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RESEARCH ARTICLE

Effects of the MV *Rena* oil spill on intertidal rocky reefs in the Bay of Plenty, New Zealand

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In the weeks following the 2011 *Rena* oil spill, a series of surveys was initiated on eight rocky intertidal reefs to describe the distribution of oil and to assess the impacts of oil on ecological communities. Consistent but relatively low cover of oil occurred at two sites (Mt Maunganui and Moturiki). The area covered by oil had decreased by c. 90% after 5 months due to natural weathering processes. There were immediate effects of oil fouling on the mussel *Limnoperna pulex* and its associated fauna, with reductions in the number of mussels and infaunal taxonomic richness. However, no ecological effects on any of the communities were detectable after 1 month. Overall, the ecological effects of the *Rena* oil spill on rocky shore intertidal communities were small and not long-lasting, but we stress that this does not consider potential sublethal effects and their consequences on organisms.

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Intertidal diversity; *Limnoperna pulex*; New Zealand; oil spill; Rena; rocky shore

Introduction

The effects of oil spills on intertidal assemblages can be severe and long-lasting (Southward & Southward 1978; Suchanek 1993; Paine et al. 1996; Hawkins et al. 2002; Peterson et al. 2003; Gilde & Pinckney 2012). Ecological effects of oil spills depend not only on the types of biological communities present in the area where oil is dispersed, but also on a variety of interacting factors including the type of oil, its quantity, local physical environmental factors, topography, tidal fluctuations, prior exposure to oil and the choice of remedial action taken (Straughan 1972; O'Brien & Dixon 1976). Documented impacts following oil spills into the marine environment have ranged from lethal to sublethal, direct and/or indirect effects at the individual level (e.g. interfering with photosynthetic uptake), population level (e.g. changes in abundance, reproductive ability and recruitment dynamics) and community level (e.g. via modified trophic pathways and lower diversity; O'Brien & Dixon 1976; Suchanek 1993; De Vogelaere & Foster 1994; Driskell et al. 2001).

On 5 October 2011, the MV *Rena* (37,209 gross t) ran aground on Otaiti (Astrolabe Reef) carrying 1733 t of oil (Schiel et al. 2016). Over the following 6 days approximately 350 t of heavy fuel oil (HFO) 380 were released from the fuel tanks, much of which was deposited onshore by winds between 9–11 October in the Mōtītī Island and the Mt Maunganui/Papamoa region (Maritime New Zealand 2013; *Rena* Recovery 2013). A total of

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1041 t of 'oiled waste' such as sand and driftwood were removed from the shorelines of Mt Maunganui and Papamoa in the 2 weeks following the grounding (Maritime New Zealand 2013). The amount of oil released was considerably less than other spills globally, due to the MV *Rena* being a container vessel rather than an oil tanker and the rapid removal of much of the onboard oil after the grounding (Maritime New Zealand 2013). Nevertheless, the close proximity of the grounding to the coast, the relatively unspoiled shoreline habitats of the region, and the high cultural and societal values placed on the coast in this region (particularly for collecting seafood and recreation), meant that there was significant potential for ecological and social impacts.

The intertidal landscape in the Bay of Plenty comprises predominately sandy beach habitats but with rocky reefs at Mōtītī Island, Maketu, Mt Maunganui and Whakatane, and smaller rocky outcrops protruding from the sandy beaches at Whiritoa, Waihi Beach and surrounding Moturiki. Of the c. 1733 t of oil onboard the MV *Rena*, some 350 t were not recovered and much of it was washed onshore. Oil was observed being washed onto rocky reefs at Mōtītī Island, Maketu, Mt Maunganui and Moturiki, within the first 2 days following the spill, and at the latter two sites settled mostly in the upper shore on bare rock or on beds of the black mussel *Limnoperna pulex* (D.R. Schiel, pers. obs.). Although oil was spread widely along the coast as far east as Maketu, it was patchy in its distribution (Battershill et al. 2013). Containers and debris from the vessel were more widely distributed, found as distant as Waihi Beach and East Cape within Bay of Plenty, and Great Barrier Island in the Hauraki Gulf (*Rena* Recovery 2013).

We surveyed eight of the predominant and accessible rocky reefs in Bay of Plenty, describing the distribution of oil contamination and the ecological communities at these sites. Intensive quantitative sampling was done where oil deposition was most concentrated. This included the size, distribution and abundance of oil patches, immediate effects on resident organisms and, with follow-up surveys, the consequences of the oil on intertidal organisms and communities.

Methods and materials

Spatial distribution of oil on rocky intertidal reefs

Moturiki

The exposed eastern shore of Moturiki (37°37′56.3″S, 176°11′4.3″E) was sampled in November 2011, and in June and October 2012. Quadrats (1 × 1 m) were used to record the number and sizes of oil patches and the substratum these patches were on. Oil patch size was recorded using Vernier calipers taking the maximum length and the maximum width. Twenty-five quadrats were used to continuously sample along three 25 m transects running parallel to each other along the shore and positioned in the upper mid tidal zone (c. 0.14 m above mean sea level [MSL]), lower high zone (c. 1.06 m above MSL) and splash zone (c. 1.32 m above MSL). This covered the entire available intertidal habitat at this reef, as the lower zone was covered by sandy beach.

Mt Maunganui

The reef at Mt Maunganui (37°37′36.4″S, 176°10′32.6″E) was larger and more gently sloping compared to the more vertical reef at Moturiki. The shore was extensively searched and no oil patches were found in the mid and low shore zones, but oil was present on boulders in the high tidal zone. We therefore marked 12 boulders (ranging from 0.6 m^2 to 64 m^2 in surface area) in the high zone and the density (i.e. number of patches per area) and sizes of oil patches and the substrata they were on were recorded in November 2011, June 2012 and October 2012.

All other sites

A further six sites within the Bay of Plenty (Whiritoa, Waihi Beach to the northwest and Kohi Point, Ohope, and two sites at East Cape to the east; see Figure 1), were surveyed in March or June 2012 and October 2012. All sites were searched for oil patches and any oil patches found were measured and recorded. The community composition was surveyed using 10 randomly placed 1 m^2 quadrats in the low (if not sandy beach), mid and high zones, and the per cent cover of algae and sessile invertebrates and the counts of mobile invertebrates were recorded (see Schiel 2011 for full description of sampling methodology). We were unable to sample at Mōtītī Island and Maketu reefs.

The effects of oil on ecological communities

Due to limited previous background data being available from the sites where most of the oil deposition occurred, and due to reefs being non-contiguous in their distribution, a before–after, control–impact (BACI) design was not possible. We therefore attempted to quantify any differences in community structure between oiled and non-oiled patches at one of the most heavily impacted sites, Moturiki, in November 2011. Most of the oil at Moturiki was in the mid and high zones, where it was found

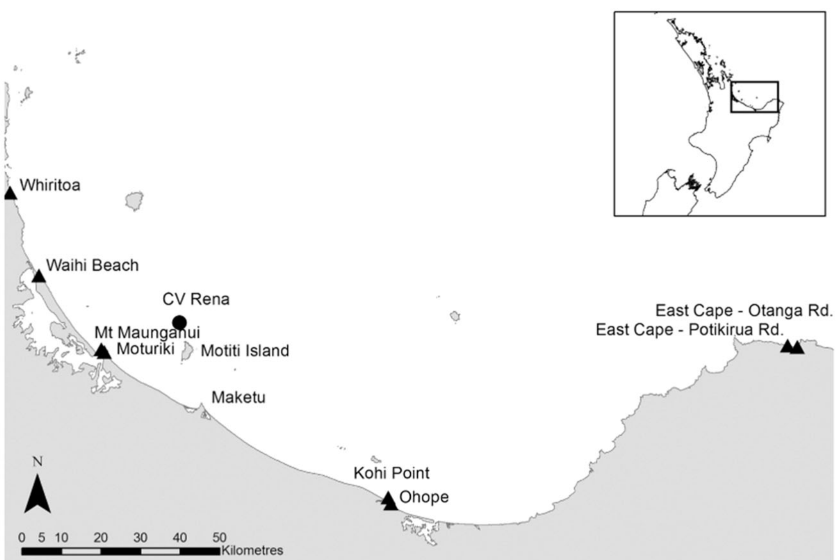

Figure 1. Sites sampled within the Bay of Plenty (those sampled for oil are indicated by black triangles).

predominately on bare rock and little black mussels (*Limnoperna pulex*). To determine the effects of oil on the mussel community, five small patches (5 × 5 cm) were scraped out of areas in the mid-zone *L. pulex* beds that had obvious oil fouling on and among the mussels. All fauna and sediment were retained and preserved in 70% ethanol. For comparative purposes, five patches within the same area of reef where there was no obvious oil deposited on the mussel shells and in the interstitial spaces of the mussel bed, were scraped and collected for comparison (for pictures, see Figure S1). Patches were also taken from within mid-zone *L.* pulex beds at Moturiki, Whiritoa and Waihi Beach in June and October 2012 for spatial and temporal comparison of the assemblages within *L. pulex* beds.

In order to assess the relationship between the quantity of oil and patterns of mussel and infaunal mortality, the oil from 5 × 5 cm patches of *Limnoperna* was scraped off using a scalpel and weighed. This patch size was in the mid to high range of sizes at this reef (see Results). Live (at the time of sampling) and recently dead (determined by attached valves with no tissue within) mussels were counted. Infauna from all samples were identified to the highest possible taxonomic resolution (usually species) and enumerated.

In November 2011, ten 10 × 10 cm areas within the same *L. pulex* mussel bed at Moturiki were permanently marked with tags at the corners. Five areas were covered with oil and five had no visible oil on or between mussels, but all had 100% cover of *L. pulex*. Plots were monitored in March, June and October 2012 and the per cent cover of the major space occupiers (*L. pulex*, *Chamaesipho columna* and bare rock) was recorded.

Statistical analyses

Spatial distribution of oil on rocky intertidal reefs

To analyse differences in the density (per m^2) and area (cm^2) of oil patches at Moturiki, we used a two-way repeated measures analysis of variance (rmANOVA) to test for the effects of shore height (upper-mid, lower-high and splash zones) and time (November 2011, June 2012, October 2012). At Mt Maunganui, a one-way rmANOVA was used to test the effect of time (November 2011, June 2012, October 2012) on the number and area of oil patches. Homogeneity of variances was assessed using Cochran's test and, when necessary, per cent covers were arcsine transformed and counts were log transformed to fulfil the assumptions of ANOVA. Where data did not conform to the assumption of sphericity for rmANOVA (Mauchly test, $P < 0.05$), Wilks' lambda multivariate test for repeated measures was used to alter the error degrees of freedom and thereby the F statistic, reducing the chance of a type I error.

The effects of oil on ecological communities

Linear regression was used to determine the relationship between oil weight (g) within mussel patches and taxa richness, number of individuals, and the density of live and dead *L. pulex* in oiled and non-oiled patches from Moturiki 1 month after the oil spill (November 2011). Community composition between the oiled and non-oiled patches from Moturiki was analysed using PermANOVA (using fourth-root transformation and Bray-Curtis similarity resemblance matrices) and compared to samples taken at this site in June and October 2012, and to samples from Whiritoa and Waihi Beach.

The 10 × 10 cm plots marked in situ at Moturiki were analysed using two-way rmANOVA for the effects of time (November 2011, June 2012, October 2012) and treatment (oiled and non-oiled) on the per cent cover of *L. pulex*, *C. columna* and bare space. Where necessary, per cent covers were arcsine square-root transformed to achieve homogeneity of variances.

Results

Oil was present at four of the eight rocky intertidal reefs sampled. The two sites in the vicinity of where most of the oil was deposited (Mt Maunganui and Moturiki) had the greatest oil cover, and Waihi Beach and Whiritoa to the northwest had a very low cover that did not persist (see below).

Moturiki, Waihi Beach and Whiritoa were all small, vertical rocky outcrops at the ends of long sandy beaches, where the low shore zone was covered by sand and the mid and high shore zones dominated by filter-feeding invertebrates. The mid zone was dominated by matrices of *L. pulex* and *C. columna*, with high abundances of the small grazers *Austrolittorina cincta* and *A. antipodum* and the whelk *Haustrum scobina*. The high zone was dominated by bare space and *C. columna*. In contrast, Mt Maunganui is a large, fragmented reef with large boulders. The communities here were separate from those of the other three sites (Figure 2) and had three distinct tidal zone communities (as indicated by the spread of points on the principal coordinates analysis [PCO] plot). The low zone was dominated by large brown macroalgae (*Carpophyllum maschalocarpum*, *Xiphophora chondrophylla* and *Dictyota kunthii)*, and the red algae *Pterocladia lucida* and *Corallina officinalis*. The mid zone was dominated by encrusting coralline algae, the turfing alga *Corallina officinalis* and ephemeral algae (*Colpomenia* spp., *Splachnidium rugosum*, *Ulva* spp.), and the high zone was dominated by bare space and the barnacle *C. columna*.

Spatial distribution of oil on rocky intertidal reefs

Oil was concentrated, albeit patchily (photograph in Figure S2) on the high shore zone at Mt Maunganui and the mid to high shore zone at Moturiki. There were two very small patches of oil found in June 2012 at Whiritoa in the high zone (mean area of patch = 0.22 ± 0.14 cm^2) and six patches found in June 2012 at Waihi Beach in the supralittoral zone (mean area of patch = 32.78 ± 13.38 cm^2), but no oil patches were found at Whiritoa or Waihi Beach in October 2012, despite thorough checking.

Oil patch density

The number of oil patches per m^2 in the high and splash zones at Moturiki tended to increase, while the number of patches in the upper-mid zone decreased through time (Figure 3A; time × shore height interaction $F_{2,144} = 12.31$, $P < 0.0001$). Mt Maunganui

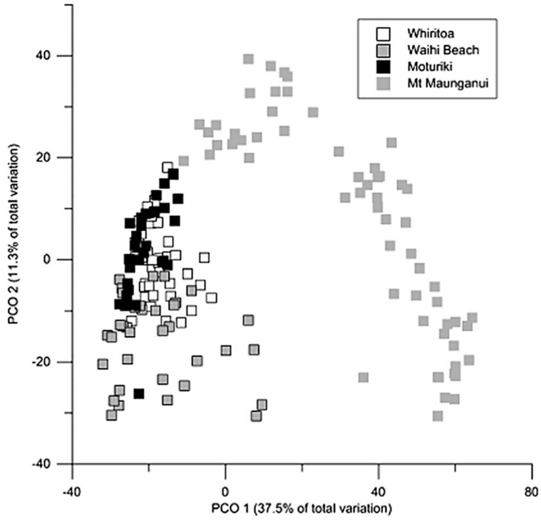

Figure 2. Principal coordinates analysis (PCO) plot of the community composition at the four sites where oil patches were found (Moturiki, Mount Maunganui, Whiritoa and Waihi Beach). All data are fourth-root transformed using Bray-Curtis similarity. Data points represent the community composition in a 1 m^2 plot at Mt Maunganui in the low, mid and high zones (n = 10/zone) and in the mid and high zones at Moturiki, Whiritoa and Waihi Beach (n = 10/zone/site). Data from two monitors for each site are included here.

had around double the density of oil patches than did Moturiki (Figure 3), and density of patches did not change over time (Figure 3B).

Oil patch area

The mean area of patches and the total area covered by oil decreased through time in all zones (Figure 4). By far the greatest initial cover by oil at Moturiki was in the upper portion of the mid tidal zone, but this was almost entirely gone by June 2012 (Figure 4A–B; Wilks' lambda time × shore height interaction, $F_{4,142}$ = 5.68, P < 0.0001). At Mt Maunganui (Figure 4B) there was greater initial cover of oil than at Moturiki, but this was almost exclusively on boulders in the high tidal zone. Again, most of this was gone by June 2012 when the total area of oil patches was around one-tenth of what it was in November 2011 ($F_{2,22}$ = 5.10, P < 0.05).

The size distribution of patches became heavily skewed towards the smallest sizes through time (Figure 5) as patches eroded. At both sites, few of the larger patches remained by June and October 2012, and the great majority of them were < 10 cm^2 (Figure 5C–F). By October 2012, only around 4% of patches at Mt Maunganui were greater than 30 cm^2.

Oil patch settlement on reef organisms

The oil settled primarily on four main groups of basal habitat: bare rock, the barnacle *C. columna*, the little black mussel *L. pulex* and the red alga *Apophlaea sinclairii*

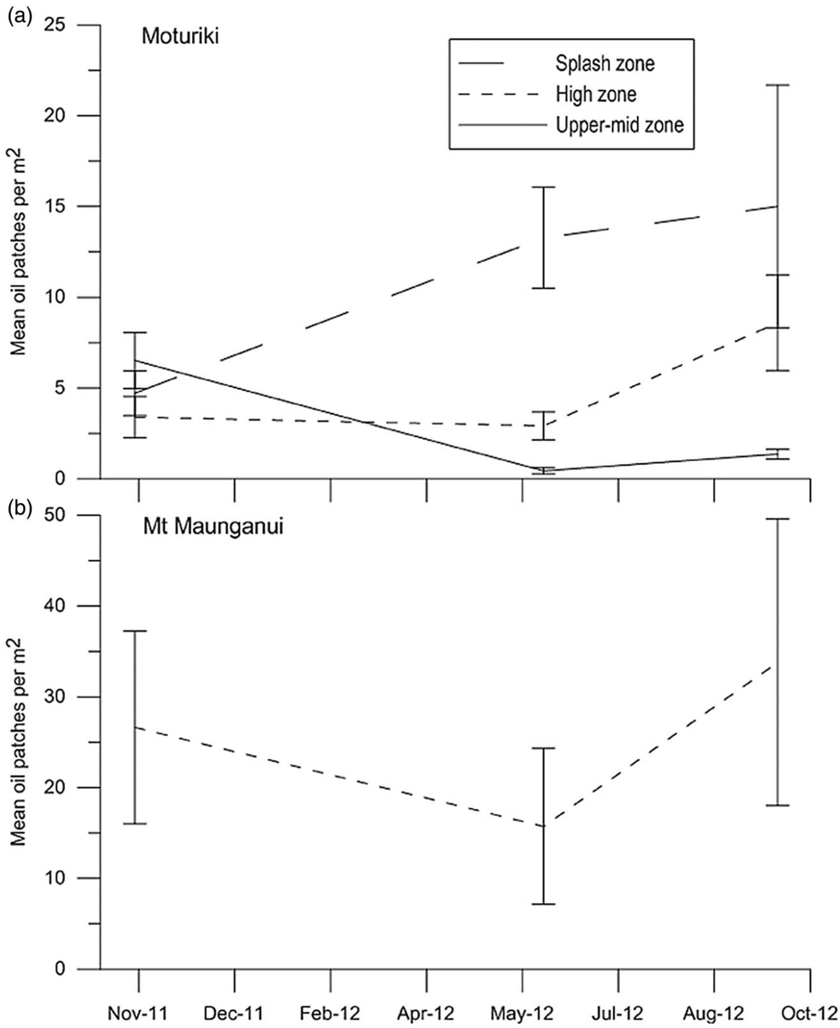

Figure 3. Mean (± SE) number of oil patches per m^2 in the upper-mid, high and splash zone transects. **A,** At Moturiki; **B,** and in the high zone at Mt Maunganui in November 2011, June 2012 and October 2012. Note the different scaling of the y-axes.

(Figure S3). Overall, the distribution of oil reflected the prevalence of cover types; for example, most oil was found on bare rock, which was the most abundant basal habitat accounting for 52% (± SE = 5.6) of cover in the high zone at Moturiki and 70% (± SE = 9.6) in the high zone at Mt Maunganui (Figure 6).

The effects of oil on ecological communities

The oiled patches in the *L. pulex* bed in November 2011 at Moturiki had between 0.9–16.5 g of oil per 5 × 5 cm scraping. Due to the small sample size and one replicate oil patch having a much greater weight of oil than the others, this particular sample had great leverage on the regression plots (Figure 7). Analysis showed that there was a negative

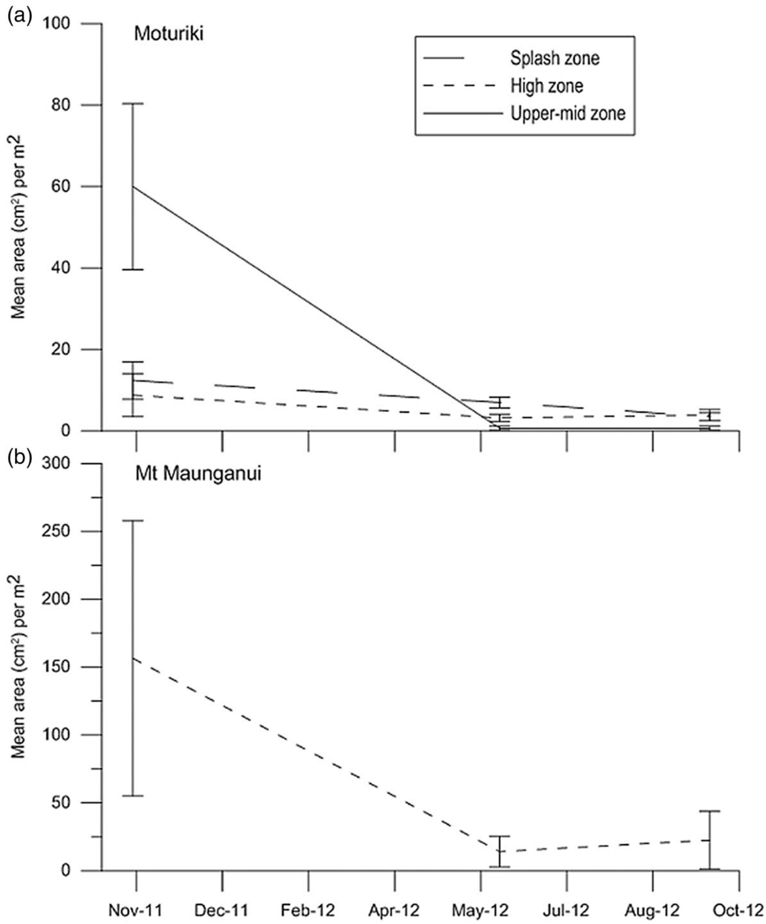

Figure 4. Mean (± SE) area covered by oil patches per m^2 along the 25 m transects. **A,** In the upper-mid, high and splash zones at Moturiki; **B,** and in the high zone at Mt Maunganui. Note the different scaling of the y-axes.

effect of the oil on the *L. pulex* assemblage at Moturiki in November 2011 (Figure 7). A total of 15 taxa were identified, with a mean taxa richness 62% higher in non-oiled areas, and significantly fewer taxa per sample with increasing oil (Figure 7A, R^2 = 0.71, $F_{1,8}$ = 20.21, P < 0.01). Three of the 15 taxa were found exclusively in non-oiled plots (*Notoacmea parviconoidea*, *Sypharochiton pelliserpentis*, and an unidentified microgastropod). The total number of individuals was also negatively correlated with the presence of oil, with a mean of 25% more individuals in non-oiled areas (Figure 7B, R^2 = 0.61, $F_{1,8}$ = 12.55, P < 0.01). Oiled areas had fewer polychaetes (Nereididae spp., Syllidae spp.) and *C. columna* individuals than non-oiled plots. The number of *L. pulex* individuals was significantly greater in the non-oiled plots (Figure 7C, R^2 = 0.41, $F_{1,8}$ = 5.66, P < 0.05) and there were significantly more empty *L. pulex* shells in the oiled plots (Figure 7D, R^2 = 0.95, $F_{1,8}$ = 166.5, P < 0.0001).

There was no significant difference in the community composition between patches with and without oil at Moturiki in November 2011 (pseudo-$F_{1,8}$ = 0.87, P = 0.55,

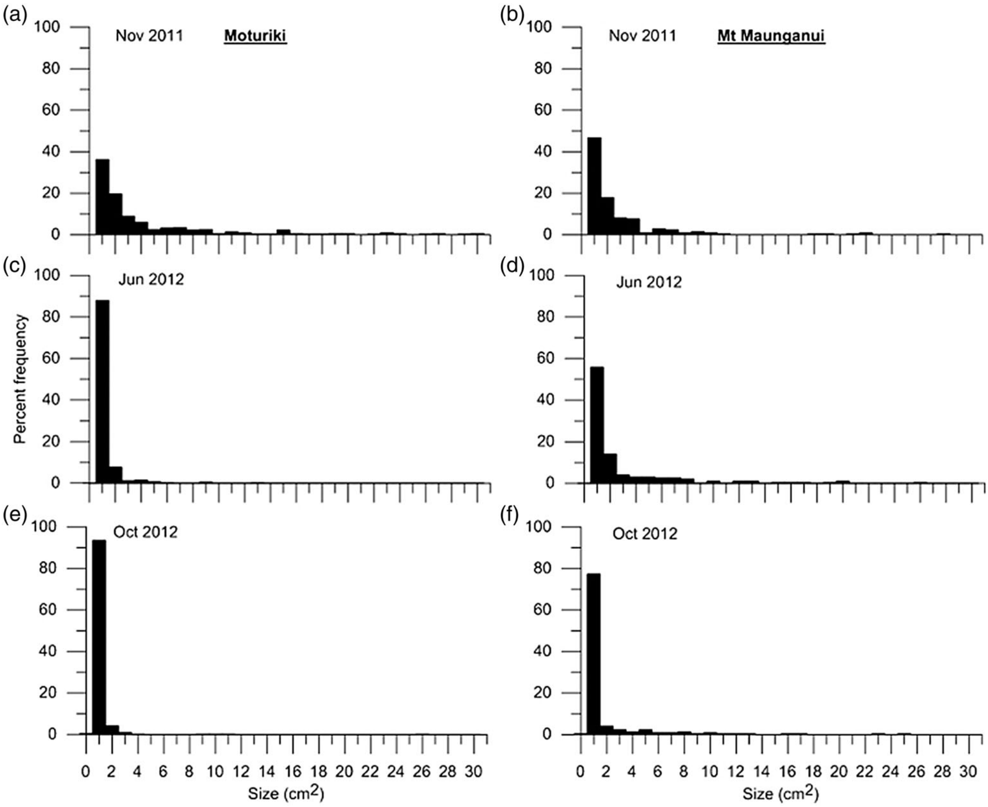

Figure 5. Size-frequency distribution of oil patches (cm^2). **A, B,** In November 2011; **C, D,** June 2012; **E, F,** October 2012 at Moturiki (left panel) and Mt Maunganui (right panel). n = 315, 416, 624 at Moturiki and 212, 199, 225 at Mt Maunganui in November 2011, June 2012 and October 2012, respectively.

Figure 8). There was a site × time interaction in community composition (pseudo-$F_{2,29}$ = 2.27, P < 0.001, Figure 8), with pairwise tests showing that Moturiki was different to Whiritoa (P < 0.01) and Waihi Beach (P < 0.01) in June and October. Whiritoa and Waihi Beach had different community compositions in October (P < 0.05), but not in June (P > 0.05).

In the *L. pulex* plots monitored in situ there was a significantly lower per cent cover of *L. pulex* in June and October 2012 compared to November 2011 and March 2012, regardless of whether plots were oiled (Figure 9A; Wilks' lambda $F_{3,6}$ = 36.8, P < 0.001). There was significantly greater cover of *C. columna* in October 2012 than at the three earlier monitoring times (Wilks' lambda $F_{3,6}$ = 5.06, P = 0.04) with no effect of oil on their abundance across the monitoring times (Figure 9B; treatment: P = 0.6, time × treatment: P = 0.1). Corresponding to the decrease in *L. pulex* cover, there was an increase in the cover of bare space in June 2012 through to October 2012 ($F_{3,6}$ = 11.7, P < 0.01) in oiled and non-oiled plots (Figure 9C). The cover of oil reduced from 100% on the mussel plots to less than 10% in the 5 months following the oil spill (March 2012; Figure 9D).

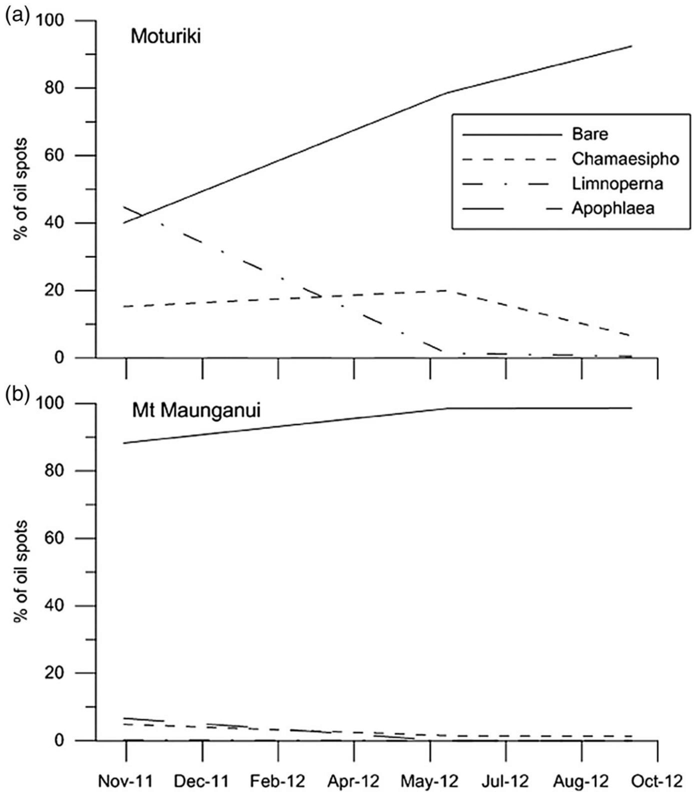

Figure 6. Percentage of oil patches on bare space, *Chamaesipho* spp., *Limnoperna pulex* and *Apophlaea sinclairii*. **A,** At Moturiki; **B,** and at Mt Maunganui in November 2011, June 2012 and October 2012.

Discussion

The oil spill following the grounding of the MV *Rena* in the Bay of Plenty resulted in highly localised contamination on rocky intertidal shores but had minimal ecological impact. After 1 year, the effects on biotic communities were not detectable despite an initial decline in diversity and abundance of infaunal organisms and the continued, albeit reduced, presence of oil patches on the rocky shore.

Spatial distribution of oil on rocky intertidal reefs

Oil was found on the rocks at Mt Maunganui, Moturiki, Waihi Beach and Whiritoa immediately following the oil spill, although oil cover was generally low and patchy. One year after the oil spill there was still some coverage of weathered oil at Mt Maunganui and Moturiki in the intertidal zone, but this was restricted to the upper reaches of the shore where there was a predominance of bare rock and few organisms. The increase in oil patch density through time likely reflects weathering and abrasion processes that break up larger patches into numerous smaller patches, increasing density but reducing the total area covered. The reduction of oil patch area was likely due to weathering rather than a loss of oil-fouled biota, as there was no reduction in the cover of *L. pulex*

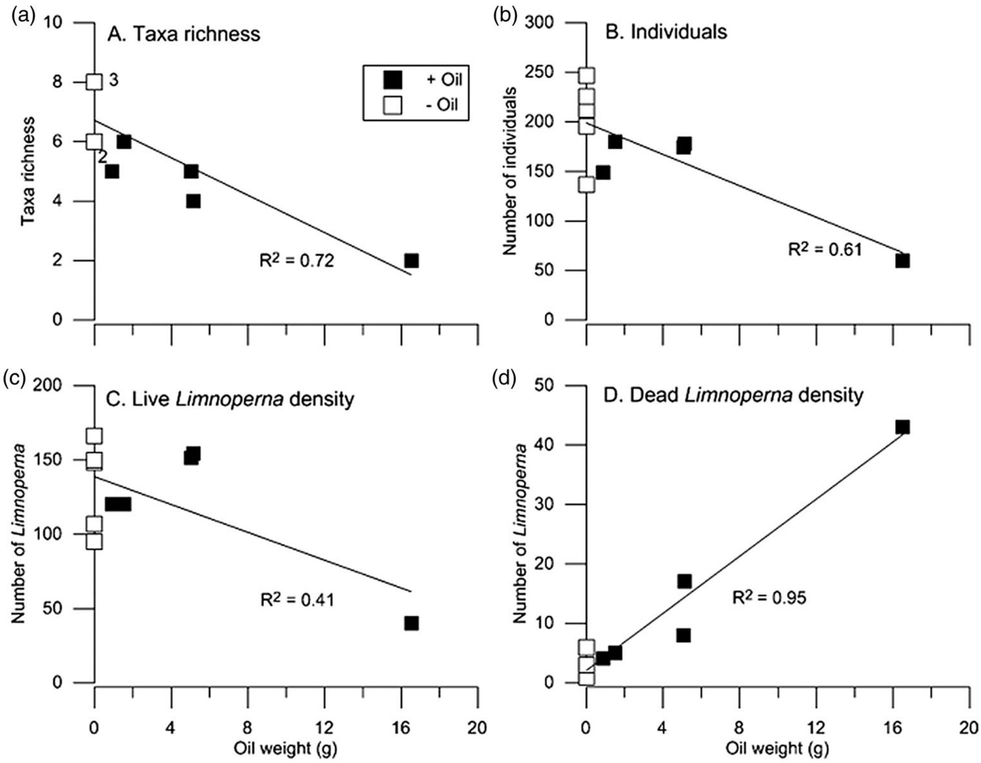

Figure 7. Effect of oil on taxa richness, number of individuals and density of *Limnoperna*. **A,** Taxa richness; **B,** number of individuals; **C,** density of live *Limnoperna pulex*; **D,** density of dead *Limnoperna pulex* in five replicate oiled and non-oiled 5 × 5 cm patches within the mid-zone *Limnoperna pulex* mussel bed at Moturiki in November 2011.

or *C. columna* in the marked areas in situ at Moturiki (where most of the oil was deposited) until after March 2012, when there was a reduction in *Limnoperna* cover across oiled and non-oiled patches, probably due to other disturbance events (e.g. storms). The greatest reduction of oil was in the mid zones, and was likely due to longer submersion times, more intense wave action and sand scour.

Overall, around 90% of oiled patch area was lost over the 5 months following the MV *Rena* grounding, rates that are comparable to other shores following oil spills. De Vogelaere & Foster (1994), for example, found that natural weathering of oil from the *Exxon Valdez* spill was extremely rapid within Herring Bay in Prince William Sound, Alaska, and most patches were gone within 1 year. Slower rates of weathering (20%–26% per annum) were recorded in other areas of the sound (Peterson et al. 2003), but these areas in Alaska had a much higher initial cover of oil than did the Bay of Plenty.

Effects of oil on ecological communities

Understanding the effects of oil spills is difficult due to spills being unreplicated events, non-randomly distributed, and spanning sites that have many confounding factors (Wiens et al. 2001). There is often high variation in biotic communities between sites

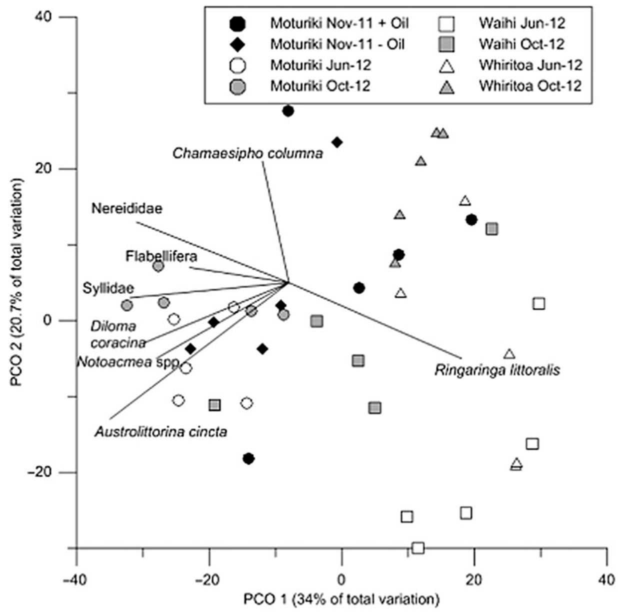

Figure 8. Community composition of 5 × 5 cm patches within the *Limnoperna pulex* mussel bed at Moturiki with and without oil in November 2011, and patches without oil at Moturiki, Waihi Beach and Whiritoa in June 2012 and October 2012 (there were no patches that were oiled at Moturiki in June 2012). Nereididae & Syllidae, polychaete worms; Flabellifera, isopods; *Diloma coracina & Austrolittorina cincta*, herbivorous gastropods; *Notoacmea* spp., limpets; *Ringaringa littoralis*, amphipod; *Chamaesipho columna*, barnacle.

and a shortage of prior data for robust comparisons (Paine et al. 1996; Parker & Wiens 2005; Díez et al. 2009). Here, we focused on the effects of oil on biological communities within one of the most oiled reefs (Moturiki). Despite this, the impacts were low and only short-lasting due to the patchy distribution of oil and the relatively low biodiversity and high turnover of species in the upper shore zones where most of the oil was deposited.

Following a much larger oil spill in Santa Barbara, California, there were larger effects on the ecological communities, particularly those dominated by barnacles and surfgrass (Foster et al. 1971; Driskell et al. 2001), with areas higher on the shore taking longer to recover than those on the lower shore due to the amounts of oil deposited up-shore and also demographics (such as recruitment rates) of those species residing higher on the shore (van Tamelen et al. 1997). Benthic invertebrate communities can be highly affected by oil, which can accumulate in the interstitial spaces and underneath habitat formers (e.g. mussels) and take longer to dissipate, thereby greatly changing infaunal communities (Suchanek 1993; Peterson et al. 2003). Some infaunal molluscan taxa have been shown to be particularly sensitive to oil pollution. For example, the limpet *Nacella macquariensis* and the chiton *Plaxiphora aurata* were among the most common invertebrates that washed up dead after the *Nella Dan* ran aground at Macquarie Island (Pople et al. 1990). This pattern was reflected in our results with an absence of limpets (*Notoacmea parviconoidea*) and chitons (*Sypharochiton pelliserpentis*) in oiled samples, whereas they did occur in low

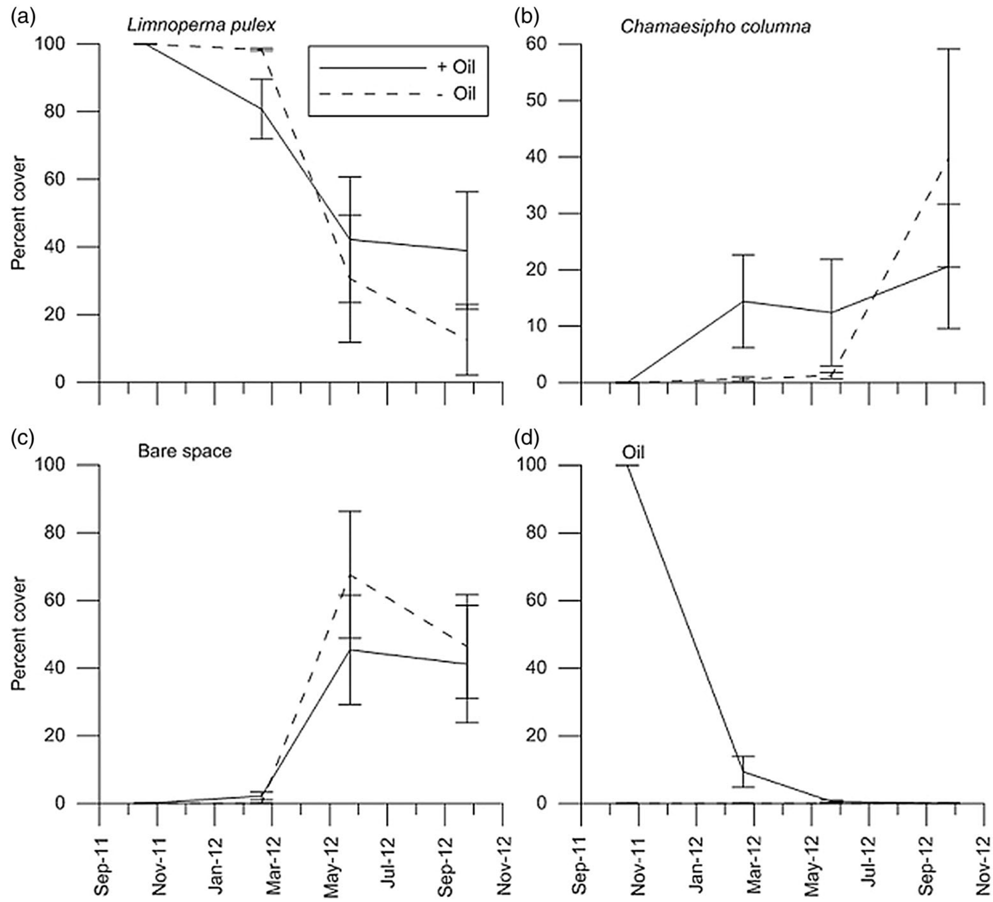

Figure 9. Mean (± SE) per cent cover. **A,** *Limnoperna pulex*; **B,** *Chamaesipho columna*; **C,** bare space; **D,** oil in patches with oil (+oil) and without oil (–oil) in the *Limnoperna pulex* bed at Moturiki.

abundance in non-oiled samples from Moturiki 1 month following the oil spill. There was also a negative effect of oil on the density of live mussels (*L. pulex*), taxa richness and the number of individuals within the infaunal community, although it should be noted that these relationships were strongly influenced by one sample having a high density of oil.

The cover of oil in the marked areas decreased significantly in 4 months and there was little detectable effect of oil on the mussel bed community at Moturiki 1 month after the oil spill, with overlap in the community composition of oiled and non-oiled samples. It is likely that the reef at Moturiki was affected by storm events that occurred between March and June 2012, resulting in highly localised removal of *L. pulex* in the mid zone consistent with wave action, rather than a lasting effect of oil. These bare areas were then colonised by the barnacles *C. columna* and *Austrominius modestus*, and then *L. pulex,* a common successional sequence that occurs on these reefs following natural disturbance, due to the dynamic conditions associated with constant sand scour and high levels of wave action (Lilley 2004).

What limited the ecological impacts of the MV Rena *oil spill?*

The limited impacts of MV *Rena* oil spill on the rocky shores of the Bay of Plenty are probably due to several factors, including the relatively small size of the oil spill, the type of oil spilled (HFO rather than crude oil), sea and weather conditions at the time of the spill (and when the oil reached the shore), the topography of the rocky coastline, habitat types into which most of the oil washed up, and the efficacy of low-impact cleaning methods.

The majority of the oil found in this study was distributed in the upper intertidal zones, probably because heavy seas occurred in the days following the grounding of MV *Rena* (10 and 11 October), which deposited the oil mostly high on the shore. Furthermore, the steep shoreline topography (at Moturiki) may have reflected waves, a process that can keep oil off rocks (Gundlach & Hayes 1978). The rate of oil removal from rocky shores is a function of wave climate: the greater the wave energy, the more rapid the rate of removal (Gundlach & Hayes 1978), a factor that likely led to the c. 90% reduction in the oiled area observed in this study. It is somewhat fortunate that these factors interacted as they did to distribute oil on the upper rather than lower intertidal zone, as washed-up oil might have had a greater impact on the more speciose lower shore (cf. van Tamelen et al. 1997). Indeed, at the impacted sites here, the upper zones were dominated by bare space, encrusting algae, barnacles and small mussels, compared to the more structurally complex macroalgal or larger mussel beds (*Perna canaliculus*) in the low zones. Often these more complex, diverse communities can be less resilient following a disturbance such as an oil spill. For example, following the *Prestige* oil spill in France, some low shore taxa (e.g. ascidians and sponges) were either slow to recover or did not recover during a 9-year study (Castège et al. 2014) and, at Macquarie Island, holdfast communities of the low shore fucoid alga *Durvillaea antarctica* had not recovered 7 years after the *Nella Dan* spill (Smith & Simpson 1998).

In many cases following oil spills, attempts at removing oil from a shore using detergents, hot-water high-pressure sprays and chemical dispersants have led to more damage beyond the initial impact of the oil (Foster et al. 1971; Southward & Southward 1978; De Vogelaere & Foster 1994; Stekoll & Deysher 2000; Hawkins et al. 2002). Southward & Southward (1978) showed that, following the *Torrey Canyon* spill off the coast of Cornwall, UK, rocky intertidal areas that received a heavy application of dispersants took more than 9–10 years to recover, while areas that received a light application in areas with high wave action recovered after 5–8 years. Hawkins et al. (2002) showed a more extreme case following the same oil spill, where community recovery of areas took 10–15 years following the use of dispersants, compared to 2–3 years in areas where no dispersants were applied. One result of these studies is that lower-impact methods of controlling the distribution of oil (such as booms), cleaning by hand with low-impact wiping, and allowing the ecosystem to recover naturally through time are now being employed more than are high-impact techniques such as harsh scrubbing, burning, hot-water washing and dispersants (Paine et al. 1996). De Vogelaere & Foster (1994) claimed that intensive mechanical cleaning following oil spills increased damage and slowed recovery, and these methods should be avoided if the desired outcome is to decrease the environmental damage following oil spills. High-impact clean-up techniques such as the use of heavy machinery and chemical dispersants were largely (though not completely) avoided in the clean-up of the *Rena* oil spill. Using low-impact cleaning methods, combined with the relatively small amounts of oil landing on rocky substrata, unquestionably helped to limit the ecological effects of the oil spill on rocky reefs.

In summary, 1 year following the grounding of the MV *Rena*, the ecological effects on rocky intertidal communities due to oil deposition were relatively minor compared to other oil spills due to a fortunate coincidence of factors. Collectively, we learned a lot about dealing with oil spills along heterogeneous coastlines, and can only hope that these lessons will be remembered if any future such events occur. We also note that this study was on distributional impacts and losses of biota and did not address potential sublethal (e.g. compromised growth and reproduction) or indirect effects (modified trophic relationships) that can span multiple cohorts and change community dynamics (Peterson et al. 2003).

Supplementary data

Figure S1. Patches of *Limnoperna pulex* at Moturiki in November 2011. Left: patches with no visible oil on or within the mussels, right: oil is stuck to mussel shells and in interstitial spaces (indicated by inset lines). Each frame covers 10 × 10 cm.

Figure S2. Oil patches on the bare rock of the high shore zone at Mt Maunganui in November 2011 (each side of the ruler is 50 cm, for scale).

Figure S3. Clockwise from top left: oil patches on *Chamaesipho columna*, bare rock, *Limnoperna pulex* and the red alga *Apophlaea sinclairii*.

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