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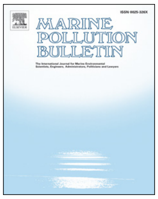

Baseline

Oil spill from the Era: Mangroves taking eons to recover

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ABSTRACT

Mangroves are highly susceptible to oil exposure. Depending on the severity, oil exposure can result in initial defoliation and eventual recovery through to mass mortality and complete loss of habitat. Some aspects of the impact of oil on mangroves and their recovery are well studied, but the focus has been on short-term responses, and the understanding of the longer-term trajectory of mangrove recovery from oiling is very limited. Here, we combine field results from sampling in the two years following a significant oiling event, with analysis of canopy cover in aerial images from before the event to 26 years afterwards. Approximately 100 ha of a monospecific stand of *Avicenna marina* mangroves were oiled as a result of a spill from the Era tanker in Spencer Gulf in southern Australia in September 1992. While lightly oiled trees made a full recovery, trees in heavily oiled areas experienced mass defoliation and ultimately mortality within several months of the oiling event. An analysis of aerial images indicated that there was no recovery in heavily oiled areas for 10 years following the oiling event. Between 10 and 25 years, seedling establishment and growth saw canopy cover increase to 35% of pre-oiling cover within heavily oiled areas. Predictive modelling estimates that complete recovery of mangroves to pre-oiling cover will take 55 years (median prediction in 2047). Our findings indicate that although mangroves can recover following a heavy oiling event, the rate of recovery can be slow, with full recovery in the order of half a century, much longer than has previously been anticipated.

1. Introduction

Mangroves are an ecological community of plants that inhabits coastal intertidal areas in tropical, subtropical and, in some places, warm temperate waters (Bunting et al., 2018; Krauss and Friess, 2011). Mangrove trees have elaborate adaptive mechanisms to cope with the pressures of tidal inundation, salinity stress, and anoxic soils: salt excluding roots, salt excreting leaf glands, aboveground roots for stability, and aerial roots that allow oxygen transport to submerged roots (Lee et al., 2014). These same adaptive mechanisms, however, make mangroves especially susceptible to anthropogenic disturbance, through the detrimental impacts of pollution, including exposure to hydrocarbons (Lee et al., 2006).

1.1. Oil toxicity and its impact on mangroves

Coastal mangrove forests are highly susceptible to oil pollution (Hensel et al., 2014). Oil entering mangrove forests in tidal areas does so at or near high tide, smothering aerial roots and potentially also leaves. Oiling of aerial roots can suffocate the root system. Oiling of leaves reduces transpiration and respiration rates by blocking stomata and may also lead to eventual leaf mortality (Baker, 1970). The severity of oil exposure for mangroves largely depends on the amount and type of oil entering the intertidal zone (Duke, 2016). A large oil spill can result in substantial smothering of leaves and the aerial root system which can quickly suffocate and kill mangroves within a few weeks to months (Duke et al., 1997). A smaller spill, or the periphery of a large spill, may only lightly coat mangrove roots and leaves, leading to defoliation but without tree mortality or on-going impacts on plant productivity (Duke, 2016; Lewis, 1983). The type of oil is also a key determinant in the severity of impacts on mangroves. While heavy oils (high specific gravity) are particularly proficient at coating and smothering small plants and aerial root systems, lighter oils (low specific gravity) are more toxic to mangroves (Hensel et al., 2014; Lai and Lim, 1984; Wardrop et al., 1987). In addition to the key determinants of impact, amount and type of oil, several other factors also influence the response of mangroves to oil: e.g. oil age (weathering), oil dispersant used (Wardrop et al., 1987), mangrove species (Duke et al., 1998b) and sediment type (Duke and Burns, 1999). These factors potentially also affect subsequent recovery.

Mangrove forests typically follow an ordered set of conditional states after suffering an oiling event, described by Duke (2016) as initial

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impact, primary and secondary effects, and eventual habitat recovery (except in cases of complete loss). Based on Da Silva et al. (1997), the timing of four generalised stages is: 1) initial impact of about one year, where propagules and seedlings are killed, 2) structural damage, to about 2.5 years, 3) stabilisation, after about 5 years, where mangrove deterioration ceases but recovery is not evident, and 5) recovery, over variable periods, where the mangrove forest improves via colonisation and increased density.

While there are many studies reporting the initial impact and subsequent recovery of mangroves following oiling events (see Duke (2016) for a comprehensive list), most report data only within a few years of oiling rather than on long-term (10+ years) impact and recovery. Recent modelling of the data that are available from longer-term studies estimates full mangrove recovery at 25–30 years (Duke, 2016). However, Duke (2016) cautions that the paucity of existing long-term data limits the precision of modelling, highlighting the need for more long-term data to refine predictions of complete recovery after oiling.

1.2. *The Era oil spill*

On August 30, 1992, a docking accident involving the unladen tanker Era released an estimated 296 t of heavy Bunker fuel oil (a blend of diesel and heavy residual oil) at Port Bonython, in Spencer Gulf, South Australia (Fig. 1). Within hours of the release, the oil slick was sprayed with oil dispersants Corexit 9527 and 7664 from vessels, and then again the following day from fixed-wing aircraft using Ardrox dispersant. Despite these dispersal efforts, an estimated 57 t of oil stranded along 12 km of mangrove coastline south of Port Pirie, on the other side of the gulf to the accident (Fig. 1; Connolly and Jones, 1996; Keesing et al., 2018; Wardrop et al., 1996). The stranded oil penetrated up to 50 m into the monospecific forest of *Avicennia marina* mangroves, with an estimated 75–100 ha of forest experiencing some degree of oiling (Fig. 2; Wardrop et al., 1996). An estimated 4.2 ha of mangrove forest were oiled heavily, 7.3 ha moderately, and 38 ha lightly. The remaining impacted areas (30–55 ha) experienced very light oiling (see Table S1 for a description of these classifications).

The severity of defoliation observed across the impacted area was correlated with the degree of oiling (Wardrop et al., 1996). In lightly oiled areas, trees experienced minor leaf damage and rapidly recovered, while in moderately and heavily oiled areas, mangroves were either severely or completely defoliated. By 5 November 1992 (nine weeks after oiling), extensive defoliation was recorded in the heavily oiled areas, impacting an area of approximately 2.3 ha. By March 1996 (~ 3.5 years after oiling), the area of extensive defoliation had expanded to 3.2 ha. Trees that were completely defoliated had not recovered by the end of the four-year field survey period. In moderately oiled areas, trees exhibited leaf damage but showed no sign of canopy loss. The impacts in lightly oiled areas were minor and after an initial minor loss of oiled leaves following the oiling event, mangroves were fully recovered within the four-year field survey period.

Given the importance, and paucity, of long-term data on mangrove recovery from oiling, here we expand upon the initial field surveys to investigate the long-term recovery patterns of mangroves oiled heavily during the 1992 Era event. We hypothesised that mangrove canopy cover would follow a trajectory similar to that described by Duke (2016) and da Silva et al. (1997): initial mortality indicated by substantial reduction in canopy coverage, followed by stabilisation and recovery through increased canopy coverage. We focussed on heavily oiled areas because our objective was to provide more certain time estimates for this example of long-term mangrove recovery.

2. Study site

Spencer Gulf, on the coast of the state of South Australia, Australia, is a large (460 km^2) marine embayment, considered an inverse estuary due to a semi-arid climate and minimal river inputs (Gostin and Hill, 2014). Extensive monospecific stands of the mangrove *Avicennia marina* line the wide intertidal zone of much of the gulf's coasts (Seddon et al., 2000; Dittman and Baggalley, 2014; Lymburner et al., 2020).

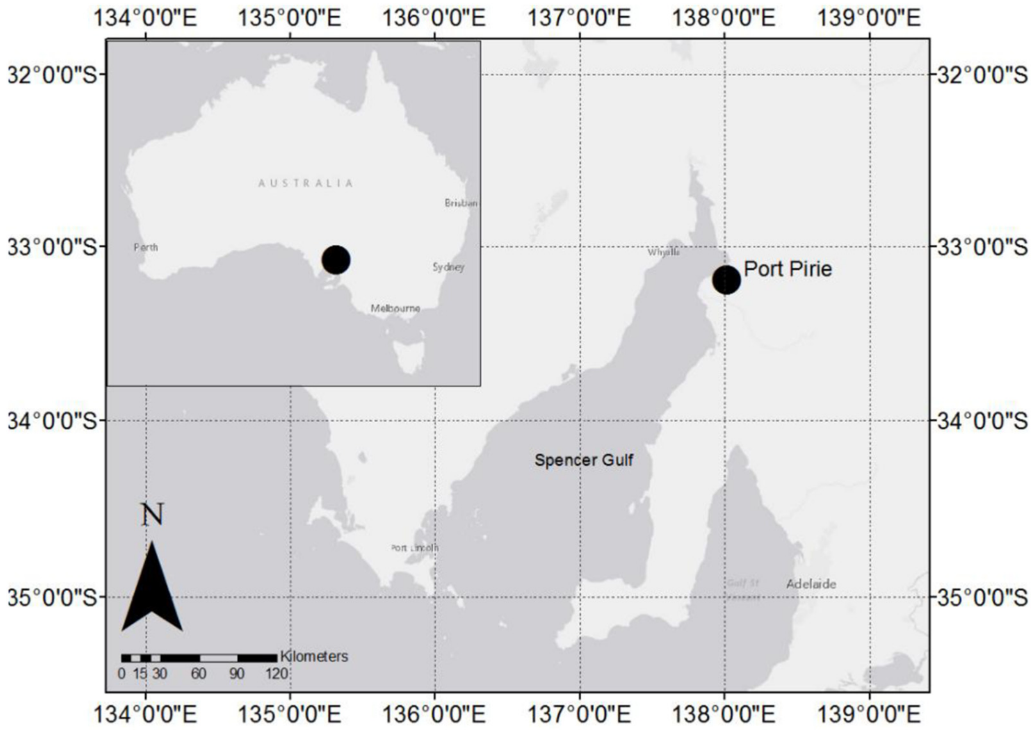

Fig. 1. Map of location. Map showing study location (black circles) near Port Pirie, Spencer Gulf, South Australia.

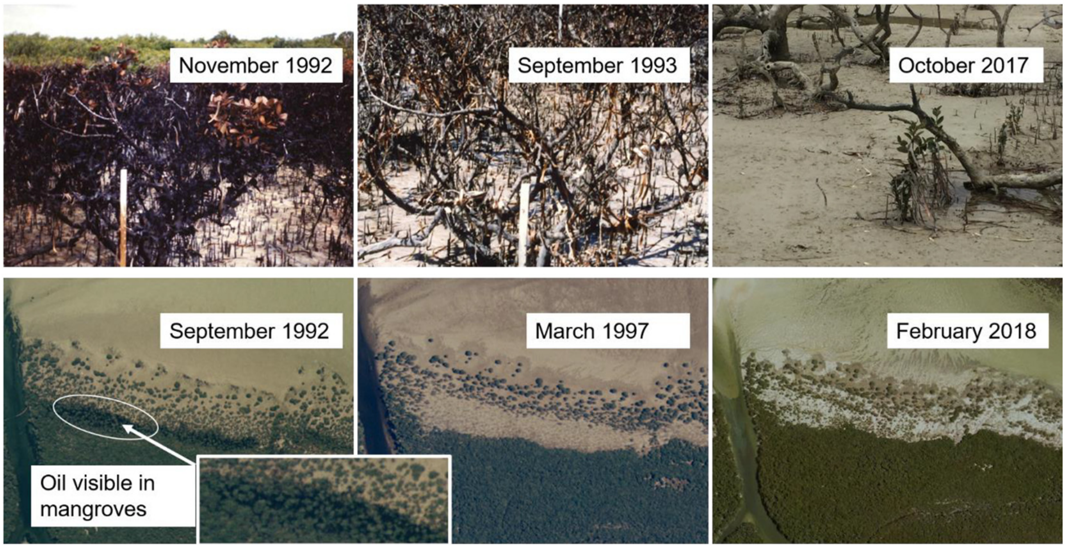

Fig. 2. Images of mangroves at different stages: Top row from left, all in heavily oiled areas: two months after oiling; ten months after oiling; sapling recruits 25 years after oiling. Bottom row from left, all aerial images: 11 days after the oil spill – note oil visible in mangroves; 4.5 years after oiling – showing clear loss of habitat; 25 years after oiling – showing partial recovery.

3. Methods

3.1. Analysis of loss and recovery of mangrove canopy

The most suitable imagery for investigating fine-scale changes in mangrove cover over time in this region is aerial images. Imagery at 15,000:1 and 25,000:1 scales of the oiled area was available for:

- 1981 (the only pre-oiling year available, 9 years pre-oiling)
- 1992 (in September, taken immediately post-oiling but with canopy intact and thus representing the canopy at oiling rather than post-oiling)
- 1994 – 2 years post-oiling
- 2002 – 10 years post-oiling
- 2006 – 14 years post-oiling, and
- 2018 – 26 years post-oiling.

Four sites (S1–S4) identified as heavily oiled in the original field survey (Wardrop et al., 1996) were used to measure temporal changes in mangrove percent cover from 1981 to 2018. Aerial images permitted excellent separation of canopy (green) and non-canopy (cream coloured sediment), verified in a site visit in 2018. Supervised classifications were conducted in QGIS using the SCP plugin. Land-cover classifications in each of the four heavily oiled sites were defined as either non-canopy or canopy. Classifications used a minimum distance algorithm optimised for the heavily oiled regions for each year. After classifications were conducted, raster images were imported into R (version 3.4.4; R Core Team, 2018), binarised using the 'raster' package and masked to the heavily oiled regions. The area of mangrove (as percent cover) within each heavily oiled site for each year was then calculated.

3.2. Predictive modelling of full recovery period

To estimate the time to full canopy recovery, we used the most appropriate statistical model for situations such as this that have few time points and no prior knowledge of the shape of the response curve. We thus used a general additive model (GAM), with penalised regression spline smoothers (limited to 3 knots). This allowed us to make predictions about recovery based on non-linear trends in canopy cover observed following the oiling in 1992 (including site as a random effect). The model was fitted with restricted maximum-likelihood estimation using the 'gam' function in the R package 'mgcv', and model diagnostics were evaluated using the function 'gam.check'. Data fitted assumptions of homoscedasticity and normality of residuals. Following model-fitting, percent cover of mangrove forest was predicted in each site for each year between 1994 and 2050. The mean predicted percent cover across sites and 95% confidence intervals were calculated.

4. Results

In the 11-year period leading up to the Era oiling event in September 1992, mangrove canopy cover remained largely the same (1981 = 79%, 1992 = 81%; error estimates on Fig. 3A; total of 2.5 ha area). By 1994, two years after the event, canopy cover had substantially reduced to 10% (0.2 ha total), resulting from mass mortality at heavily oiled sites during that initial two-year period (Fig. 3A). By 2002, ten years after the event, mean canopy cover across all sites had reduced marginally further to 7.7% (still 0.2 ha). At this time, however, some variability among sites was observed, with one site (S2) showing a marginal increase from 13 to 14% cover, and another (S4) remaining stable (albeit at 2% cover). From 2002 to 2018 there was a steady increase in mean canopy cover, increasing to 17% in 2006 and to 32% in 2018. By this time, the extent of recovery varied substantially among sites, from S2 (45% cover by 2018) down to S4 (25% by 2018). Site S3 recorded just a very minor increase in canopy cover between 2006 and 2018 (27 to 28%). Based on observed data, the non-linear predictive model estimated complete recovery of canopy cover to pre-oiling levels by 2047 (± 2.4 years), 55 years after the oiling event in 1992 (deviance explained = 84.8%; Fig. 3B).

5. Discussion

The aim of this study was to combine retrospective aerial analysis with initial field surveys of oiling coverage and impact assessments to investigate the long-term recovery of a mangrove forest following a heavy oiling event. At the Era oiling event, the extent of oiling ranged along a scale of severity, from light to moderate to heavy oiling. While the impact and recovery in the light and moderate oiled areas were reported in Wardrop et al. (1996), the long-term impacts and recovery of mangroves in the heavily oiled areas remained unknown, making this oiling incident a particularly useful case to monitor the long-term recovery of a mangrove forest following a significant oiling event.

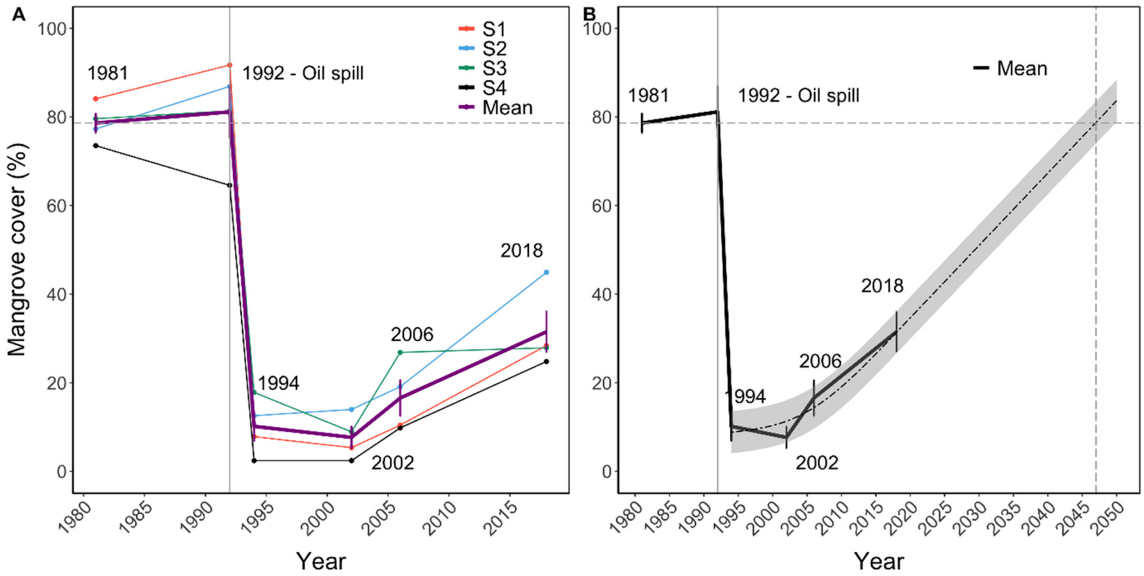

Fig. 3. Trajectory of loss and recovery of mangrove canopy following the 1992 oiling event, (A) observed data, and (B) predictive modelling showing estimated time to full recovery. Panel A: solid coloured lines represent mangrove cover at each site. Solid black-line represents mangrove cover averaged across sites (± SE). Panel B. Dashed black line represents predicted mangrove cover averaged across sites, with 95% confidence intervals in grey. The solid grey vertical lines indicate the time of the Era oiling event in September 1992. The dashed grey vertical lines indicate predicted recovery in 2047 corresponding to average mangrove cover in 1981 (grey horizontal dashed line, 79%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Heavy oiling led to complete defoliation and mass mortality of mangroves, with no initial indications of recovery until ten years following the oiling event. After 26 years, canopy recovery was patchy (Fig. 2), with recovery less than half of the pre-impact cover. Most oiling impact and recovery studies only report the impacts and recovery of mangrove forests within a few years of the oiling event (see Hensel et al. (2014) and Duke (2016)), with little published information on the long-term effects of oiling on mangrove recovery. The current study provides valuable information about recovery from heavy oiling - clearly at 26 years post-impact, the mangrove canopy is far from fully recovered.

Changes in canopy cover from the initial oil spill incident in 1992 through to 2018 support our hypothesis that impact and recovery projections would follow similar trajectories to those described by Duke (2016) and Da Silva et al. (1997). After the Era oil spill there was an initial deterioration of tree health and ultimately tree mortality, resulting in loss of canopy cover over two years, followed by a significant period of prolonged degradation at the site, where canopy cover deteriorated further before beginning to show signs of recovery more than ten years after the oiling event. These results resemble the trajectory described in Duke (2016) where, following the initial oiling impact, plants will enter into a sublethal or lethal state indicated by defoliation, death or slow recovery in the initial 1–5 years, followed by stabilisation and the beginning of significant recovery. Full recovery after the Era spill, however, is taking considerably longer than would be expected based on existing models. Best estimates to date are of full recovery after 25–30 years, with wide confidence limits because of the paucity of data (Duke, 2016). Our median prediction of full recovery in the current study at 55 years after impact provides important additional information, indicating that much longer recovery periods are possible.

The location of this oil spill is relevant to the finding of a very long recovery time. The mangroves of Spencer Gulf are near the highest latitudes of mangroves globally, in a semi-arid zone (Duke et al., 1998a; Friess et al., 2019). Both factors, the temperate climate and the aridity, tend to limit growth of mangroves (Duke et al., 1998a). It is conceivable, therefore, that the trajectory described for this location might represent the situation towards the slowest recovery after oiling.

Mangrove recovery within lower intertidal, seaward mangroves may be further constrained by global change impacts such as sea level rise and increased storm events, which could hinder seedling re-establishment in low intertidal and exposed areas (Krauss et al., 2014; Lovelock et al., 2015a; Lovelock et al., 2015b). The most recent survey of sediment accretion and sea level rise at Port Pirie found that mangrove sediments were increasing at the same rate as sea level (measurement of 0.3 mm.yr^{-1} in 1996; Harvey et al., 1999), although the rate of sea level rise in Spencer Gulf has increased since then (White et al., 2014). Recent field inspections did not detect any conspicuous erosion or shoreline retreat. Nevertheless, future climate scenarios might impact ongoing recovery. For example, seedling establishment and survival following an oiling event are hampered by the impacts of wind and waves (Duke and Burns, 1999), which are likely to increase in severity due to increased extreme storm events as a result of climate change and global heating (Stott, 2016). Further, mangrove mortality can ultimately lead to increased erosion and loss of surface elevation (Cahoon et al., 2003; Duke et al., 2017; Ouyang et al., 2017). Combined with the impact of increasing sea-levels, mangroves could face lower surface elevation and increased duration of tidal inundation to the point where the terrain becomes unsuitable for mangrove recolonisation and results in a complete loss of habitat (Krauss et al., 2014; Atwood et al., 2017). Research capable of addressing the confounding effects of mangrove mortality from oiling events and global change impacts on mangrove re-establishment is a priority.

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CRediT authorship contribution statement

Rod M. Connolly:Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Visualization, Writing - review & editing.**Finnian N. Connolly**:Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing - review & editing.**Matthew A. Hayes**:Formal analysis, Methodology, Visualization, Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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