used in the field, was superimposed on the screen to standardise biomass estimates.

Ranks at all sites are made in reference to a series of quadrat photographs of similar seagrass habitats for which above-ground biomass has previously been measured. The relative proportion of the above-ground biomass (percentage) of each seagrass species within each survey quadrat was also recorded. Field biomass ranks were then converted into above-ground biomass estimates in grams dry weight per square metre (g DW m^{-2}). At the completion of sampling, each observer ranked a series of calibration quadrats that represented the range of seagrass biomass in the survey. After ranking, seagrass in these quadrats were harvested and the actual biomass determined in the laboratory. A separate regression of ranks and biomass from these calibration quadrats was generated for each observer and applied to the field survey data to standardise the above-ground biomass estimates.

Figure 4. Sampling sites were assessed by deep water sled tows with CCTV mounted camera system and free-divers to measure seagrass biomass and species composition.

Habitat Mapping and Geographic Information System

All survey data was entered into a Geographic Information System (GIS) for presentation of seagrass species distribution and abundance. Satellite imagery of the Bowen/Abbot Point area with information recorded during the monitoring surveys was combined to assist with mapping seagrass meadows. Three seagrass GIS layers were created in ArcMap:

- ***Habitat characterisation sites*** – site data containing above-ground biomass (for each species), dbMSL, sediment type, time, latitude and longitude from GPS fixes, sampling method and any comments.
- ***Seagrass meadow biomass and community types*** – area data for seagrass meadows with summary information on meadow characteristics. Seagrass community types were determined according to species composition from nomenclature developed for seagrass meadows of Queensland (Table 1). Abundance categories (light, moderate, dense) were assigned to community types according to above-ground biomass of the dominant species (Table 2).
- ***Seagrass landscape category*** – area data showing the seagrass landscape category determined for each meadow.

Isolated seagrass patches
The majority of area within the meadows consisted of un-vegetated sediment interspersed with isolated patches of seagrass

Aggregated seagrass patches
Meadows are comprised of numerous seagrass patches but still feature substantial gaps of un-vegetated sediment within the meadow boundaries

Continuous seagrass cover
The majority of area within the meadows comprised of continuous seagrass cover interspersed with a few gaps of un-vegetated sediment.

Table 1. Nomenclature for seagrass community types in the Port of Abbot Point.

Community type	Species composition
Species A	Species A is 90-100% of composition
Species A with Species B	Species A is 60-90% of composition
Species A with Species B/Species C	Species A is 50% of composition
Species A/Species B	Species A is 40-60% of composition

Table 2. Density categories and mean above-ground biomass ranges for each species used in determining seagrass community density in the Port of Abbot Point.

Density	Mean above ground biomass (g DW m^{-2})				
	H. uninervis (narrow)	*H. ovalis* *H. decipiens*	*H. uninervis* (wide) *C. serrulata/rotundata*	*H. spinulosa* *H. tricostata*	*Z. muelleri*
Light	< 1	< 1	< 5	< 15	< 20
Moderate	1 - 4	1 - 5	5 - 25	15 - 35	20 - 60
Dense	> 4	> 5	> 25	> 35	> 60

Each seagrass meadow was assigned a mapping precision estimate (±m) based on the mapping methodology utilised for that meadow (Table 3). Mapping precision estimates ranged from 20m to 50m for the inshore meadows. The mapping precision estimate was used to calculate a range of meadow area for each meadow and was expressed as a meadow reliability estimate (R) in hectares. Additional sources of mapping error associated with digitising aerial photographs onto base maps and with GPS fixes for survey sites were embedded within the meadow reliability estimates.

Table 3. Mapping precision and methodology for seagrass meadows in the Port Abbot Point.

Mapping precision	Mapping methodology
20-50m	Subtidal meadow boundaries determined from free diving surveys; Relatively high density of survey sites; Recent aerial photography aided in mapping.

2.2 Environmental data

Irradiance (Photosynthetically Active Radiation (PAR) mol photons m^{-2} day^{-1}) conditions within the seagrass meadows at Abbot Point have been assessed at three inshore meadows and at three offshore sites since September 2011 using custom built benthic data logging stations (Figure 3; Figure 5). A dual logger system was introduced to the program in April 2013. Each logging station consisted of 2π cosine-corrected irradiance loggers (Submersible Odyssey Photosynthetic Irradiance Recording System, Dataflow Systems Pty. Ltd., New Zealand) with supporting electronic wiper units. Irradiance loggers were calibrated using a cosine corrected Li-Cor underwater quantum sensor (LI-190SA; Li-Cor Inc., Lincoln, Nebraska USA) and corrected for immersion effect using a factor of 1.33 (Kirk 1994). Readings were made at 15 minute intervals and used to estimate total daily irradiance (PAR) reaching seagrasses. The electronic wiper unit fitted to each irradiance logger automatically cleaned the optical surface of the sensor every 15 minutes to prevent marine organism fouling.

Environmental data was obtained from the Australian Bureau of Meteorology (www.bom.gov.au) and the Department of Environment and Heritage Protection (www.ehp.qld.gov.au).

Figure 5. PAR & temperature loggers deployed at Abbot Point

2.3 Developing initial light thresholds for Abbot Point seagrasses

To help refine a range of relevant light thresholds for the dominant seagrass species at Abbot Point a review of the range of species specific light requirements from existing literature, as well as data from ongoing studies was used. For the purposes of this report only the results from studies that occur in the same region as Abbot Point, describe actual benthic light in mol photons, and examine the same species or the same genus to the key species potentially affected by dredging at Abbot Point; *Halophila* spp. (deep water) and *H. uninervis* (inshore) were used.

Once a range of relevant light threshold values for the dominant seagrass species at Abbot Point was determined from the literature and ongoing studies, we then examined how this range of values fit with the recorded light history and occurrence of seagrass at the Abbot Point monitoring sites to refine locally relevant light requirement thresholds.

To evaluate light over a practicable timeframe for measuring impacts to the plant at the inshore sites dominated by the larger growing *H. uninervis*, light data was integrated as a rolling fourteen day mean of the total daily irradiance. Current understanding of seagrass response pathways indicate under low light stress conditions, physiological adjustments first occur over a matter of days whereas plant-scale changes take place after a number of weeks (McMahon et al. 2013). An assessment of integrated light over a two-week period is therefore in line with both tidally-driven fluxes in light (e.g. re-suspension of bottom sediments due to shear stress) as well as a period of time preceding apparent morphological change.

At offshore sites, light was integrated over a seven day period. A shorter interval was used due to the fast response time of *Halophila* spp. to light and the comparative lack of below ground energy stores for these species compared with the shallow species *H. uninervis*. There are little to no carbohydrate reserves to rely on when light is limiting and physiological acclimation is limited prior to seeing apparent morphological changes or shoot loss in *Halophila* spp. While it is unclear how quickly changes may occur in some populations, a seven day average should mainly remove the extreme variability from the dataset and provide an opportunity to discern if clear trends between light and seagrass abundance exists at the offshore sites.

Abbot Point light trends were then compared against changes in seagrass biomass between consecutive sampling events.

Biomass and irradiance data were assessed at offshore sites 3 and 4 (*Halophila*) and at inshore meadow 7 (*Halodule*). Inshore meadow 9 was excluded from analysis as it has not had any significant amounts of *H. uninervis* recorded at the site since light loggers were deployed and therefore would not provide evidence of light that supports this species' growth. Offshore site 1 was excluded because it is located on a shallow shoal (Clark shoal) which is traditionally dominated by *H. uninervis* and not considered to be a true deep water site. *Halodule uninervis* has not been present at the site consistently since TC Yasi and therefore would not provide evidence of light that supports this species' growth.

Light and biomass data from Abbot Point were only evaluated from 2013 onwards as there was only one logger deployed at each site before this time. Using the period when dual loggers were available at each site allowed for a higher level of confidence in the light data as any potential and non-obvious erroneous data could be removed, and relationships between light and seagrass biomass could not be interrogated with confidence.

2.4 Statistical analysis

Seagrass biomass change

Prior to analysis, data exploration protocols were conducted as defined by Zuur et al. (2010) including checks for zero inflation of biomass data. Following data exploration, all biomass data were square-root transformed to increase homoscedasticity. Generalised linear models or zero inflated Gamma Hurdle models were used where appropriate to analyse both offshore and inshore biomass data. Following analysis all residuals were inspected visually and pairwise comparisons were made using a Tukey's Honest Significant Differences (HSD) test in the multcomp package (Hothorn et al. 2008). Analysis was conducted using R (R Development Core Team 2014).

Pooled data for offshore seagrass above-ground biomass was compared between dates with a generalised linear mixed-effects model (GLM) in the statistical package program R (R Development Core Team 2014). We used R and *lme4* (Bates et al. 2012) to perform a linear mixed effects analysis of the relationship between biomass and date. Due to the repeated sampling of each site, we held site as a random factor to account for any collinearity in the data. As fixed effects we entered year and date, and the interaction between the two into the model. A 'null' model was set up and then all other models with the fixed effects as factors were run. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. P-values were obtained by likelihood ratio tests of the full model with the effect in question against the model without the effect in question. The significant model with the lowest AIC number was selected as the most appropriate model to describe the data. Using the *multcomp* package (Hothorn et al. 2008) in R, multiple comparisons of means using Tukey HSD analysis were completed as described previously.

For meadows and sites with zero-inflated data a binomial-Gamma hurdle model was used to quantify the effects of date (Zuur et al. 2012). Linear regressions using a Gamma distribution are appropriate for continuous data that are > 0 (Zuur et al. 2007). However, the Gamma distribution does not allow for zero values. Therefore, the hurdle model approach models the zero data separately from the non-zero data by first quantifying the effect of date on the presence or absence of seagrass biomass with a binomial regression, and then analysing the non-zero biomass data with a linear regression using a Gamma distribution. When visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality, p-values were obtained by maximum likelihood ratio tests of the model with the effect in question against the null model. Analysis was conducted using the *lme4* package (Bates et al. 2013). Following analysis with the binomial-Gamma hurdle model, all residuals were inspected visually and pairwise comparisons were made using a holm adjusted Tukey's HSD test as described previously.

Light and its effect on seagrass

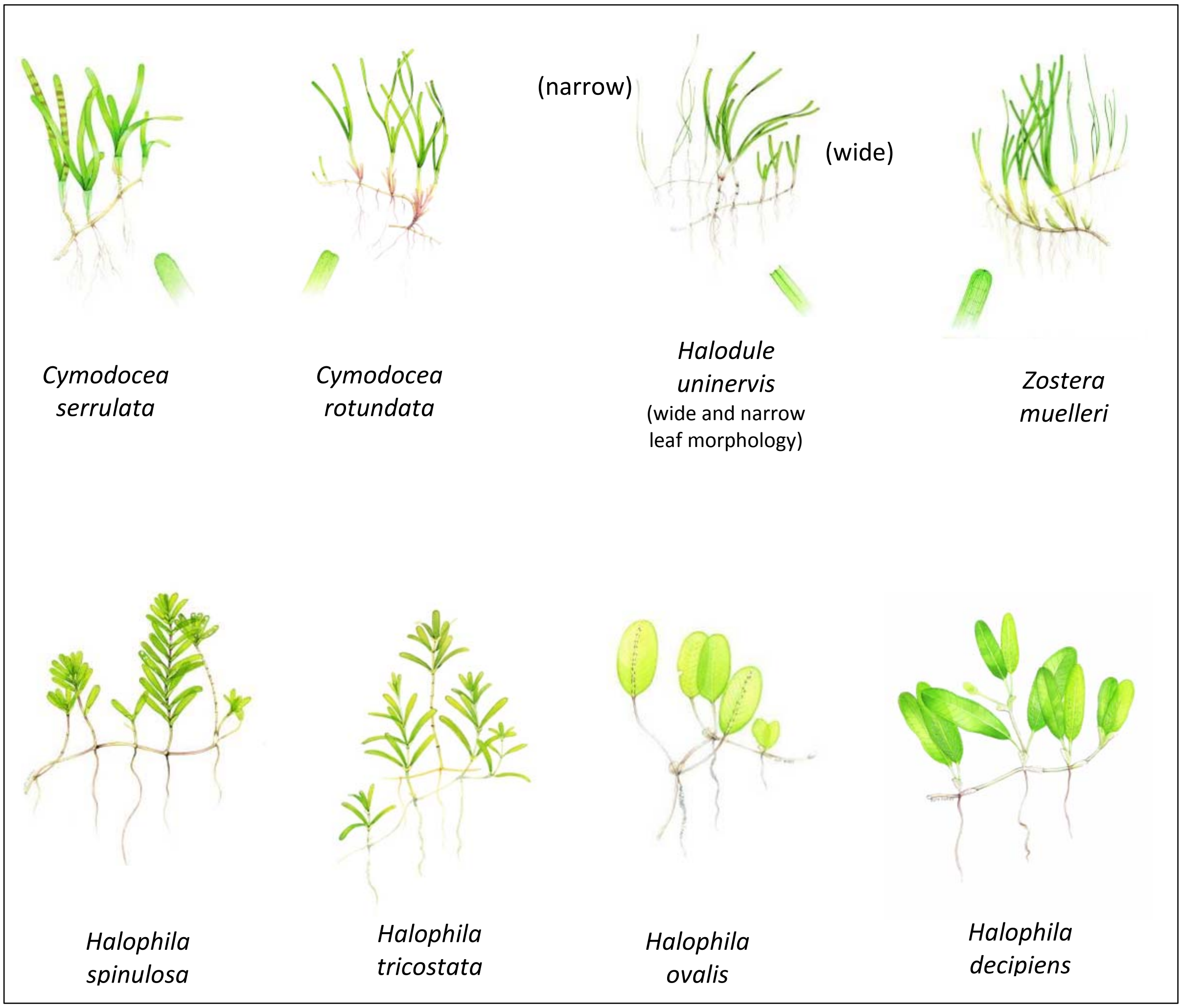
Generalized additive mixed models (GAMM) were used to examine the effects of irradiance (PAR) on seagrass biomass using the "mgcv" package for R (Wood 2014). GAMMs were used because the functional form of the response variable biomass to the continuous covariate light was unknown; GAMMs fit a non-parametric model to the data where the functional form is not specified a priori, but instead additive non-parametric functions are estimated using smoothing splines to model covariates (Zuur et al. 2014).

For offshore sites seagrass biomass was modelled separately as a function of 7, 14 and 30 days mean irradiance leading up to the sampling period. Two offshore sites were sampled (sites 3 and 4) so meadow was modelled as a random effect term in each model. For inshore seagrass the effect of 14, 30 and 90 days mean irradiance on seagrass biomass, and only *H. uninervis* biomass, were run as separate models. Analysis was only conducted on the *H. uninervis* dominated meadow 7 so no random effect term was included.

For both offshore and inshore meadows only the growing season data were modelled. Normalised residuals were inspected for each model using residual plots and qq-plots for violations of the assumptions of homogeneity of variance and normality (Zuur et al. 2014).

3 RESULTS

Eight seagrass species have been identified within the Abbot Point region since broad scale surveys of the area began in 1987 (Figure 6). Of particular note was the presence of *Halophila tricostata* in the September 2013 baseline survey and the September 2014 offshore monitoring survey (Figure 2). The September 2013 baseline survey was the first record of this species in the Abbot Point/Bowen region.



Cymodocea serrulata

Cymodocea rotundata

Halodule uninervis (wide and narrow leaf morphology)

Zostera muelleri

Halophila spinulosa

Halophila tricostata

Halophila ovalis

Halophila decipiens

Figure 6. Seagrass species identified in the Abbot Point/Bowen region.

3.1 Quarterly Assessments of Established Monitoring Meadows and Sites

Seagrass species, distribution, abundance and changes in the monitoring meadows

Following the summer of 2010/11, significant and sustained losses in biomass and distribution of seagrasses at both inshore and offshore monitoring sites were observed. Since then there has been a cycle of modest biomass increase followed by declines as a result of various storm and cyclone events that have affected the Abbot Point region (TC Oswald, TC Dylan and TC Ita). Since TC Ita there has been significant recovery of offshore *Halophila* spp. meadows (Figure 1), and while some coastal monitoring sites have had modest increases in biomass since 2010/2011, these increases were not statistically significant. The exception to this was inshore Meadow 9 where there was a significant increase in biomass through 2014, however this was driven by increases in colonising *H. ovalis* in the meadow and not its' previous foundation species *H. uninervis*.

Coastal monitoring meadows

The coastal monitoring meadows at Abbot Point have consisted of highly variable, isolated to aggregated patches of seagrass traditionally dominated by *H. uninervis* (Figures 7-11). The exception to this is Meadow 3 west of Euri Creek which was dominated by *Z. muelleri* (Figure 7). In this monitoring program (2008-2014) seagrass above-ground biomass, when present, at the inshore monitoring meadows has ranged from 0.005 g DW m^{-2} (Meadow 5 2009) to 13.84 g DW m^{-2} (Meadow 7 2014). The area of individual meadows when present have ranged from 1.2 ha (Meadow 9 2013) to 234.28 ha (Meadow 9 2014) (Figures 7-11; Appendices A.1). This variability and the values recorded are similar to those found in other comparable inshore meadows such as those in Townsville and Gladstone (Carter et al. 2015; Davies et al. 2015).

In March 2011, following the 2010/2011 floods and TC Yasi, four of the five coastal monitoring meadows were absent. Meadow 7 dominated by *H. uninervis* was the only meadow to persist after the floods, however by September 2012 no seagrass was recorded in any of the five coastal monitoring meadows. Since September 2012, seagrass has only been present consistently in Meadow 7 and Meadow 9. Meadow 9 was traditionally a *H. uninervis* meadow and since the major declines and complete losses of seagrass, *H. ovalis* has dominated this meadow (Figure 11). *Halodule uninervis* re-established in the meadow in July 2014 and by September 2014 made up 21.5% of the overall seagrass biomass. By December 2014 however, when the meadow recorded its' highest ever biomass, the meadow consisted completely of *H. ovalis* again (Figure 11).

For the first time since November 2010 a small patch of *Z. muelleri* was found in Meadow 3 (near Euri creek) in December 2013. Although this patch disappeared in the March 2014 survey *Z. muelleri* was present, albeit in small amounts, through the 2014 growing season (Figure 7). Seed-bank assessments conducted in Meadow 3 during 2012 found no *Z. muelleri* seeds, parts of seeds or pericarps (outer casing of seed) in any sediment cores, indicating the *Zostera* seed-bank in Meadow 3 has either an extremely low density of seeds or is non-existent. No seed sampling has been conducted as part of the current monitoring since 2012.

Also of note was the presence of *H. uninervis* (wide form) in Meadows 3 and 7 in 2014. *H. uninervis* is a foundation species for these meadows at Abbot Point and is an encouraging sign of early recovery.

Offshore monitoring sites

Offshore seagrass habitat has generally been dominated by highly variable, low biomass, isolated to aggregated areas of *H. spinulosa*. The exception to this is offshore Site 1 which was previously dominated by *H. uninervis*. Offshore Site 1 is located on Clark Shoal and therefore shallower (~5-7m below MSL) than all other offshore monitoring sites, allowing *H. uninervis* to grow in this area. Due to its shallower depth, offshore Site 1 is treated separately to the other offshore sites when conducting analysis.

Seagrass biomass at offshore monitoring sites has been highly variable between surveys, with seagrass at some of the blocks within sites being absent for periods of time, and all meadows undergoing major sustained declines in biomass after the 2010/2011 floods and TC Yasi (Figures 12-15; Appendix A.1). From

March 2011 through to September 2012, biomass slowly increased at three of the four offshore monitoring sites (Sites 2-4). By January 2013 however, seagrass at the offshore monitoring sites underwent declines again (Figures 12-15; Appendix A.1). These declines coincided with destructive winds and flooding from TC Oswald that passed by the Abbot Point region in January 2013. Since TC Oswald, TC's Dylan and Ita are likely to have also hindered offshore seagrass recruitment and recovery. Despite these cyclones, by September and December 2014 there was significant increase in biomass at offshore sites 2-4 ($p = <0.001$).

An encouraging sign of returning seagrass was the presence of *H. uninervis* in the 2014 growing season at offshore Site 1 (Figure 12). This species has been absent at this site for just under four years. There was a sudden shift from what was previously a *H. uninervis* dominated site, to 100% *H. spinulosa* in March 2011, the first survey after the floods (Figure 12). *Halophila spinulosa* was the dominant species when seagrass re-emerged again in early 2013, before disappearing until late 2014 when *H. uninervis* re-established at the site (Figure 12). No seagrass was present at offshore Site 1 in the December 2014 survey.

H. uninervis was also present at offshore Site 3 in both the March and December 2014 surveys (Figure 14). The last time *H. uninervis* was present at this site was prior to TC Yasi where it consistently contributed a small amount of biomass to the overall species composition of the area. Species composition at offshore sites 3 and 4 has remained relatively consistent throughout the monitoring program with *H. spinulosa* the dominant species, followed by *H. ovalis* and *H. decipiens*, with *H. uninervis* (wide and narrow forms) making up the rest of the species composition (Figures 14 and 15). *H. tricostata* was also present at offshore Site 3 in the September 2014 survey.

Seagrass at Site 2 was dominated by *H. spinulosa* immediately following the floods (March 2011), however, by May 2011 species composition had shifted to *H. decipiens* (Figure 13). Since May 2011 the proportion of biomass made up by *H. decipiens* has gradually decreased with *H. spinulosa* returning to be the dominant species again.

Cymodocea serrulata has not been found at any monitoring site since September 2012.

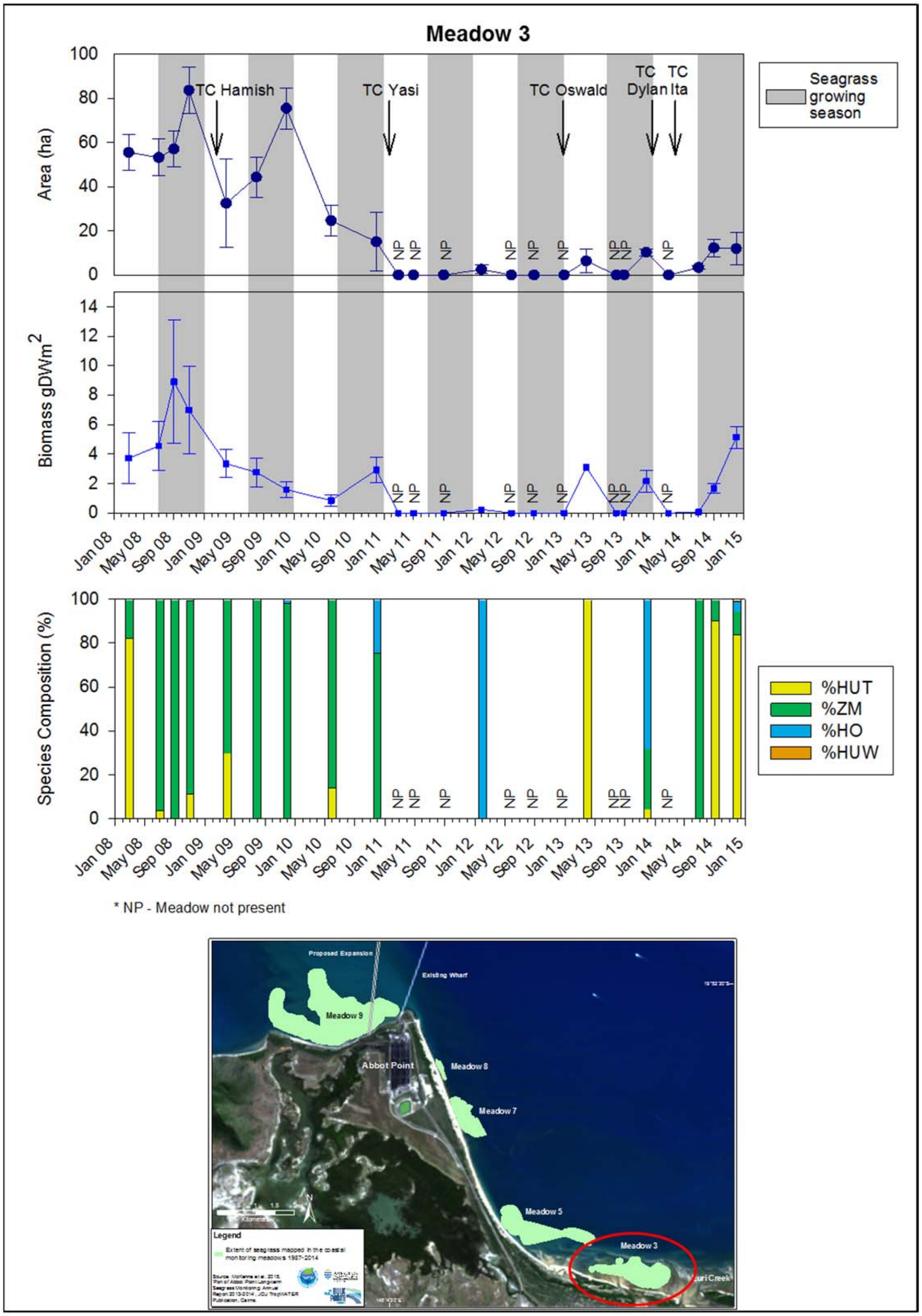


Figure 7. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at inshore monitoring Meadow 3.

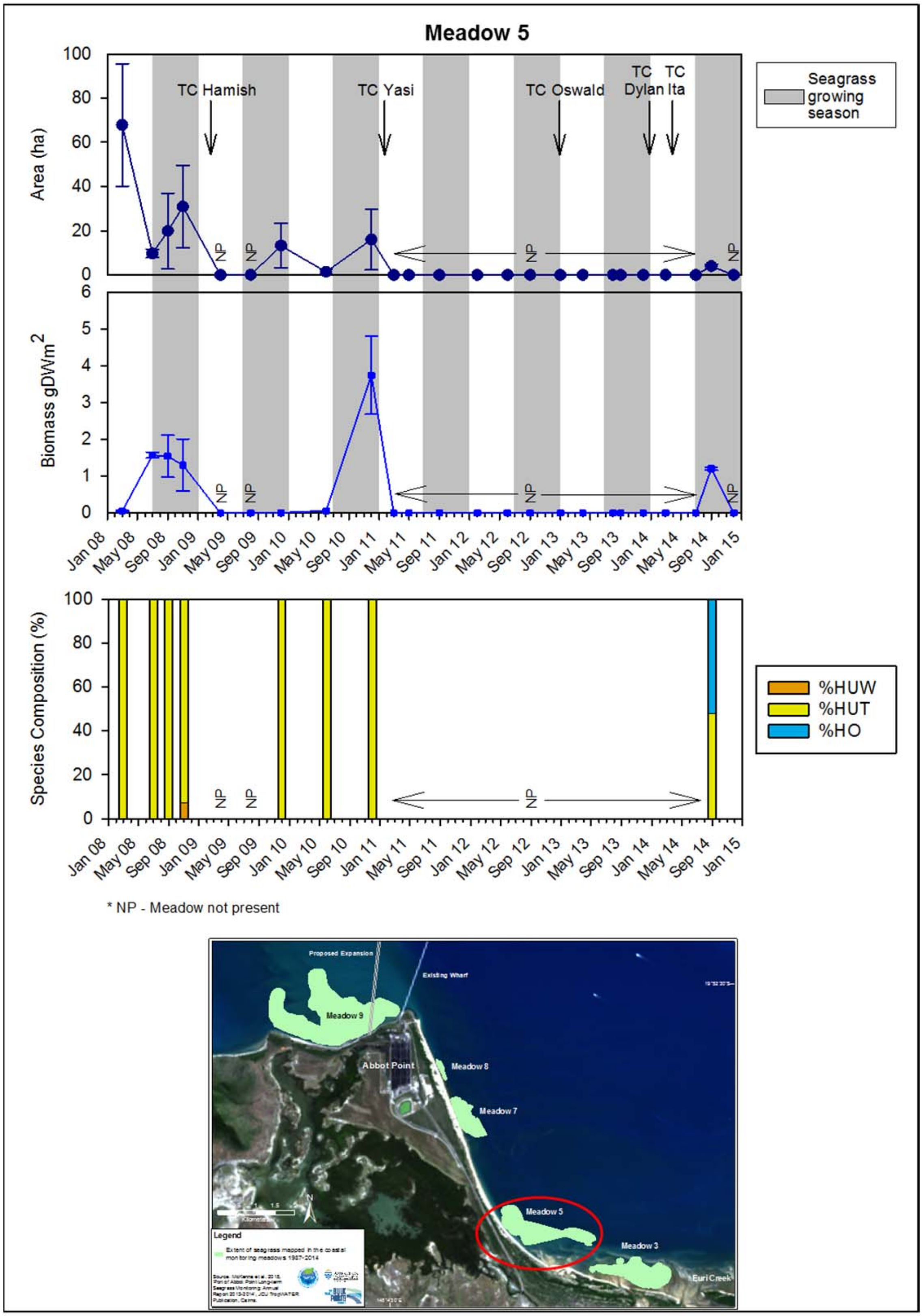


Figure 8. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at inshore monitoring Meadow 5.

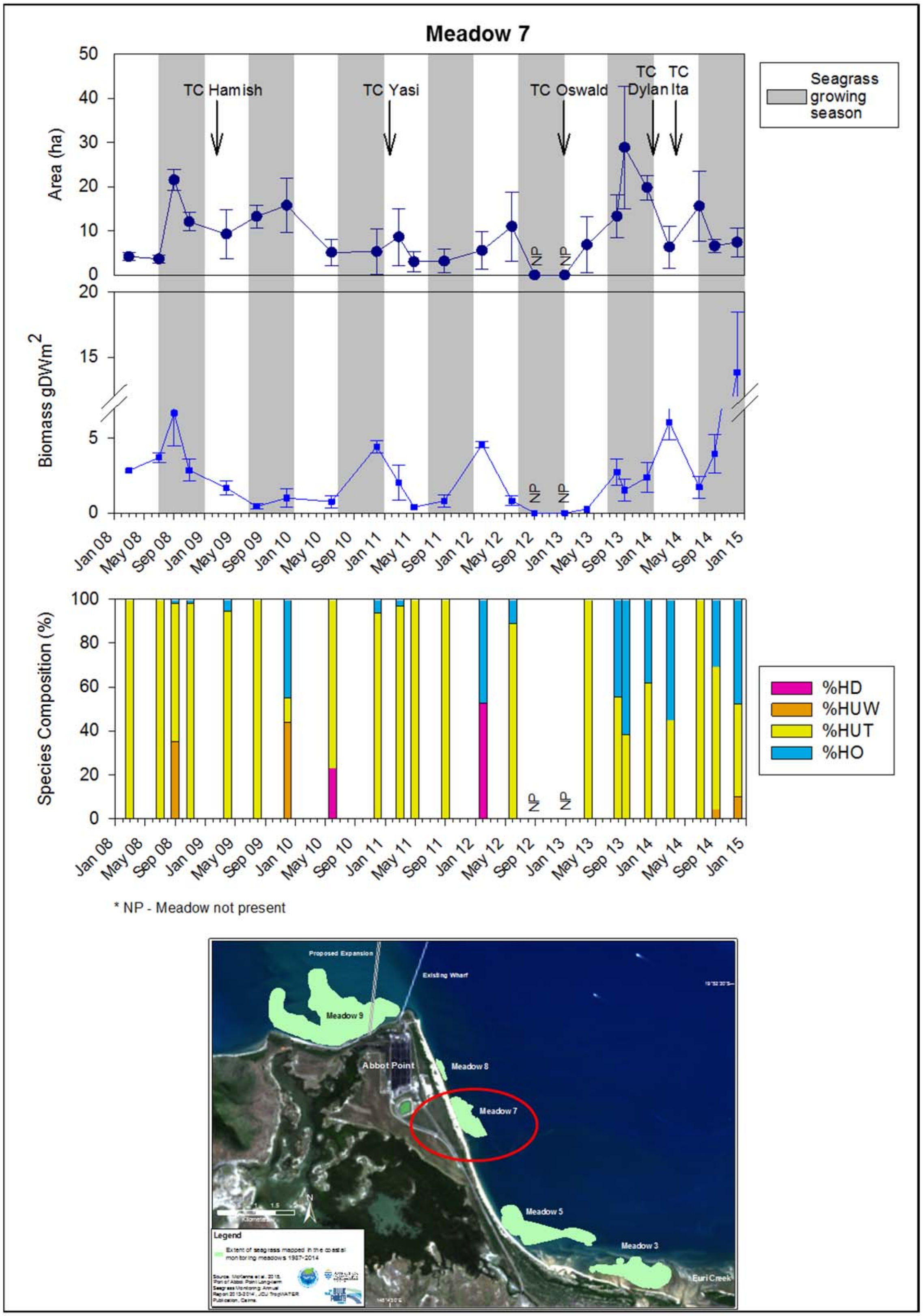


Figure 9. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at inshore monitoring Meadow 7.

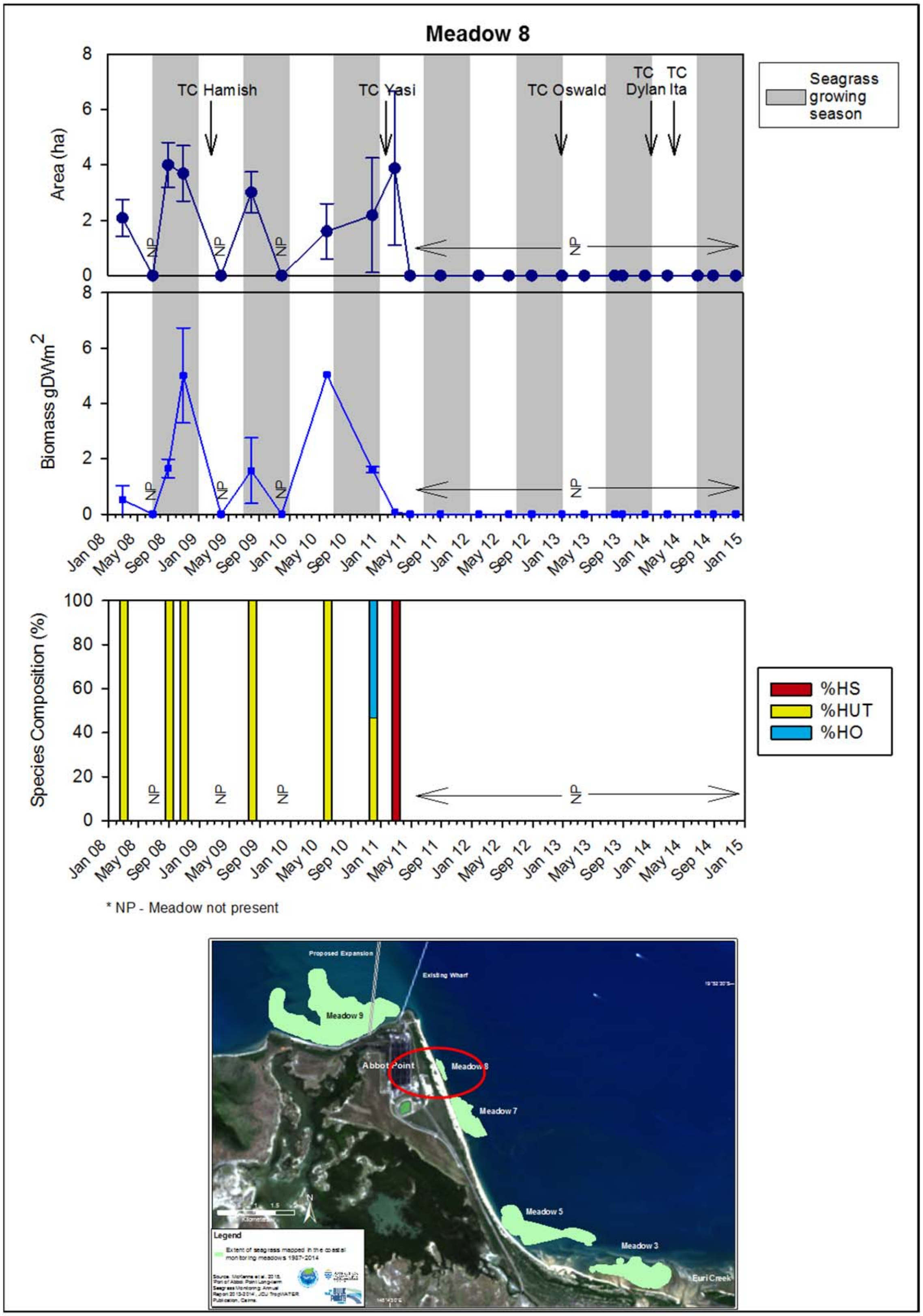


Figure 10. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at inshore monitoring Meadow 8.

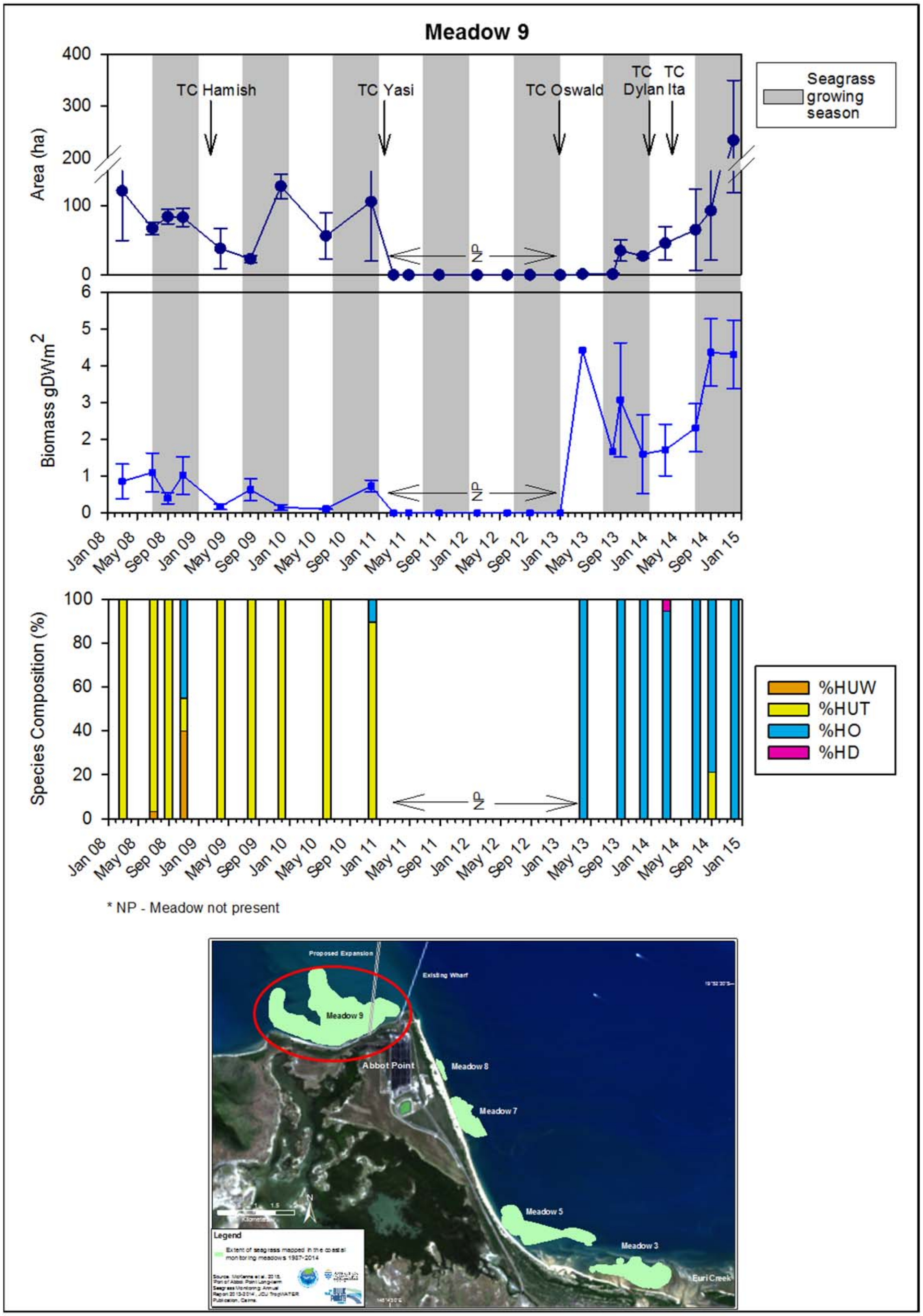


Figure 11. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at inshore monitoring Meadow 9.

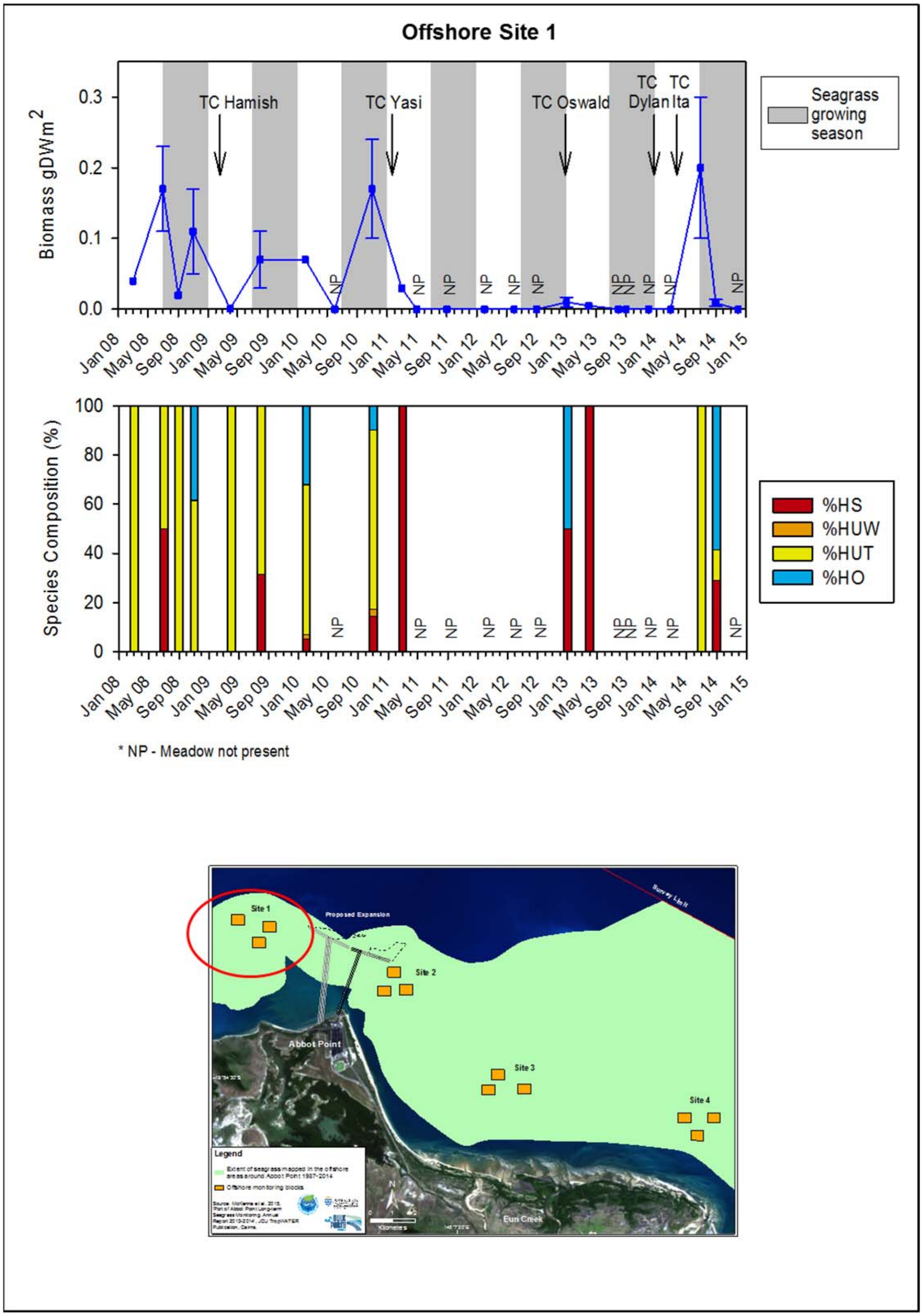


Figure 12. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at offshore monitoring Site 1.

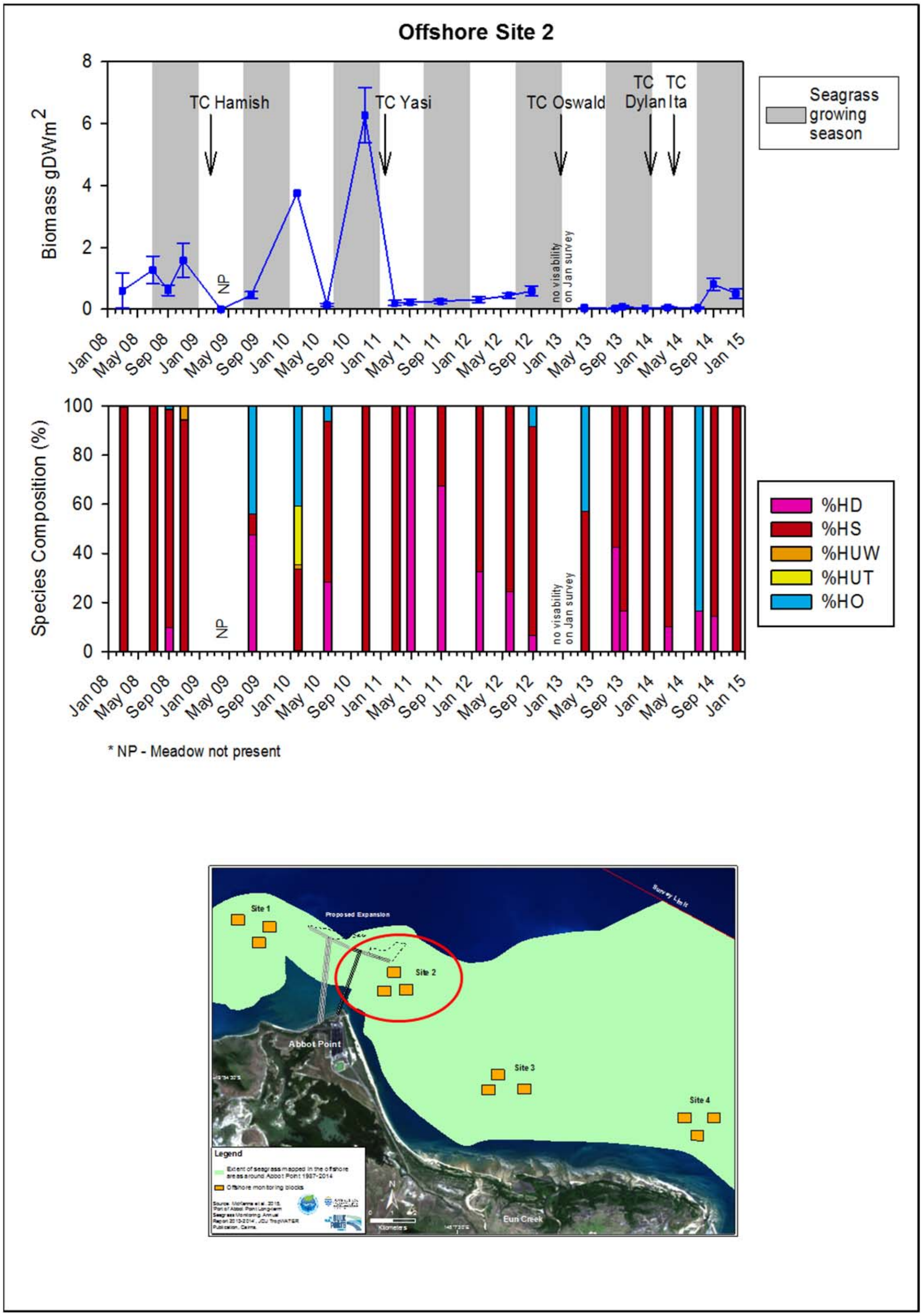


Figure 13. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at offshore monitoring Site 2.

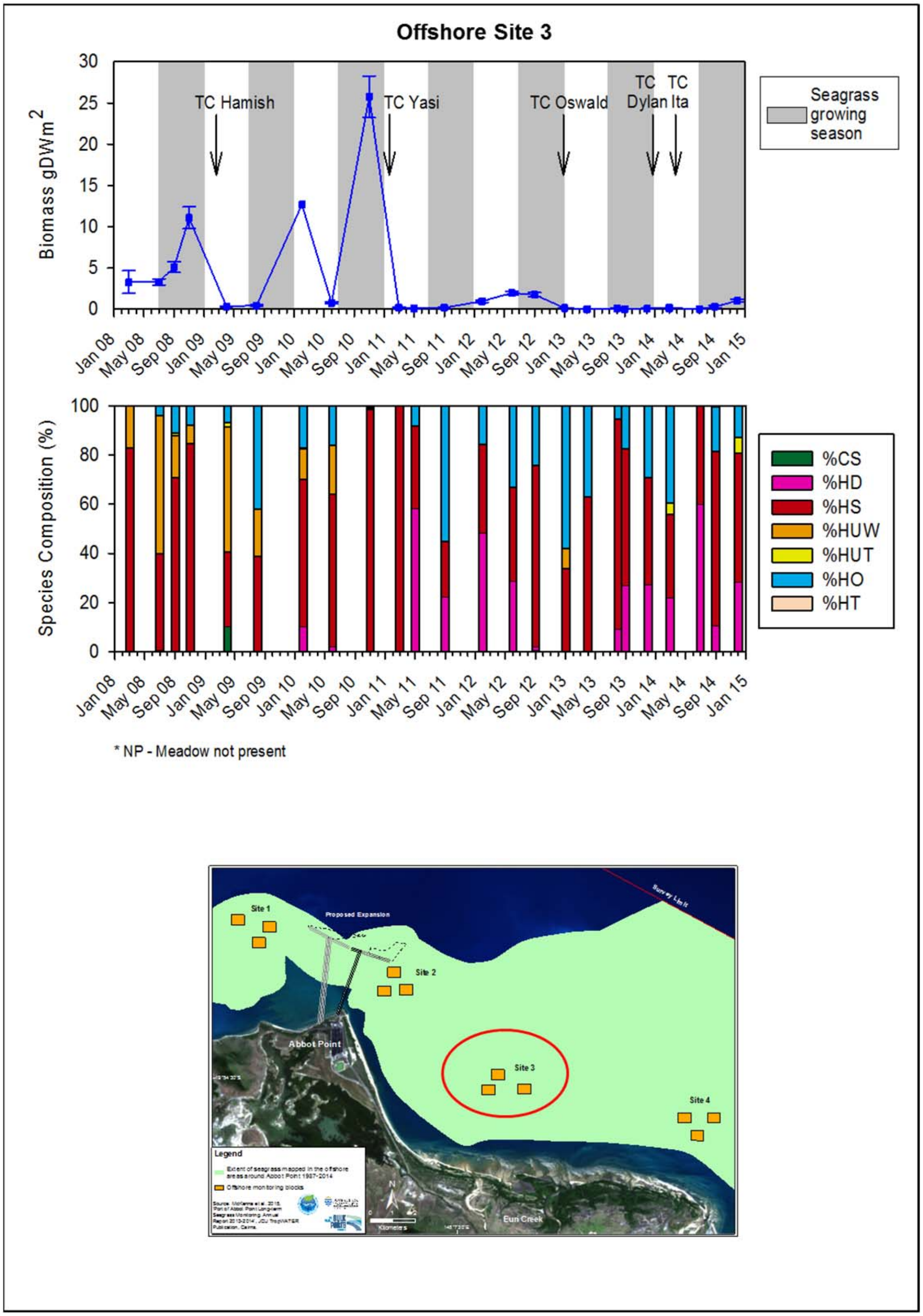


Figure 14. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at offshore monitoring Site 3.

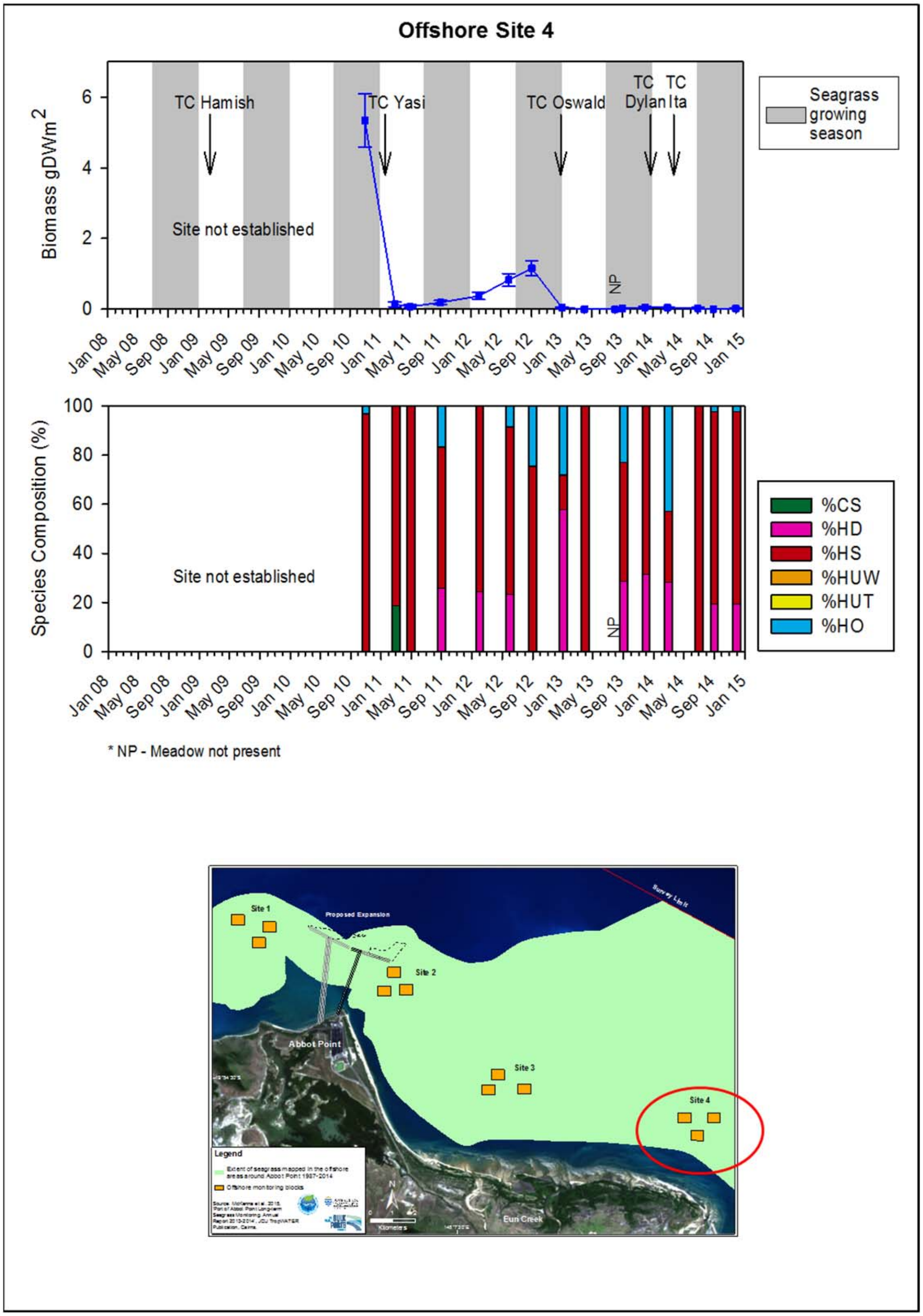
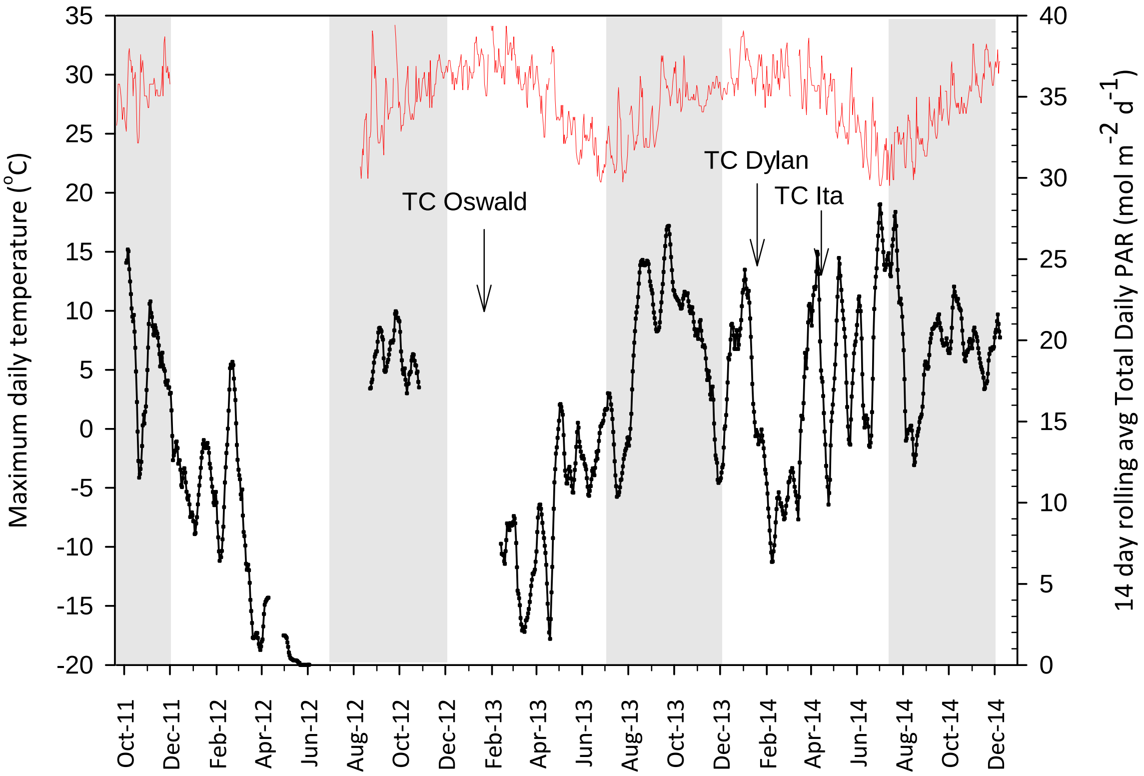


Figure 15. Mean meadow biomass (g DW m^{-2}), total meadow area (ha) and species composition at offshore monitoring Site 4.

3.2 General Light (PAR) and Temperature Trends

Light and water temperature data collected *in situ* at monitoring sites in 2014 generally followed established seasonal trends; water temperature peaking in summer and light in spring (Figures 16a-c). Since light data has been collected, available light at offshore sites (3 & 4) has ranged from 0 – 6.2 (2014) mol photons m^{-2} d^{-1}. At offshore Site 1, the shallower site on Clark shoal, available light ranged from 0 – 13.03 (2014) mol photons m^{-2} d^{-1}, while at the inshore monitoring sites available light has ranged from 0 – 39.19 (meadow 3 2014) mol photons m^{-2} d^{-1}. The maximum instantaneous water temperature recorded at the seabed at any of the sites was 34.2°C in September 2012 at coastal Meadow 3 (Euri Creek) (Figure 16a). This corresponded with a spike in PAR (30.6 mol m^{-2} d^{-1}) and a midday low tide of 0.52m. Meadow 3 is the shallowest of all monitoring areas and during low tide the shallow water over the meadow can become super-heated.

Meadow 3



Meadow 7

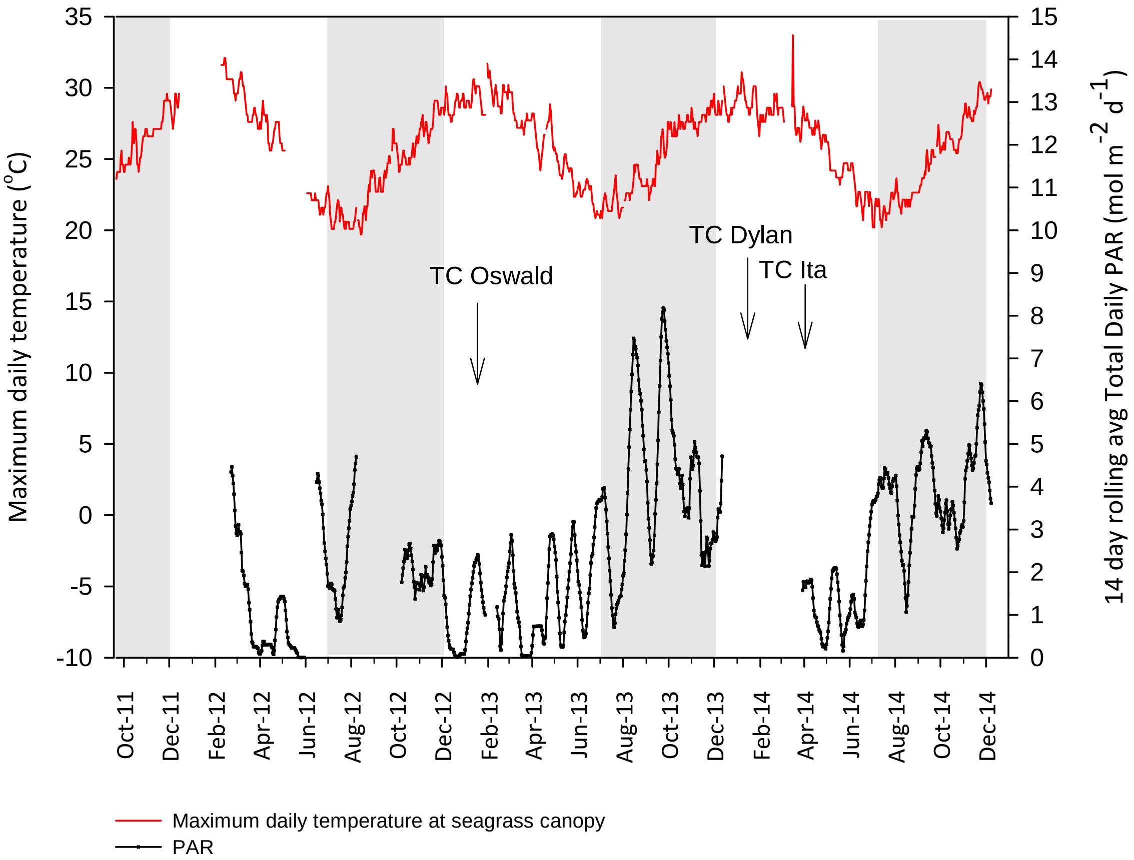
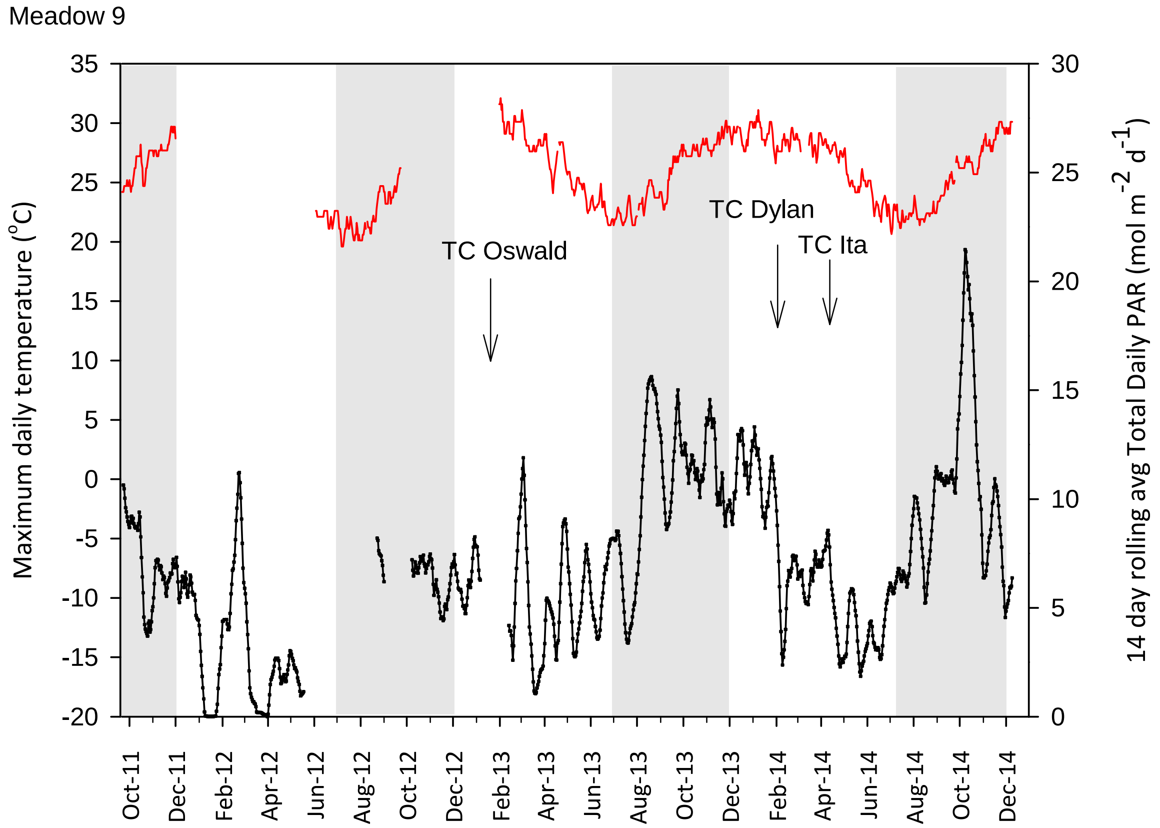


Figure 16a. Total daily PAR (mol m^{-1}day^{-1}), maximum daily water temperature (°C), and above-ground biomass (gDW m-2) at inshore meadows 3 and 7, September 2011-December 2014.



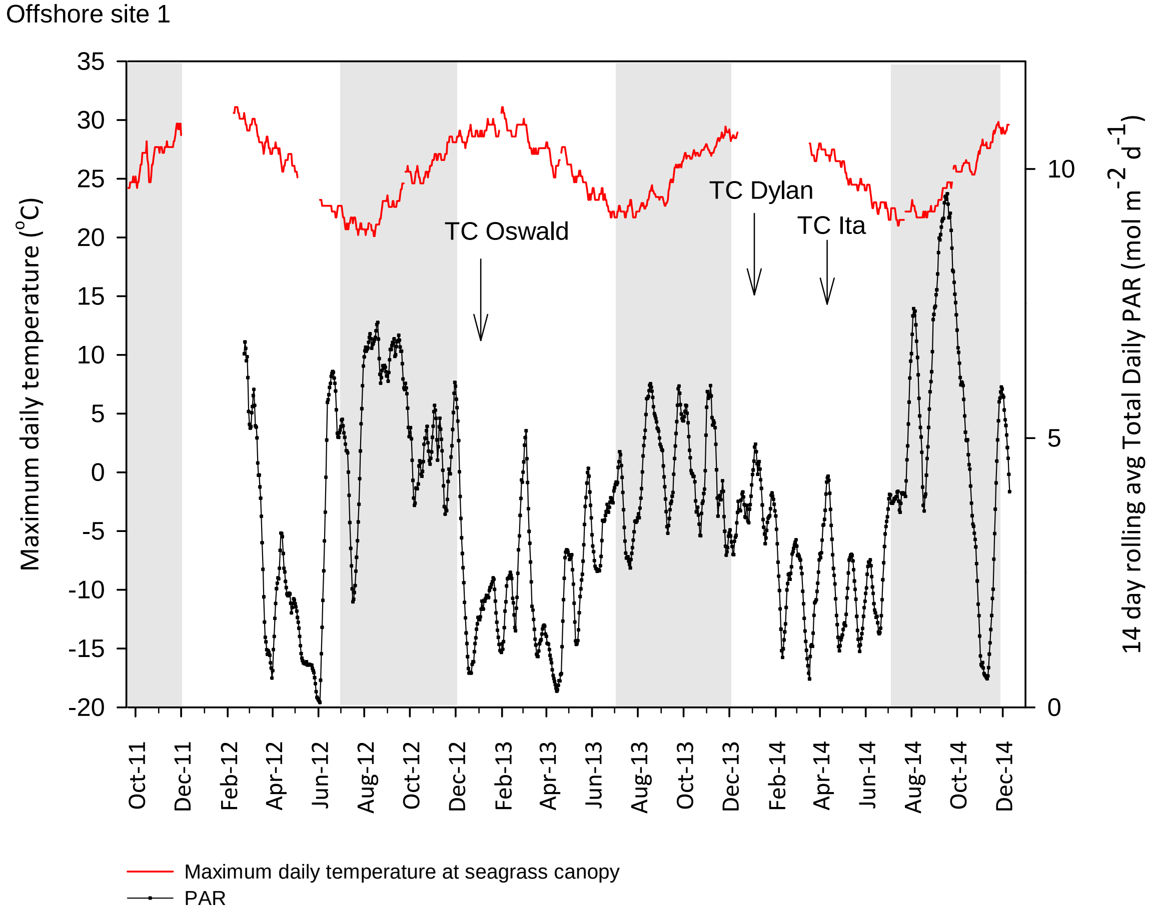
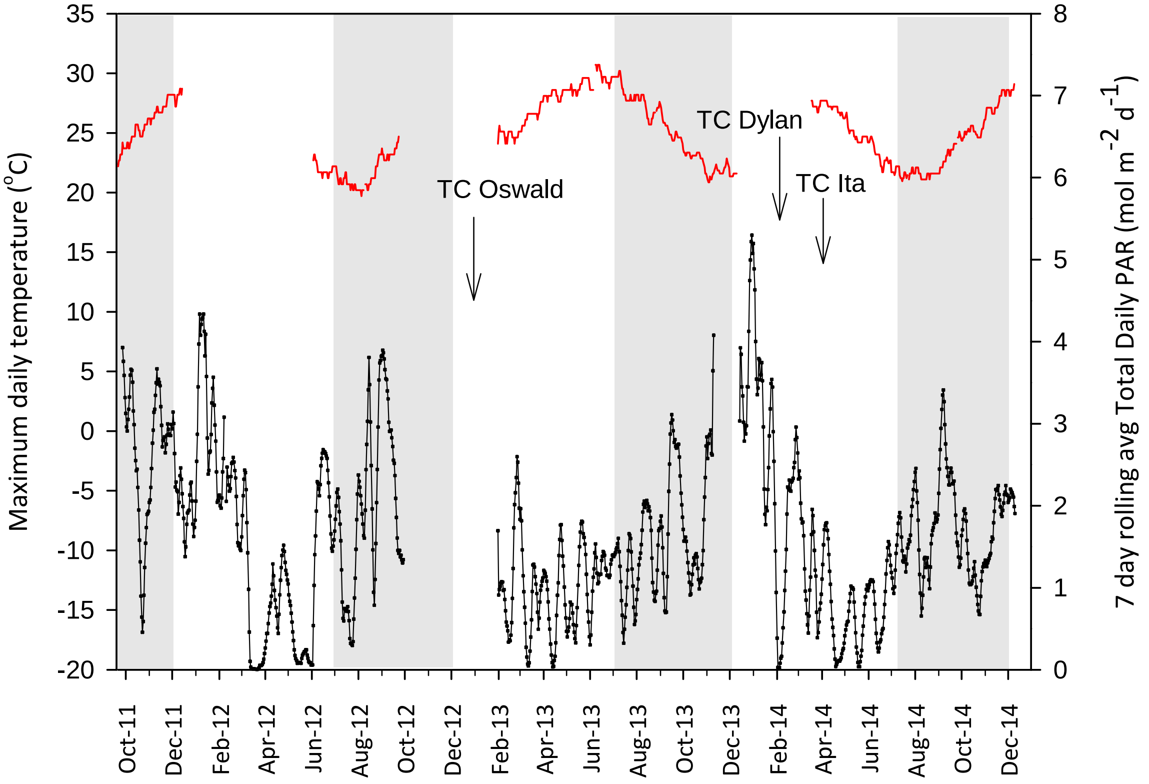


Figure 16b. Total daily PAR (mol $m^{-1}day^{-1}$), maximum daily water temperature (°C), and above-ground biomass (gDW m-2) at inshore meadows 9 and Offshore site 1, September 2011-December 2014.

Offshore site 3



Offshore site 4

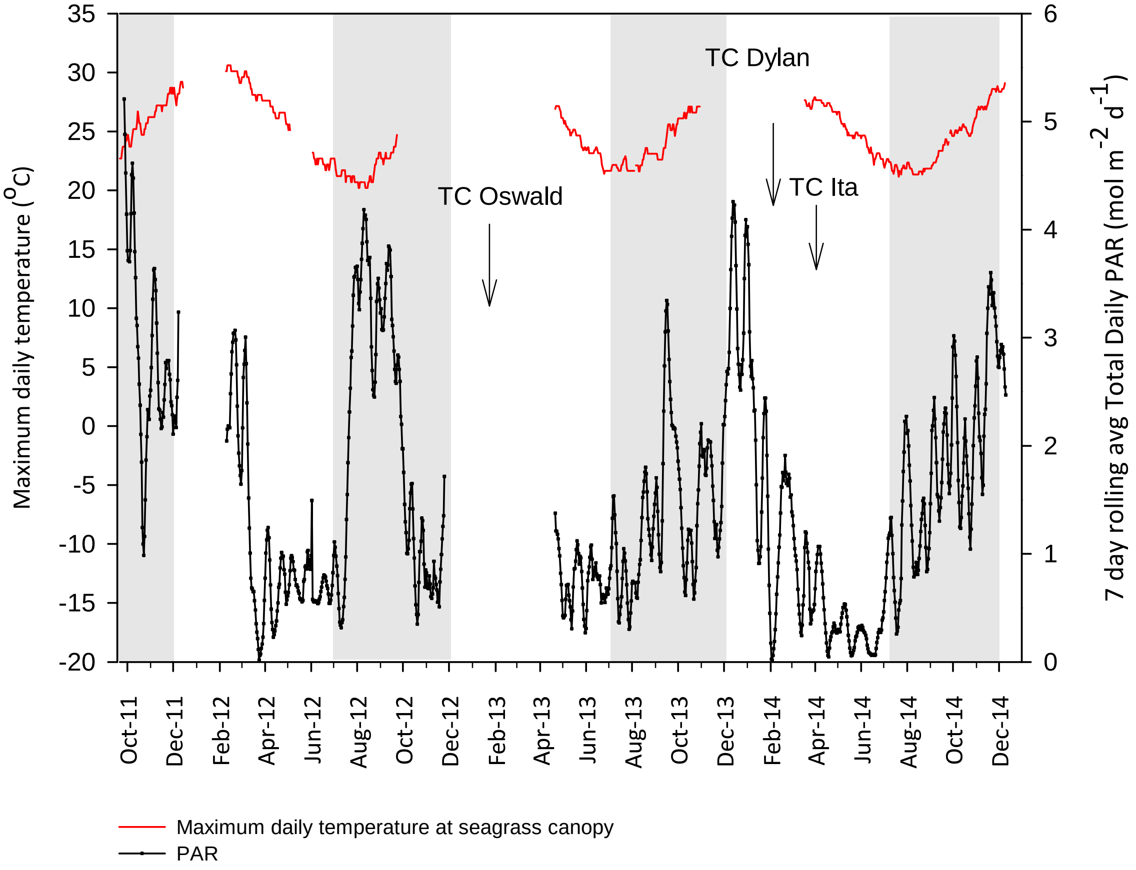


Figure 16c. Total daily PAR (mol m^{-1}day^{-1}), maximum daily water temperature (°C), and above-ground biomass (gDW m-2) at Offshore sites 3 & 4, September 2011-December 2014.

3.3 Developing Abbot Point seagrass light thresholds

From the review of literature and our groups ongoing studies we found that a threshold range of between 1 and 2 mol photons m^{-2} d^{-1} over a rolling seven day average was appropriate to interrogate the Abbot Point light and seagrass change data set for deep water *Halophila* species. These values were derived from Chartrand et al.'s (2014) work on *H. decipiens* and *H. spinulosa*. These species were collected from Green Island (offshore from Cairns) and Abbot Point and subjected to different light and temperature regimes in mesocosm experiments. The key findings of the studies so far show that deep water *H. decipiens* and *H. spinulosa* shoot density was negatively affected by light treatments of 1 mol photons m^{-2} d^{-1} compared to typical ambient growing season conditions and control light treatments of 3.2 mol photons m^{-2} d^{-1}. A critical light threshold in the range of 1-2 mol photons m^{-2} d^{-1} was identified from the study and the long-term field monitoring program, and is currently being examined further as part of ongoing field monitoring and research for its validity. *Halophila decipiens* shoot density significantly declined after 2 weeks under low light treatments whereas *H. spinulosa* was not affected until 4 weeks.

For inshore *H. uninervis* meadows we found that a threshold range of between 3 and 5 mol photons m^{-2} d^{-1} over a rolling 14 day average was appropriate to interrogate the Abbot Point light and seagrass change data set. These values were derived from field and laboratory experiments on *H. uninervis* at Magnetic Island (Collier et al. 2012a; Collier et al. 2015 subm). Collier et al. (2015 subm) tested the response of *H. uninervis* shoot density and growth rates to six light levels ranging from 0 to 23 mol photons m^{-2} d^{-1} in cool (~23°C) and warm (~28°C) temperatures over 14 weeks. This study found that low light levels (≤3.3 mol photons m^{-2} d^{-1} treatments) had a significant negative affect on shoot density in cool temperatures between 10 – 14 weeks and in warm temperatures between 4 – 7 weeks.

Previous work at Magnetic Island off Townsville (Collier et al. 2012a) determined light thresholds required for the long-term survival of tropical seagrass meadows dominated by *H. uninervis* identified during 'real-time' loss of seagrass. The thresholds in this study were determined during natural *in situ* reductions in light and concurrent with seagrass loss. The study found that a significant loss (>50%) in seagrass occurred at <4 mol photons m^{-2} d^{-1}, while minimum light levels associated with seagrass gain occurred when light was >5 mol photons m^{-2} d^{-1}. In a separate study, Collier et al. (2012b) also found *H. uninervis* shoot density declined in the lab after 8.7 weeks when held under 4.4 mol photons m^{-2} d^{-1}.

We then examined how the literature and ongoing study derived values fit with the recorded light history and seagrass change data from the Abbot Point monitoring sites. Offshore *Halophila* spp. above-ground biomass was significantly correlated with average light intensities at 7 days ($p<0.001$), 14 days ($p<0.01$) and 1 month ($p< 0.05$) prior to sampling events during the growing season when analysed. The most recent sampling of *Halophila* spp. at offshore site 3 found light stayed relatively constant between 1-1.5 mol photons m^{-2} d^{-1} for longer than one month prior to sampling and resulted in the highest total biomass recorded at the site since dual light loggers were deployed in 2013 (Figure 17A). When we applied the literature derived light threshold range for deep water *Halophila* species (1-2 mol photons m^{-2} d^{-1}) to the Abbot Point light history and seagrass change measurements, we found that a threshold of 1.5 mol photons m^{-2} d^{-1} best described the light conditions at which seagrass biomass was maintained (Figure 17A & B).

An interrogation of the literature derived light threshold range for *H. uninervis* of between 3-5 mol photons m^{-2} d^{-1} with the recorded light history and seagrass change measurements at Abbot Point found a threshold of 3.5 mol photons m^{-2} d^{-1} best described the light conditions at which seagrass biomass was maintained (Figure 17C). In particular three sampling intervals provided an indication that when light leading up to sampling was ≥3.5 mol photons m^{-2} d^{-1} for approximately one month prior to sampling, seagrass was present or had increased from the previous sampling event (Figure 17C).

It was difficult to refine the threshold with further confidence due to the impact of tropical cyclones and major storm events on the coastal seagrass meadows during the monitoring period. This resulted in very low abundances of *H. uninervis* at the meadows and limited the ability of statistical analyses to model any trends in seagrass biomass with light (Figure 17C). It was only since December 2014 that coastal seagrass had returned in reasonable densities, and indeed the increase in biomass at this time was preceded by more than one month of light above 3.5 mol photons m^{-2} d^{-1}. In addition the light loggers at the key coastal *H. uninervis* meadow (as well as Meadow 9) were stolen at some point after the December 2014 logger exchange so no light data was available for comparison at these meadows between December 2014 and May 2015. Large changes in light history were also recorded between the 3 monthly sampling events earlier in the monitoring program. So it was difficult to resolve the seagrass condition between these events and whether biomass had in fact increased as a response to high light between quarterly seagrass sampling but had once again declined with the lower light in the month preceding sampling. As a consequence of these issues the statistical analysis failed to find significant relationships.

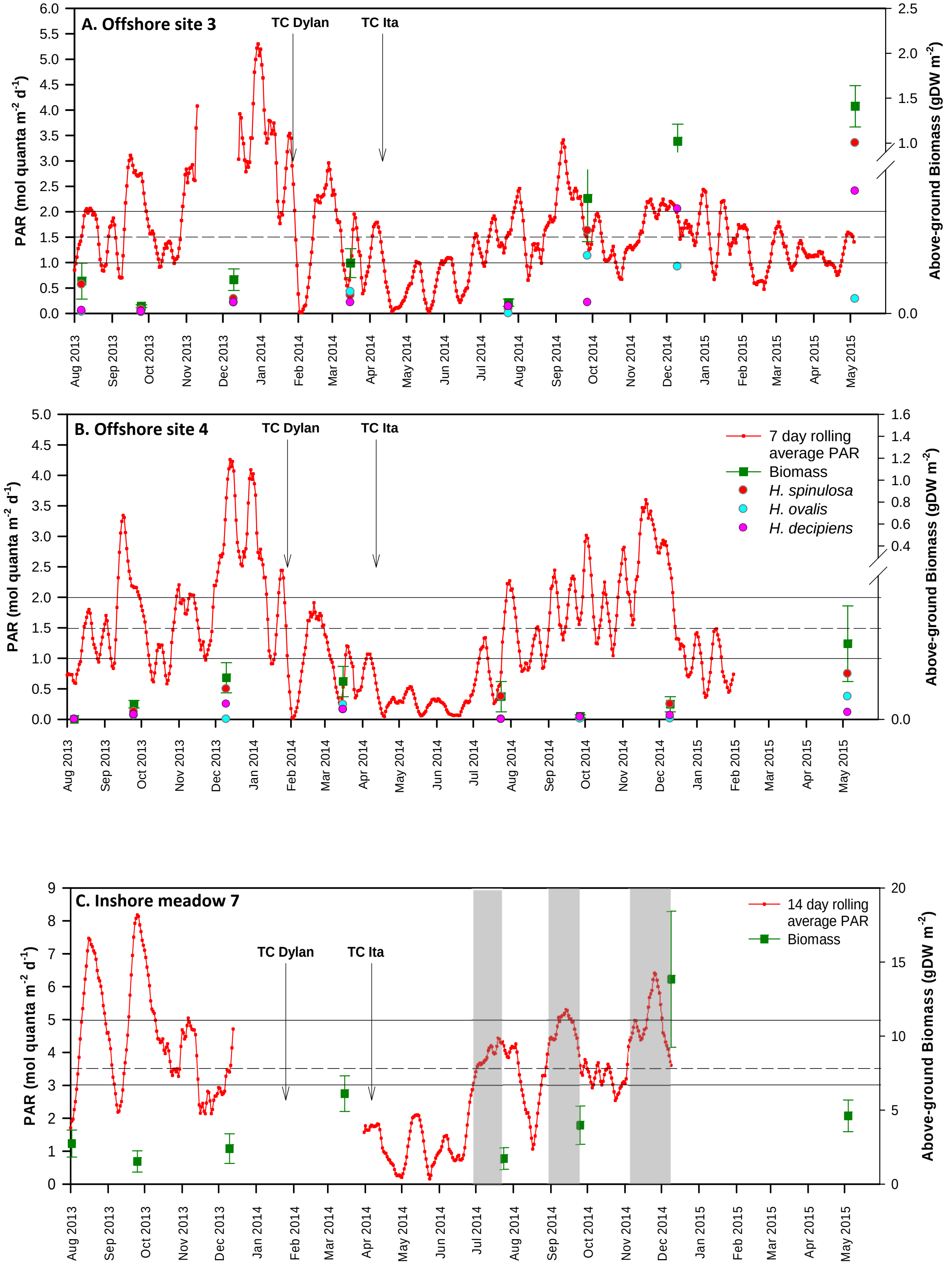


Figure 17. Rolling seven day and 14 day average light (mol photons m^{-2} d^{-1}) at offshore monitoring sites 3 (A) 4 (B) and inshore meadow 7 (C) from August 2013 to May 2015, and mean (±SE) above-ground biomass at quarterly sampling events. Shaded areas in (C) represent periods of time leading up to sampling where ≥3.5 mol photons m^{-2} d^{-1} for a month and seagrass increases were observed

3.3 General Abbot Point Climate Patterns During Monitoring

There have been numerous significant weather events that have directly affected the Bowen/Abbot Point region since the monitoring program began in February 2008. Several monsoonal troughs and cyclones have resulted in major rainfall leading to flooding, tidal surges and high wind gusts. Notably, the La Niña system that ran from July 2010 to June 2011 and TC Yasi (February 2011) had a significant impact on weather conditions in the area, and the remnant low of TC Oswald in January 2013 produced severe weather over nearly all of eastern Queensland. In January 2014 TC Dylan crossed the coast near Bowen as a category two system causing increased tides, storm surge, heavy rainfall and gale force winds (BOM 2015). TC Ita crossed the Bowen/Abbot Point coast in a south easterly direction in April 2014 as a category one system. Gale force winds and damaging wind gusts were recorded at Townsville and Mackay (BOM 2015).

Rainfall

The La Niña system in 2010/11 was one of the strongest on record and contributed to the extremely high and prolonged rainfall experienced in Queensland from November 2010 to March 2011 (Figure 18). Following this, rainfall for the majority, between 2011 and 2014 remained below average. The exception to this has been the months of March and July 2012, January, March, May and November 2013, and March, April and August 2014. During TC Ita flash flooding occurred in Bowen with 110mm of rainfall falling in one hour (BOM 2015.) Despite the occurrence of TC's Dylan and Ita, total annual rainfall in Bowen in 2014 was below the long-term average for the first time in five years (Figure 18 inset).

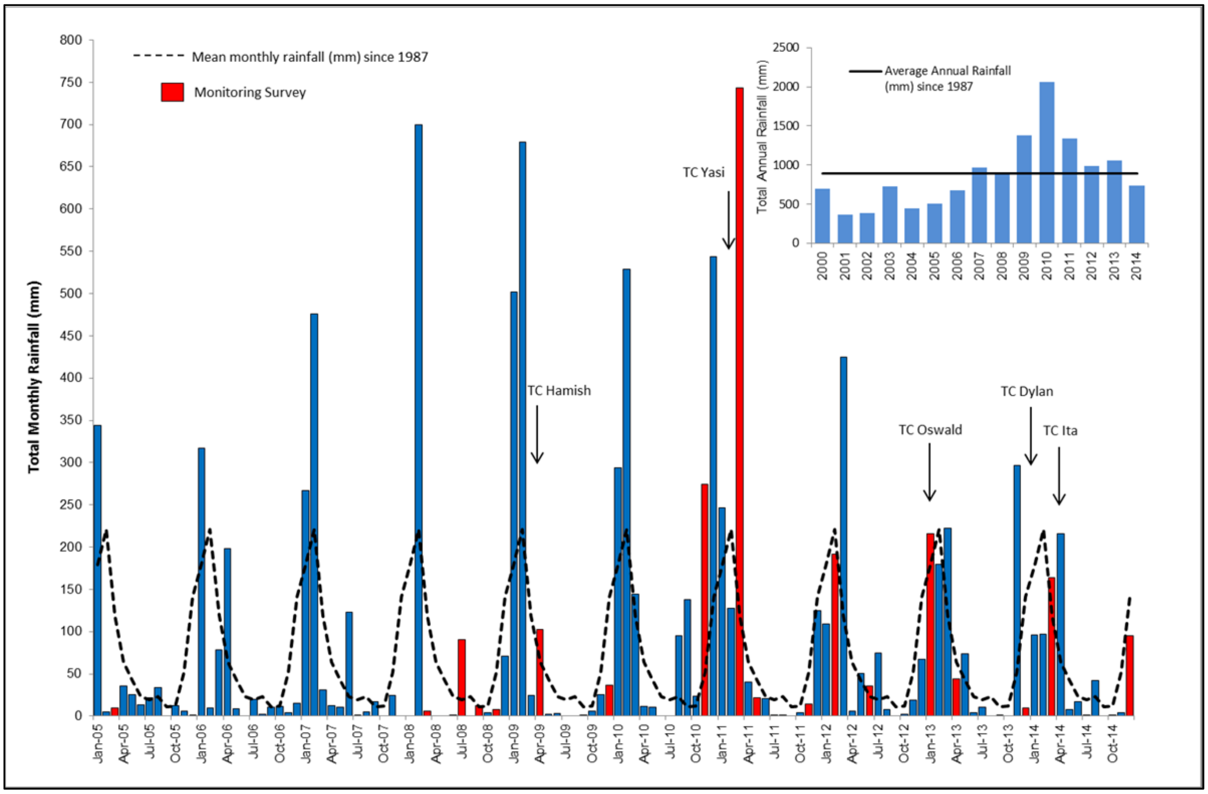


Figure 18. Total monthly rainfall (mm) from January 2005 to December 2014 and (inset) total annual rainfall from 2000 to 2014 for the Bowen area. Data source www.bom.gov.au (Station #033257). * note - 2014 contains some unvalidated data

River Flow (Don River)

The major rainfall that occurred in summer 2010/11 coincided with high flows within the Don Basin; the catchment area for Abbot Point. Don River flows exceeded monthly averages from November 2010 through to November 2011, with 2011 having the highest total annual river flow since 1991 (Figure 19). River flow remained below the long-term average until March 2012 when it peaked to nearly five times the long-term monthly river flow average coinciding with large rainfalls (Figure 18 & 19). Since then, river flow has generally remained below the long-term average with the exception of January 2013 and April 2014 where high flows coincided with TC Oswald and TC Ita respectively (Figure 18). Total annual river flow was below the long-term average in 2014 and for the second year in a row (Figure 19 inset).

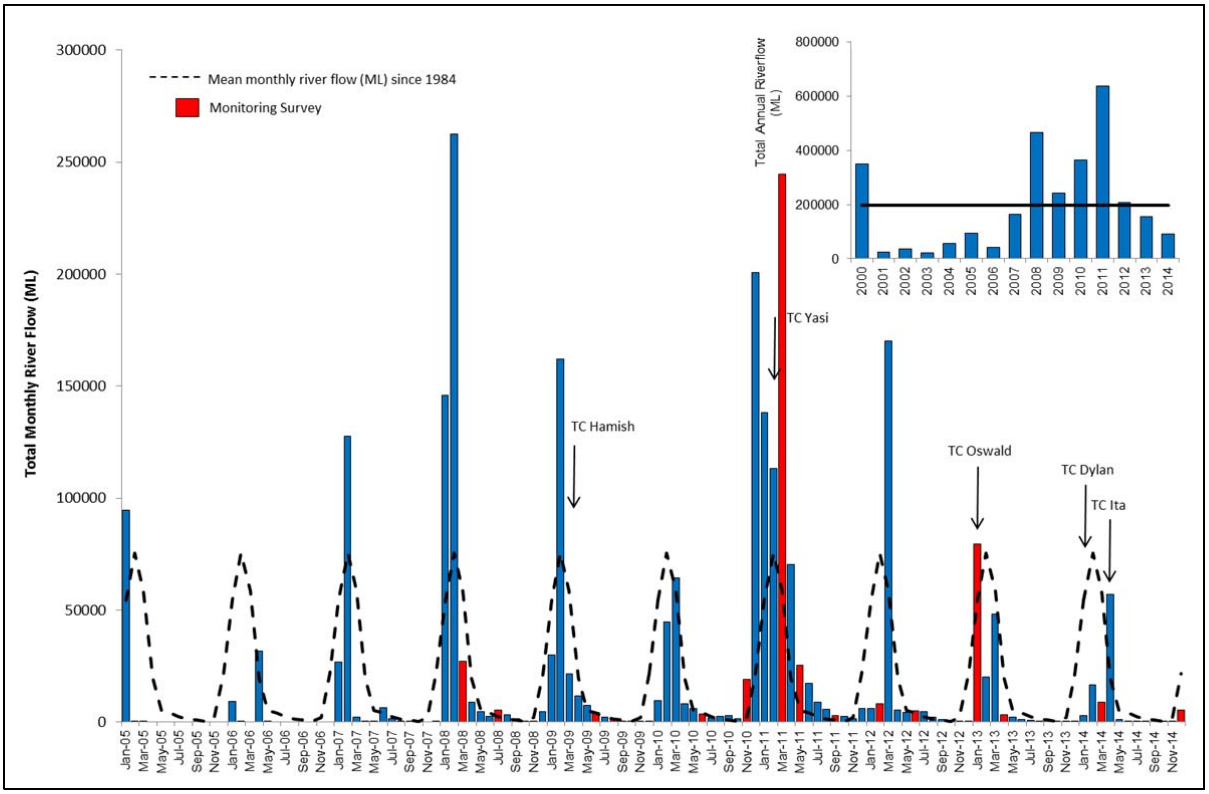


Figure 19. Total monthly river flow from January 2005 to December 2014 and (inset) total annual river flow from 2000 to 2014 for the Don River. Data source: www.ehp.qld.gov.au (Station #121003A).

Mean cloud cover

Cloud cover is measured visually by estimating the fraction (in eighths or oktas) of the dome of the sky covered by cloud (BOM 2015). A completely clear sky is recorded as zero okta, while a totally overcast sky is 8 oktas. The presence of any trace of cloud in an otherwise blue sky is recorded as 1 okta, and similarly any trace of blue in an otherwise cloudy sky is recorded as 7 oktas (BOM 2015). As expected the number of cloudy days was higher in the wet season at the beginning and end of 2014 with small sporadic spikes of cloudy days within June and August The highest number of clear days was recorded between August and September 2014 (Figure 20).

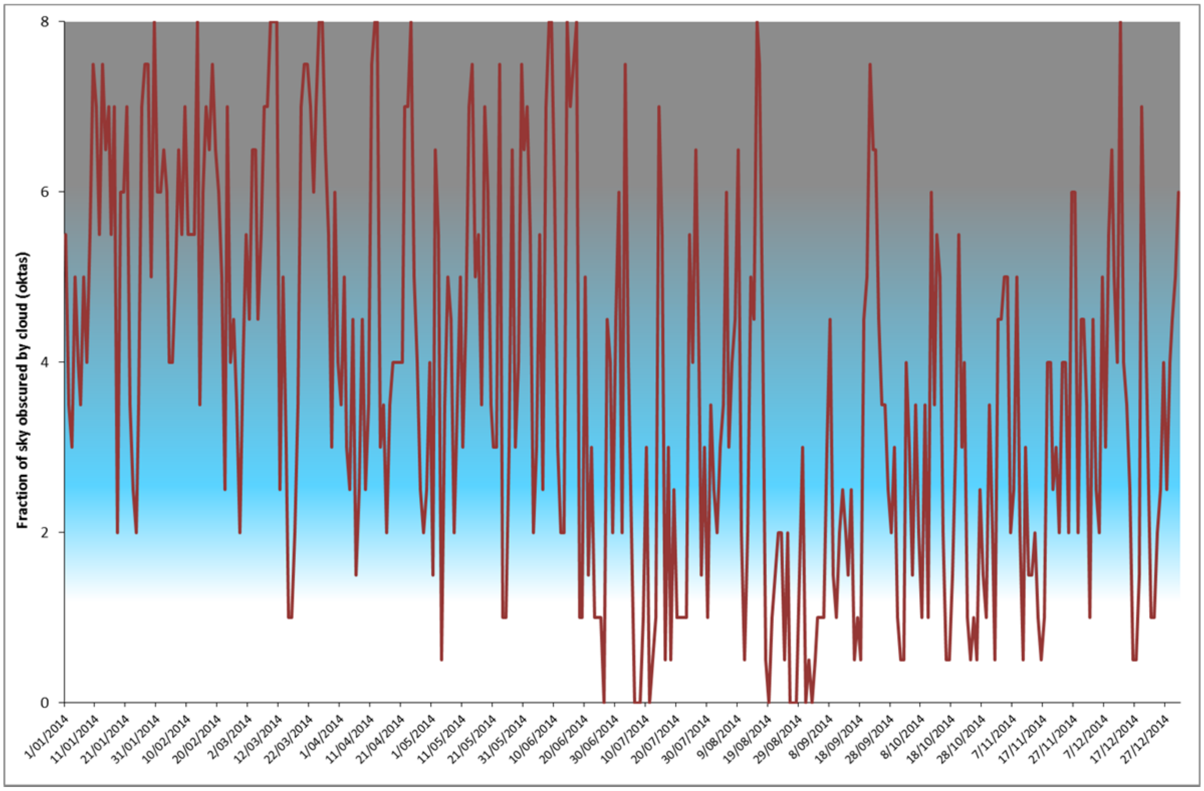


Figure 20. Mean number of clear and cloudy days between March and December 2014 (0 = clear day; 8 = cloudy day). Data source www.bom.gov.au (Station #33257).

4 DISCUSSION

By the end of 2014 offshore *Halophila* spp. meadows at Abbot Point recorded significant increases in above-ground biomass from losses which occurred following TC Oswald. The majority of inshore meadows also increased in biomass and area, however, much of this increase was driven by colonising *Halophila ovalis* in the meadow and not their previous foundation species *Halodule uninervis* and *Zostera muelleri.* The return of *H. uninervis* and *Z. muelleri* at some of the inshore meadows are positive signs however of initial re-establishment. Full recovery of the inshore meadows would only be achieved with a major return of these foundation species.

The declines in seagrass biomass and distribution that occurred at Abbot Point as well as in many other locations in the wet and dry tropic regions of Queensland were linked to prolonged severe weather events such as high rainfall, flooding, storms, turbid water conditions and cyclones associated with La Niña climate patterns (Rasheed et al. 2014; Petus et al. 2014). Throughout 2013 and 2014 conditions in the seagrass growing season have generally been much more favourable at Abbot Point and have likely contributed to the increases in seagrass biomass and distribution at the majority of Abbot Point monitoring sites.

The combination of high rainfall, high river flow and cyclones can negatively impact seagrass either physically (burial, scouring, direct removal of plants and seed-banks) (Preen et al. 1995; Bach et al. 1998; Campbell & McKenzie 2004) or physiologically (light limitation, excess nutrients and herbicides, and changes in salinity) (Björk et al. 1999; Ralph et al. 2007; Chartrand et al. 2012). The quality and quantity of light is a critical determinant of seagrass growth and abundance (Ralph et al. 2007; Chartrand et al. 2012) and low light levels are thought to be the primary factor limiting the growth of many seagrasses (Waycott et al. 2005). As low light conditions are prolonged, physiological responses to changes in light availability may occur first, providing short term relief from low light conditions, followed by morphological responses, and finally biomass loss occurs and meadow-scale loss becomes apparent (Longstaff and Dennison 1999; Ralph et al. 2007; Collier et al. 2012b). Studies of seagrasses in tropical regions have indicated that genera such as *Zostera* and *Halodule* have significantly greater light requirements than other genera such as *Halophila* species, and that *Halophila* spp. will react faster to impacts such as light deprivation compared to larger species (Bach et al. 1998; Longstaff & Dennison 1999; Collier et al. subm 2015).

Based on assessments of relevant literature values, ongoing studies and analysis of *in situ* light and seagrass change data collected at Abbot Point, preliminary light thresholds for *H. uninervis* and *Halophila* spp. were determined: 1.5 mol photons m^{-2} d^{-1} over a rolling 7 day average best described the light conditions at which offshore *Halophila* spp. biomass was maintained, while for the inshore *H. uninervis* meadows, it was found that 3.5 mol photons m^{-2} d^{-1} over a rolling 14 day average best described the light conditions at which seagrass biomass was maintained. The thresholds developed were based on the need to ensure the protection of seagrasses from potentially deteriorating light conditions, while also having a credible fit with measured background light variability inherent within the local meadows, and local light requirements for the species. Our suggested light thresholds are in line with experimental results from Chartrand et al. (2014) and Collier et al. (2015 subm) and field studies by Collier et al. (2012a) that described ranges of light requirements that encompass our suggested initial thresholds. Future plans for incorporating light based triggers for seagrass management at Abbot Point should remain flexible to allow additional information from ongoing data collection, or any additional new studies to be incorporated in refining the thresholds.

Utilising these initial light threshold values shows that over the last two growing seasons (approximately July to December) there has been enough light to support and maintain seagrass at Abbot Point. The relatively slow re-establishment of seagrass at Abbot Point despite improving environmental conditions is most likely due to the near complete disappearance of meadows and species, with little remaining seagrass from which recovery, maintenance, growth and expansion could occur. In addition, recovery has likely been stalled as a result of impacts caused by TC's Oswald, Dylan and Ita. Manipulative field experiments at Abbot Point and Cairns have demonstrated that *H. uninervis* and *Z. muelleri* have a high reliance of on asexual reproduction for recovery (Rasheed 2004; Rasheed et al. 2014). This, combined with the suspected lack of seed-banks/reserves of these species at Abbot Point has important implications for recovery potential, and suggests that re-establishing these meadows may be a slow process which in other locations can take up to more than ten years (Kirkman 1978; Birch and Birch 1984; Hyland et al. 1989; Poiner et al. 1989; Campbell and McKenzie 2004).

While the presence of *H. uninervis* since 2013 and more recently *Z. muelleri* is a positive sign, recovery is at a critical juncture and it will be important that these adult plants persist and expand to ensure ongoing recovery, particularly in the absence of substantial seed reserves for the species at Abbot Point. It is possible that seagrass at inshore meadows may divert most of their energy on persistence of the population and clonal expansion during this initial recovery phase, rather than producing more seeds and germination of new seedlings (Shafer and Bergstrom 2010). It will be critical then how this initial re-establishment of seagrass copes over the next twelve months as seed banks are unlikely to have been replenished as yet. Regular seed bank assessments of the monitoring meadows would be a critical addition to the monitoring program to more fully understand the resilience and capacity for recovery of these seagrass meadows.

Implications for Port Management

Results of the latest surveys indicate that there has been a significant increase in the biomass of offshore *Halophila* spp. meadows in 2014, while seagrass recovery at inshore sites has been modest. It is likely that multiple years of climate induced seagrass decline are likely to have left a legacy of reduced resilience to further impacts and the next twelve months will be critical for Abbot Point seagrasses. If the newly established patches of *Z. muelleri* and *H. uninervis* at inshore sites remain through the 2015 senescent season and there are no major climatic events that impact meadows, then continued growth and expansion of seagrass in 2015 could occur.

Other Queensland seagrass monitoring locations such as Cairns, Townsville and Gladstone have also recorded increases in biomass and distribution at monitoring sites since major declines (Carter et al. 2015; Davies et al. 2015; Jarvis et al. 2015). Cairns and Townsville monitoring sites have recorded an increase in larger 'foundation' species such as *Cymodocea serrulata,* Z. *muelleri* and *H. uninervis*. The increase in seagrass at these sites has also been attributed to at least two years (2013 and 2014) of climate conditions favourable for seagrass growth; average or below average temperatures, rainfall and river discharges, and light levels considered sufficient for seagrass growth (Carter et al. 2015; Davies et al. 2015; Jarvis et al. 2015). The differential rates of recovery of seagrass meadows across the state following wide-scale declines emphasises the importance of understanding the drivers of local resilience and recovery of seagrasses in Abbot Point. Considering the state of seagrass resilience will be important in managing potential impacts of future port activities and developments especially considering the generally reduced state of resilience for most meadows.

While the monitoring program provided a sound basis for developing local light thresholds for *Halophila* spp. and *H. uninervis*, these values are initial values only and should remain flexible to incorporate any new data as it comes to hand. In addition, there has not yet been sufficient recovery of *Z. muelleri* to develop local light thresholds for this species at Abbot Point. Some of the following actions could provide further strengthening of the light thresholds for application in active management:

- *Increase the seagrass sampling frequency to monthly during the growing season* to provide a period of more frequent seagrass change data to assess against fluctuating light levels, and better refine thresholds. Currently the 3 monthly period between seagrass sampling limits the ability to effectively assess these relationships;
- *In situ shading studies* to quantify the impact of different light levels and light reduction regimes on seagrass morphometrics (biomass, percent cover and shoot density). This will allow us to physically force the light into the range where we suspect declines will occur and arrive at more accurate thresholds;

- *Laboratory studies:* further quantify and test the impacts of different light levels and light reduction regimes on seagrass morphometrics, photosynthetic efficiency and oxygen production and respiration against controlled conditions;
- *Investigate the effects of changes in the spectral quality of light* associated with dredge plumes. The quality of the light environment reaching seagrasses may be as important as the quantity of light received. Applying photosynthetic usable radiation (PUR) in place of PAR could resolve any effects of wavelength-specific water column absorption.

The threshold values for the species derived in this report were heavily informed by the *in situ* light and seagrass monitoring at Abbot Point. This monitoring has provided critical information on the light environment associated with the maintenance or increase in seagrass at the sites and emphasizes the value of keeping these loggers and seagrass monitoring in place leading up to dredging. In addition, given the large changes that have occurred in Abbot Point seagrass biomass and distribution as a result of climatic events, it will be important to maintain monitoring as multiple years of climate induced seagrass decline are likely to have left a legacy of reduced resilience to further impacts. Continued monitoring throughout the dredging program and as part of longer term ambient seagrass monitoring will also help assist in separating out port related versus regional causes of seagrass change detected in the monitoring program.

In summary, results of the 2014 Abbot Point long-term seagrass surveys indicate:

1. Coastal seagrasses in the Abbot Point area remain in a vulnerable state;
2. Positive signs of seagrass re-establishment include significant increases in biomass of offshore *Halophila* meadows, modest increases of biomass and distribution at some inshore meadows, and the re-emergence of *Z. muelleri* and *H. uninervis* to meadows where they have been absent since the 2010/2011 La Niña and TC Yasi related losses;
3. Light and climate conditions appeared to be favourable for seagrass growth and the delay in recovery observed is likely a reflection of previous large-scale declines limiting the availability of propagules from which recovery could be initiated and sustained;
4. Continuing the seagrass monitoring program is critical to tracking the recovery of seagrass in the Abbot Point region prior to any potential port development;
5. Maintaining the seagrass and light monitoring program will be important to further refining light thresholds for direct management application.

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A APPENDICES

A.1 Abundance and Distribution Comparisons 2005 - 2012

1. Mean above-ground biomass (g DW m^{-2}) of coastal monitoring meadows within the Port of Abbot Point, March 2005, February 2008 – December 2014.

	Mean Biomass ± SE (g DW m^{-2}) (no. sites present in meadow)				
Meadow #	**3**	**5**	**7**	**8**	**9**
Mar 05	0.09 ± 0.03 (6)	0.03 ± 0 (1)	0.06 ± 0 (1)	0.03 ± 0 (1)	1.63 ± 0.54 (16)
Mar 08	3.71 ± 1.72 (8)	0.05 ± 0.02 (9)	2.84 ± 0 (1)	0.52 ± 0.52 (2)	0.86 ± 0.47 (17)
Jul 08	4.55 ± 1.68 (15)	1.57 ± 0.08 (3)	3.72 ± 0.33 (4)	NP	1.10 ± 0.53 (12)
Sep 08	8.91 ± 4.17 (11)	1.54 ± 0.57 (6)	6.7 ± 2.21 (12)	1.65 ± 0.33 (2)	0.40 ± 0.15 (17)
Nov 08	6.98 ± 2.95 (14)	1.34 ± 0.71 (6)	2.87 ± 0.74 (9)	5.01 ± 1.72 (3)	1.02 ± 0.51 (20)
Apr 09	3.34 ± 0.95 (9)	NP	1.68 ± 0.46 (8)	NP	0.17 ± 0.08 (10)
Aug 09	2.76 ± 0.99 (14)	NP	0.43 ± 0.18 (7)	1.57 ± 1.18 (2)	0.63 ± 0.30 (23)
Dec 09	1.59 ± 0.55 (31)	0.005 ± 0.003 (5)	1.0 ± 0.62 (13)	NP	0.15 ± 0.08 (15)
Jun 10	0.84 ± 0.4 (13)	0.06 ± 0 (1)	0.76 ± 0.4 (4)	5.04 ± 0 (1)	0.11 ± 0.02 (6)
Nov 10	2.92 ± 0.86 (5)	3.74 ± 1.06 (3)	4.46 ± 0.41 (3)	1.61 ± 0 (2)	0.73 ± 0.16 (12)
Mar 11	NP	NP	2.03 ± 1.16 (5)	0.07 ± 0 (4)	NP
May 11	NP	NP	0.40 ± 0 (1)	NP	NP
Sept 11	NP	NP	0.69 ± 0.4 (3)	NP	NP
Feb 12	0.23 ± 0 (1)	NP	4.58 ± 0.19 (3)	NP	NP
Jun 12	NP	NP	0.82 ± 0.31 (5)	NP	NP
Sep 12	NP	NP	NP	NP	NP
Jan 13	NP	NP	NP	NP	NP
Apr 13	3.10 ± 0 (1)	NP	0.25 ± 0 (1)	NP	4.42 ± 0 (1)
Jul 13	NP	NP	2.74 ± 0.91 (5)	NP	1.67 ± 0 (1)
Sept 13	NP	NP	1.53 ± 0.72 (4)	NP	3.07 ± 1.55 (3)
Dec 13	2.16 ± 0.75 (3)	NP	2.40 ± 1 (4)	NP	1.60 ± 1.07 (3)
Mar 14	NP	NP	6.11 ± 1.2 (2)	NP	1.71 ± 0.7 (4)
Jul 14	0.06 (1)	NP	1.73 ± 0.73 (5)	NP	2.31 ± 0.65 (6)
Sep 14	1.67 ± 0.34 (3)	1.2 ± 0.04 (2)	3.98 ± 1.29 (3)	NP	4.36 ± 0.91 (8)
Dec 14	5.13 ± 0.76 (4)	NP	13.84 ± 4.6 (3)	NP	4.31 ± 0.93 (18)

NP – No seagrass present in meadow

2. Area (ha) of coastal monitoring meadows within the Port of Abbot Point, March 2005, February 2008 – December 2014.

Area ± R (ha)						
Meadow #	**3**	**5**	**7**	**8**	**9**	**TOTAL meadow area**
Mar 05	25.6 ± 6	21.5 ± 6.1	19.5 ± 7.1	5.6 ± 2.7	125.8 ± 41	**198 ± 62.9**
Mar 08	55.5 ± 8	67.9 ± 27.6	4.2 ± 0.9	2.1 ± 0.7	120.8 ± 71.4	**250.5 ± 108.6**
Jul 08	53.1 ± 8.3	9.7 ± 1.9	3.6 ± 0.9	NP	67.0 ± 9	**133.4 ± 20.1**
Sep 08	56.95 ± 8.06	19.83 ± 17.1	21.47 ± 2.38	4 ± 0.81	83.96 ± 10.26	**186.21 ± 38.61**
Nov 08	83.6 ± 10.5	30.9 ± 18.6	12 ± 2.1	3.7 ± 1	83.1 ± 13.1	**213.3 ± 45.3**
Apr 09	32.4 ± 19.9	NP	9.2 ± 5.6	NP	38.20 ± 28.7	**79.8 ± 54.2**
Aug 09	44.2 ± 9.3	NP	13.2 ± 2.6	3 ± 0.7	22.9 ± 5.1	**83.3 ± 17.7**
Dec 09	75.4 ± 9.3	13.3 ± 10.1	15.7 ± 6.2	NP	127.5 ± 17.8	**231.9 ± 43.4**
Jun 10	24.6 ± 6.8	1.4 ± 1	5.1 ± 3	1.6 ± 1	56.3 ± 33.3	**89 ± 45.1**
Nov 10	15.04 ± 13.2	16.04 ± 13.67	5.25 ± 5.09	2.18 ± 2.07	105.38 ± 85.44	**143.89 ± 119.47**
Mar 11	NP	NP	8.58 ± 6.46	3.88 ± 2.78	NP	**12.46 ± 9.24**
May 11	NP	NP	3.01 ± 2.23	NP	NP	**3.01 ± 2.23**
Sep 11	NP	NP	3.12 ± 2.66	NP	NP	**3.12 ± 2.66**
Feb 12	2.48 ± 2.05	NP	5.55 ± 4.16	NP	NP	**8.03 ± 6.21**
Jun 12	NP	NP	10.97 ± 7.79	NP	NP	**10.97 ± 7.79**
Sep 12	NP	NP	NP	NP	NP	**NP**
Jan 13	NP	NP	NP	NP	NP	**NP**
Apr 13	6.28 ± 5.3	NP	6.81 ± 6.4	NP	1.2 ± 1	**14.29 ± 12.7**
Jul 13	NP	NP	13.27 ± 4.84	NP	1.23 ± 1.02	**14.5 ± 5.86**
Sept 13	NP	NP	28.86 ± 13.86	NP	35.11 ± 15.47	**63.97 ± 29.33**
Dec 13	10.19 ± 1.6	NP	19.76 ± 2.79	NP	27.08 ± 2.89	**57.03 ± 7.28**
Mar 14	NP	NP	6.3 ± 4.73	NP	45.46 ± 23.84	**51.76 ± 28.57**
Jul 14	3.31 ± 0.7	NP	15.55 ± 7.9	NP	64.97 ± 58.5	**83.83 ± 67.1**
Sep 14	12.19 ± 3.84	3.93 ± 1.02	6.56 ± 1.46	NP	92.42 ± 71.5	**115.1 ± 77.82**
Dec 14	11.9 ± 7.12	NP	7.4 ± 3.24	NP	234.28 ± 115.41	**253.59 ± 125.77**

NP – No seagrass present in meadow

3. Mean above-ground biomass (g DW m^{-2}) of offshore monitoring sites in the Port of Abbot Point, March 2005, February 2008 – December 2014.

Sampling Date	Mean Biomass ± SE (g DW m^{-2}) (dominating seagrass species)			
	Site 1	Site 2	Site 3	Site 4
Mar 05*	0.08 ± 0.07	0.59 ± 0.15	3.98 ± 1.43	Site not established
Feb/Mar 08*	0.04 ± 0.04	0.60 ± 0.57	3.28 ± 1.38	Site not established
Jul 08	0.17 ± 0.06	1.27 ± 0.44	3.31 ± 0.38	Site not established
Sept 08	0.02 ± 0.02	0.61 ± 0.17	5.10 ± 0.65	Site not established
Nov 08	0.11 ± 0.06	1.58 ± 0.55	11.07 ± 1.33	Site not established
Apr/May 09	0.0006 ± 0.0006	NP	0.34 ± 0.06	Site not established
Aug 09	0.07 ± 0.04	0.46 ± 0.11	0.45 ± 0.09	Site not established
Feb 10**	0.07	3.75	12.69	Site not established
June 10	NP	0.14 ± 0.05	0.77 ± 0.12	Site not established
Nov 10	0.17 ± 0.07	6.26 ± 0.89	25.76 ± 2.52	5.34 ± 0.76
Mar 11	0.03	0.20 ± 0.08	0.20 ± 0.08	0.14 ± 0.06
May 11	NP	0.23 ± 0.09	0.20 ± 0.08	0.07 ± 0.05
Sep 11	NP	0.26 ± 0.07	0.18 ± 0.06	0.19 ± 0.06
Feb 12	NP	0.31 ± 0.09	0.97 ± 0.17	0.37 ± 0.10
Jun 12	NP	0.44 ± 0.09	1.97 ± 0.24	0.83 ± 0.18
Sep 12	NP	0.59 ±0.16	1.76 ± 0.26	1.16 ± 0.21
Jan 13	0.01 ± 0.009	NV	0.14 ± 0.03	0.04 ± 0.02
Apr 13	0.01 ± 0.009	0.04 ± 0.01	0.03 ± 0.02	0.01 ± 0.009
Jul 13	NP	0.02 ± 0.01	0.09 ± 0.05	NP
Sept 13	NP	0.08 ± 0.03	0.02 ± 0	0.02 ± 0.01
Dec 13	NP	0.03 ± 0.02	0.09 ± 0.03	0.06 ± 0.02
Mar 14	NP	0.06 ± 0.03	0.14 ± 0.04	0.05 ± 0.02
Jul 14	0.2 ± 0.1	0.04 ± 0.02	0.03 ± 0.01	0.03 ± 0.02
Sep 14	0.009 ± 0.005	0.81 ± 0.2	0.32 ± 0.12	0.004 ± 0.002
Dec 14	NP	0.51 ± 0.16	1.02 ± 0.19	0.02 ± 0.01

* - Mar 05 & Feb/Mar 08 surveys were Baseline surveys so the location of Monitoring Blocks were not established thus Biomass is derived from transects in the baseline survey that were located closest to monitoring blocks that were established in July 2008.

** - No visibility at monitoring sites; Biomass calculations approximate only: Biomass derived from calculation of shoot counts converted to biomass based on biomass and shoot relationships of similar meadow and species composition

NP – No seagrass present in monitoring blocks

NV – No visibility at site