Impacts of a fuel oil spill on seagrass meadows in a subtropical port, Gladstone, Australia – The value of long-term marine habitat monitoring in high risk areas

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A R T I C L E   I N F O

Keywords:
Seagrass
Heavy fuel oil
Intertidal habitat
Long-term monitoring

A B S T R A C T

We used an established seagrass monitoring programme to examine the short and longer-term impacts of an oil spill event on intertidal seagrass meadows. Results for potentially impacted seagrass areas were compared with existing monitoring data and with control seagrass meadows located outside of the oil spill area.

Seagrass meadows were not significantly affected by the oil spill. Declines in seagrass biomass and area 1 month post-spill were consistent between control and impact meadows. Eight months post-spill, seagrass density and area increased to be within historical ranges. The declines in seagrass meadows were likely attributable to natural seasonal variation and a combination of climatic and anthropogenic impacts. The lack of impact from the oil spill was due to several mitigating factors rather than a lack of toxic effects to seagrasses. The study demonstrates the value of long-term monitoring of critical habitats in high risk areas to effectively assess impacts.

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1. Introduction

Seagrass habitats form an important and productive component of the world’s shallow coastal waters and provide ecosystem services that rank amongst the highest on earth, on par with crops of corn and sugar cane (Björk et al., 2008; Durako et al., 1993; Ralph et al., 2007; Waycott et al., 2009). The importance of seagrass ecological functions and economic values (Costanza et al., 1997) are widely accepted, including their contribution to commercial fisheries (Watson et al., 1993) nutrient cycling (Duffy, 2006; Mellors et al., 2002), sediment stabilisation (Fonseca and Fisher, 1986) and carbon cycling (Duarte and Cebrian, 1996; Rasheed et al., 2008a).

As seagrasses are restricted to shallow-depth distributions near the land/sea margin they are particularly vulnerable to a range of natural and anthropogenic threats (Waycott et al., 2009). In Queensland, Australia, seagrasses are commonly found in sheltered coastal bays that also provide natural safe harbours and are favoured locations for port and coastal developments. This proximity of seagrasses to ports, shipping lanes and large coastal developments results in heightened risks associated with shipping, dredging and a variety of pollutants such as heavy metals, herbicides, mixed effluents and heat pollution (Erfemeijer and Lewis, 2006; Runcie et al., 2004). The threat of shipping accidents and oil spills in these areas is substantially elevated, with estimates that up to 54% of major oil spills caused by shipping occur near vulnerable ecosystems, including seagrasses (Burns et al., 1993). The impact of oil on seagrasses varies depending on the type of oil spill, the degree of contact and the species of seagrass. Smothering through algal blooms (Jacobs, 1980), shoot mortality (Dean et al., 1998; Kenworthy et al., 1993; Peirano et al., 2005) and a reduction in seagrass tolerance to other stress factors (Zieman et al., 1984) have been documented.

Changes to seagrasses caused by anthropogenic factors such as oil spills occur against a background of seagrass change driven by a range of natural drivers, including natural variability in climate and hydrodynamic conditions both seasonally and between years (Hall et al., 1999; McKenzie, 1994; Rasheed and Unsworth, 2011). Separating natural from anthropogenic causes of seagrass change is critically important to developing strategies that effectively mitigate anthropogenic activities impacting seagrass. As a result, long-term seagrass monitoring programs have been established in many Queensland locations including the Port of Gladstone with the goal of assessing the potential impacts of such anthropogenic activity.

On the 24th of January 2006 a tug boat suffered engine failure and punctured the hull of the Korean bulk carrier “Global Peace” during berthing operations in the Port of Gladstone, (AMSA, 2006). The puncture occurred in the carrier’s fuel oil tank, spilling approximately 25 tonnes of heavy fuel oil (bunker oil plus kerosene or diesel). The oil spill was contained to an area approximately
15 km long by 4 km wide, with concentrations of oil located in pockets around the wharf site and nearby areas. The extent of the oil spill was controlled by tidal movement with the oil moving up and down the channel according to tidal flow. Maritime Safety Queensland (MSQ) initiated its marine oil spill response arrangements immediately under its National Plan which resulted in the spill being contained to a relatively small area and over 18 tonnes of the oil being recovered. Despite this, prevailing weather and tidal conditions caused some oil to be deposited on the intertidal banks in areas of the port, leaving a viscous and persistent residue (Andersen et al., 2008; Melville et al., 2008) and possibly impacted areas known to contain intertidal seagrasses.

An annual long-term seagrass monitoring programme had been established in the port since 2002 (Rasheed et al., 2005, 2003). As part of this programme, large areas of seagrass have been mapped and monitored on intertidal banks in the footprint of the oil spill and nearby areas outside of the oil spill’s influence. The availability of this baseline data collected over several years and the established monitoring programme allowed a critical examination of potential impacts of the oil spill on seagrasses. This is unique as most investigations of the impacts of oil spills are generally reactive, commencing after the initial damage occurred and baseline data are often lacking with little knowledge of natural variation in seagrass at the site. Here we investigate the impacts of a fuel oil spill on seagrasses using established long-term seagrass monitoring with three years of baseline information on inter-annual change and examine potential impacts to seagrass health 1 month and 8 months post-spill.

2. Materials and methods

2.1. Long-term monitoring programme

The annual Gladstone seagrass long-term monitoring programme was established based on data collected during a baseline survey of seagrass habitat within port limits and extending south to Rodds Bay (Fig. 1). The programme examines a subset of 13 of the 129 identified seagrass meadows which represent the range of seagrass communities identified in the 2002 baseline survey. Monitoring meadows were located in areas likely to be vulnerable to impacts from port related operations and developments as well as “control” meadows from which changes could be measured. These meadows have been monitored annually from 2002 to 2006 (with the exception of 2003).

Seagrass abundance and distribution in Queensland has been shown to vary seasonally, typically with a spring/summer maxima and a winter minima (McKenzie, 1994; Rasheed et al., 2001). Sampling annually in October/November allowed seagrasses to be captured at their seasonal peak in density and distribution.

2.2. Oil spill site selection and experimental design

Five intertidal meadows (of the 13 monitored annually) located between the Calliope River and Friend Point (north of Fishermans Landing) were assessed four weeks post oil spill (27th February–1st March 2006) (Fig. 2). Four of these meadows represented the major areas that were impacted by the oil spill footprint (Fig. 2). As a control to measure any natural changes in seagrasses that had occurred since the pre-spill monitoring (October 2005) we assessed an intertidal seagrass monitoring meadow with similar species composition at Pelican Banks which was unlikely to have been affected by the spill (Fig. 2). A reconnaissance of seagrass monitoring meadows in Rodds Bay (approximately 45 km from oil spill) was also conducted. These meadows were reassessed 8 months later in October 2006.

2.3. Habitat assessment and geographical information system

The boundaries of the seagrass meadows were mapped from aerial (helicopter) surveys using a global positioning system (GPS) and digitized onto a Geographic Information System (GIS) basemap (McKenzie et al., 2001) They were conducted at low tide when seagrass meadows were exposed. The GIS basemap was constructed and projected to Geodetic Datum of Australia (GDA 94) coordinates using ArcGIS (Environmental Systems Research Institute, Inc., Redlands, CA). The precision of determining seagrass meadow boundaries was expressed as an estimate of reliability (R) (McKenzie et al., 2001). These reliability estimates ranged between ±10–15 m for the surveys and were based on the accuracy of obtaining position fixes for boundary mapping sites.

Seagrass meadow characteristics were collected at seagrass habitat characterisation sites scattered randomly within the seagrass meadow. The number of sites placed within the meadow was based on the initial baseline survey conducted in 2002 and a power analysis (Burdick and Kendrick, 2001). Seagrass habitat characteristics (seagrass species composition and above-ground biomass) along with GPS fixes were recorded at each sampling site from a helicopter hovering within a metre of the ground when the meadow was exposed at low tide. Seagrass biomass (above-ground) was determined using a modified “visual estimate of biomass” technique described by Mellors (1991) and follows the specifics of a methodology used at other seagrass sites within Queensland (Rasheed et al., 2008a,b).

2.4. Statistical analysis

Seagrass biomass data from pre-impact (October 2005), oil spill impact (February 2006) and recovery (October 2006) was analysed with Analysis of Variance in GenStat v11.1. Datasets for which variances were heterogeneous were square-root transformed as appropriate to satisfy conditions of ANOVA following McKillup (2006) and Zar (1999).

3. Results

3.1. Inter-annual seagrass change prior to oil spill (2002–2005)

Prior to the spill five seagrass species occurred in the five oil spill impact and control meadows located within and outside of the footprint of the oil spill. Zostera capricorni Aschers., Halophila ovalis (R. Br.) Hook.f., Halophila decipiens Ostenfeld, Halophila spinulosa (R.Br.) Aschers. in Neumayer, and Halodule uninervis (narrow leaf form) (Forsk.) Aschers. in Boissier.

Seagrass meadows were highly variable in the years leading up to the spill (2002–2005). Total biomass of seagrasses across oil spill assessment meadows showed a decline to a minimum in 2004 (from 8.23 down to 6.75 g DW m⁻²). Biomass increased considerably in 2005 to a peak of 9.24 g DW m⁻². The decline in 2004 came after major flooding of the local Calliope River in the wet season of 2003 and above-average flow in 2004. Local climate conditions returned to more “normal” conditions in 2005 coinciding with the recovery of seagrass. This pattern, however, was not consistent for all meadows. The Wiggins Island East meadow and North Fishermans meadow both exhibited biomass declines for all three survey years, although this was only significant for North Fishermans (F₂,10₄ = 39.95, P < 0.0001) between 2002 and 2004 (Fig. 3). Despite changes in biomass, inter-annual comparisons of total meadow area (all meadows combined) revealed little change throughout the three years ranging from 1413.8 ha in 2004 to 1543.5 ha in 2002.
Mean meadow biomass was consistently higher at Pelican Banks than the other meadows, ranging from 18.71 ± 2.13 g DW m⁻² in 2004 to 28.3 ± 3.3 g DW m⁻² in 2005. This meadow was covered by a continuous dense mat of seagrass. Interannual variation of mean biomass was more pronounced in all other meadows which had patchier seagrass landscapes (Fig. 3). The North Fishermans seagrass meadow showed the greatest variability, recording both the lowest (0.06 ± 0.04 g DW m⁻² in 2004) and second highest (2.1 ± 0.3 g DW m⁻² in 2002) mean biomass values over the three years.

All five seagrass meadows were initially dominated (greater than 50% composition) by *Z. capricorni* in 2002 and comprised smaller components of the other species. In 2004, the colonising species *H. ovalis* had displaced *Z. capricorni* in both the Wiggins Island meadows and the South Fishermans meadow to become the dominant seagrass species. This was most pronounced for the Wiggins Island West meadow where meadow composition of *Z. capricorni* reduced by 62% in 2004 to a low of 20%. *Z. capricorni* recovered in South Fishermans in 2005, although both the Wiggins Island meadows remained *H. ovalis* dominated.

3.2. Comparison of seagrass biomass and distribution pre-spill, post-spill and during recovery

3.2.1. One month post oil spill

There were some significant declines to seagrass meadows both within and outside of the oil spill footprint 1 month after the spill had occurred (Fig. 4). Total mean biomass of seagrass across all five assessment meadows (impact and control) significantly declined from the levels recorded in October 2005 (9.24–1.88 g DW m⁻²)
Similarly, total meadow area recorded its first loss greater than its expected area range change, falling from a high of 1424.6 ha to 1229.9 ha. Changes to meadows within the footprint of the oil spill were consistent with declines that had occurred in the control meadow at Pelican Banks and observations recorded from a reconnaissance survey of seagrasses in Rodds Bay 43 km to the south of the study site (Fig. 1).

The two *H. ovalis* meadows located at Wiggins Island that were the most exposed to the oil spill showed no significant change in biomass 1 month post-spill. However, while not statistically significant, the Wiggins Island East meadow had declined in biomass from 0.33 ± 0.15 to 0.06 ± 0.04 g DW m$^{-2}$, with the opposite occurring for the West meadow which had increased from 0.86 ± 0.5 to 1.3 ± 0.42 g DW m$^{-2}$. Seagrass cover had become patchier. There was a marked increase in the presence of an unidentified filamentous green algae on both Wiggins Island meadows.

The *Z. capricorni* dominated North Fishermans meadow continued a declining trend, reducing substantially to a low of

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**Fig. 2.** Location of oil spill impact assessment seagrass meadows.

**Fig. 3.** Inter-annual change in seagrass meadow above-ground biomass 2002–2005.

**Fig. 4.** Change in above-ground biomass of seagrass meadows between pre-spill, impact and recovery surveys.

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($F_{2,59} = 19.37, P < 0.0001$).
0.02 ± 0.02 g DW m\(^{-2}\). Similarly, the South Fishermans meadows showed a significant decline from 0.94 ± 0.61 to 0.24 ± 0.15 g DW m\(^{-2}\) (\(F_{2,139} = 31.65, P < 0.001\)) (Fig. 4). In addition, substantial changes to the species composition at South Fishermans had occurred with an increase in \(H.\) ovalis from 44% to 92%.

The control meadow outside of the footprint of the oil spill, Pelican Banks, also showed a significant decline in biomass from pre-spill to post-spill, similar to meadows within the oil spill footprint (\(F_{2,160} = 30.16, P < 0.001\)) (Fig. 4). A reccounissance of the \(Z.\) capricorni meadows at Rodds Bay, 43 km from the oil spill site also indicated that they had declined substantially in biomass since October 2005.

Seagrass species composition of oil spill and control assessment meadows was consistent between pre-spill and post-spill sampling, with the exception of the South Fishermans meadow which had a change in species dominance from \(Z.\) capricorni to \(H.\) ovalis. This mixed species meadow appears to regularly shift in dominance between the two species with \(H.\) ovalis being dominant in 2004.

3.2.2. Eight months post oil spill

Results from the recovery survey 8 months post-spill, showed that meadows within and outside of the footprint of the oil spill had recovered to pre-spill levels of biomass and area. Total mean biomass of seagrass across all five assessment meadows significantly increased from the levels recorded at 1 month post-spill (\(1.88-5.46\) g DW m\(^{-2}\)) (\(F_{2,190} = 19.37, P < 0.0001\)), although they averaged below the high levels recorded 12 months earlier in October 2005. Total meadow area had regained the lost coverage to be at a high for the monitoring programme of 1494.0 ha.

Biomass increases were not consistent between individual meadows, with all meadows within the footprint of the oil spill increasing in biomass to be at substantially higher levels for the recovery survey (October 2006) than in the pre-spill survey in October 2005 (Fig. 4). The Pelican Banks meadow, located outside of the footprint of the spill had not recovered to the same high level recorded pre-spill in October 2005, however, the biomass had significantly increased from 5.86 ± 0.89 to 14.17 ± 1.07 g DW m\(^{-2}\) (\(F_{2,166} = 30.16, P < 0.001\)) to be within the range of biomass levels recorded prior to the spill between 2002 and 2004.

The most ecologically important result was the significant increase in biomass observed in the \(Z.\) capricorni dominated North Fishermans meadow, reversing the declining trend that had occurred since 2002 (\(F_{2,162} = 30.16, P < 0.001\)) (Fig. 4). Seagrass biomass had increased 60-fold between February and October 2006 to 1.28 ± 0.49 g DW m\(^{-2}\). This increase in biomass was the result of an increased presence of pioneering \(H.\) ovalis, \(H.\) decipiens, \(H.\) spinulosa which had increased from 2% of the species composition to form a combined 40%.

There was also recovery of \(Z.\) capricorni in both the Wiggins Island meadows. This was most pronounced for the Wiggins Island West meadow where meadow composition of \(Z.\) capricorni increased by 49% to displace \(H.\) ovalis as the dominant seagrass species. The Wiggins Island East meadow remained \(H.\) ovalis dominated.

4. Discussion

Assessments of oil spill impacts on seagrasses where detailed baseline information is available are rare. This study examined the impacts of an oil spill on tropical seagrasses where detailed baseline data and natural inter-annual variation were already established. The post-spill and recovery seagrass assessments indicated that intertidal seagrass meadows in Gladstone had not been significantly affected by the “Global Peace” oil spill. Although oil spill assessment meadows showed a significant decline in density (biomass) and area 1 month post-spill, these changes were consistent with declines that occurred in meadows outside of the oil spill area and were likely the result of natural seasonal change. Recovery of seagrass meadows to pre-spill levels 8 months later suggests that there were other seasonal or climatic factors causing these declines.

The lack of significant impact to seagrasses from the Global Peace oil spill was likely due to several mitigating factors rather than a lack of toxic effects to the seagrass plants. Tidal conditions at the time of the oil spill may have protected seagrasses from the full effects of the spill resulting in a much reduced area, duration and frequency of potential direct contact between seagrasses and oil. The most negative effects of oil on seagrasses have been observed when leaves of intertidal plants have been exposed to direct contact with oil (Durako et al., 1993; Jackson et al., 1989; Jacobs, 1980). The oil spill at Gladstone occurred on a high neap tide, and it is likely that the intertidal meadows were not exposed until 2–3 days after the spill. By this point in time, the oil would have approached its maximum spread and photoxidation, evaporation and dissolution processes would likely have reduced the quantity of remaining oil in the area to low levels (Sauer et al., 1993; Zieman et al., 1984).

While tidal conditions were likely to have greatly reduced the potential direct interactions between oil and seagrass plants there was evidence of some interaction. Oil was observed to have settled in some seagrass areas including a section of the Wiggins Island West meadow immediately following the spill (Leonie Andersen, pers. com.). In this area seagrass leaves appeared to have lost some pigmentation and high levels of polycyclic aromatic hydrocarbons (PAHs) were recorded in sediments 1 month post oil spill (Melville et al., 2008). The lack of significant mortality to seagrasses in these areas may be due to their resilience to short term exposure to oil. Studies have found that seagrasses are able to withstand short pulsed direct contact events with oil without prolonged negative impact provided that successive contact events are minimised (Durako et al., 1993; Jacobs, 1980; Macinnis-Ng and Ralph, 2003; Thoraug et al., 1986). Thoraug et al. (1986) reported insignificant mortality of Thalassia testudinum after 5 h of exposure to Crude Oil, however mortality rates significantly increased with both the concentration of oil and the length of exposure. Macinnis-Ng and Ralph (2003) found that photosynthetic activity of \(Z.\) capricorni showed an initial decline upon pulsed exposures to aged crude oil (Champion Crude) in the field, however maximum and effective quantum yields had recovered by the end of the experiment (4 days).

The increased presence of macro-algae on the Wiggins Island East and West meadows was possibly related to the oil spill. These were the closest seagrass meadows to the site of the oil spill and were likely to have experienced the greatest concentrations of oil. A bloom of algae on intertidal seagrass beds has been documented in previous oil spill cases (Jackson et al., 1989; Jacobs, 1980; Ralph and Burchett, 1998). The algae bloom has been attributed to factors such as an increase in nutrients released from oil-killed organisms, stimulating compounds in oil, and a reduction in herbivore presence. Increased growth of algae can often lead to a smothering of seagrasses (Bulthuis and Woelkerling, 1983; Cambridge et al., 1986) and is often a sign of a reduction or change in water quality. However these meadows were also the closest to the mouth of the Calliope River and the increased algae coverage may well have been related to nutrient inputs from the river catchment rather than the oil spill.

The fact that losses of seagrass biomass in the spill area were consistent with changes at Pelican Banks and Rodds Bay (outside of the spill area) and that seagrasses recovered to pre-spill levels by October 2006 indicated that the oil spill was unlikely to be
This study highlights the value of having a long-term monitoring programme established for seagrasses in areas of high risk. Effective long-term monitoring should provide information useful to environmental managers, offering temporal cause/effect linkages not typically available in retrospective analysis (Stein and Cadieu, 2009). With a prevalence of oil spill impact studies occurring reactively to events (Durako et al., 1993; Jacobs, 1980; Kenworthy et al., 1993; Peirano et al., 2005), the need for routinely collected data to establish baseline information and associated variability are important issues identified in studies following a number of oil spills, such as the "Sea Empress" (Batten et al., 1998) and the "Prestige" (Laflon et al., 2006). Robust baseline data and an understanding of natural variability in seagrass are vital to be able to measure impact related change. In the absence of long-term monitoring data in this current study, it would have been reasonable to conclude that the low biomass and distribution recorded in impact assessment seagrass meadows in relation to the higher biomass and area of the control meadow, 1 month post-spill, was as a result of an impact from the "Global Peace" oil spill, rather than part of the natural inter- and intra-annual variability cycles for seagrasses in the region.

Acknowledgements

We wish to thank the dedicated Fisheries Queensland staff that have assisted with fieldwork between 2002 and 2006 including Stewart Campbell, Rob Coles, Simon Kerville, Skye McKenna, Anthony Roelof, Tonia Sankey and Ross Thomas. The authors acknowledge the financial support of the Port Curtis Integrated Monitoring Programme, Gladstone Ports Corporation, Fisheries Queensland and the CRC Reef Research Centre’s Ports and Shipping Programme. Finally, the symbols for diagrams are courtesy of the Integration and Application Network (ian.umces.edu/symbols), University of Maryland Centre for Environmental Science.

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