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TROPICAL OIL POLLUTION INVESTIGATIONS IN COASTAL SYSTEMS [TROPICS]: A 32 YEAR SYNOPSIS OF DAMAGES AND RECOVERY

AUTHORS

D. Abigail Renegar, Nova Southeastern University, Halmos College of Natural Sciences and Oceanography, 8000 North Ocean Drive, Dania, FL 33004 USA

Paul Schuler, Oil Spill Response Limited, 2381 Stirling Road, Fort Lauderdale, FL 33312 USA

Nicholas Turner, Nova Southeastern University, Halmos College of Natural Sciences and Oceanography, 8000 North Ocean Drive, Dania, FL 33004 USA

Richard Dodge, Nova Southeastern University, Halmos College of Natural Sciences and Oceanography, 8000 North Ocean Drive, Dania, FL 33004 USA

Anthony Knap, Texas A&M University, Geochemical Environmental Research Group, 833 Graham Road, College Station, TX, 77845 USA

Gopal Bera, Texas A&M University, Geochemical Environmental Research Group, 833 Graham Road, College Station, TX, 77845 USA

Ronan Jézéquel, Cedre, Rue Alain Colas, BP 20413, 29604 Brest -France

Bradford Benggio, NOAA SSC, 909 SE 1st Avenue, Suite 714, Brickell Plaza Federal Building, Miami, FL 33131 USA

ABSTRACT

In 1984, the Tropical Oil Pollution Investigations in Coastal Systems (TROPICS) experiment began in Bahia Almirante on the Caribbean coast of Panama. This study sought to compare the impacts of a severe, but realistic spill of untreated crude oil versus chemically treated (dispersed) crude oil on tropical marine reef, sea-grass, and mangrove ecosystems. The aim of the study was to identify and evaluate the environmental trade-offs of dispersant use in tropical marine and subtidal systems. As a result of continuing research at the site, the study became one of the most comprehensive field experiments examining the long-term impacts of oil and dispersed oil exposures in nearshore tropical communities.

Consequently, TROPICS has been the foundational and seminal field study which served as the historical antecedent for Net Environmental Benefit Analysis (NEBA), as well as the basis for follow-on Spill Impact Mitigation Analysis (SIMA) and Comparative Risk Analysis (CRA) for oil spill planning, preparation, and response. From the initial experiment in 1984, through three decades of study and data collection visits, the coral reef, seagrass, and mangrove communities have exhibited significantly different damage and recovery regimes, depending on whether the sites were exposed to non-treated crude oil or dispersed crude oil. While this study does not definitively determine whether or not dispersants should be applied in tropical nearshore environments, it is illustrative of the environmental and ecosystem trade-offs between surface oil impacts to the shoreline, compared to water column exposure from chemically dispersed oil.

This paper provides an overview of the results and observations reported in numerous previous TROPICS publications, as a progression of damage and recovery over time. With this perspective, planners and responders can use this study to predict what damages/recoveries may be expected from an oil spill incident in this environment. The results of the TROPICS experiment are examined within the context of this recent parallel research from the perspective of ongoing implications for oil spill preparedness and response.

INTRODUCTION

Beginning in 1984, a 2.5-year study in Bahia Almirante sought to evaluate the comparative spill impacts of untreated crude oil vs chemically treated (dispersed) crude oil on nearshore tropical communities. At that time, dispersant use in such environments was discouraged due to the lack of experimental data on direct environmental impacts of dispersants, despite indications of the potential benefits of such application (Dodge et al 1987). Therefore, the TROPICS study was intended to provide guidance on the environmental trade-offs of chemical dispersant use in tropical marine and subtidal systems.

Follow-up data collection visits and analysis occurred 10, 17/18, 20, 25, 30, and 32 years after the exposures. Numerous publications reporting observations and conclusions of multiple aspects of this study were produced over the ensuing years. However, those publications frequently represented only snapshots of changing conditions at each site. The purpose of this review is to provide an overview of the experiment, a summary of previous reports, and to present those observations as a timeline progression of damage and recovery.

Experimental Design and Initial Impact Assessment

The experiment simulated a severe scenario of fresh crude oil and chemically dispersed fresh crude oil at 3 experimental sites near Bocas Del Toro, Panama. The sites represented typical tropical marine habitats; (a climatological and meteorological characterization of the region can be found in Dodge et al. 1997). Each of the three 30x30 m treatment sites included a well-developed intertidal red mangrove (*Rhizophora mangle*) forest (with one white mangrove, *Laguncularia racemose* present at one site). Except for the outer fringe of the mangrove forest, each mangrove area was fully intertidal, completely inundated at high tides and exposed at low tides (an overwash forest). Invertebrate fauna included oysters (*Isognomon alatus, Pinctada imbrica*, and *Crassostrea rhizophorae*), sea urchins, starfish, shrimp, and tree snails (dominant species *Littorina angulifera*). Tree (*Aratus pisonii*) and land crabs (*Cardisoma guanhumi* and *Gecarcinus lateralis*) were also common. Several fish species were observed in the prop roots, including barracuda, snapper, and anchovies (Ballou et al. 1987).

The subtidal area of each experimental area consisted of a relatively dense region of seagrass (*Thallassia testudinium*) beds and a shallow, fringing coral reef environment paralleling the mangroves, which at the time was primarily composed of scleractinian corals *Porites porites* (or *P. furcata*) and *Agaricia tennufolia* (Ballou et al. 1987). Other fauna present included the abundant anthozoan *Zooanthus pulchellus*, as well as other anemones, sponges, starfish, urchins, sabellid worms, sea cucumbers. Numerous algal species such as *Halimeda*, *Dictyota*, *Caulerpa*, *Acanthophora*, and *Udotea* were also present throughout (Ballou et al. 1987).

Baseline data was collected at each site 8 months and 1 week prior to oil release. During the exposures, each site was fully enclosed within an oil spill containment boom immediately prior to oil release. At the crude oil only site (Site O), 953 L of Prudhoe Bay crude was released over several hours; at the dispersed oil site (Site D), 715 L of Prudhoe Bay crude pre-mixed with commercial dispersant concentrate COREXIT 9527 (to achieve a target of 50 ppm) was released over 24 hrs; at the reference site (Site R) there was no oil or dispersed crude oil released. Quantification methods for hydrocarbons in the water column, sediments, and organisms are described in Ballou et al. (1987). Assessment of impacts to mangroves and subtidal systems are described in Ballou et al. (1987), Dodge et al. (1995) and subsequent publications.

At Site O, large quantities of oil were distributed through the site by wind and tides, but collected in larger amounts in the downwind eastern corner. The oil there was observed to be very thick. After the 48 h exposure, most of the remaining, partially weathered, floating oil was removed using sorbent materials. Three days post-spill, the substrate remained covered with oil. Less oil overall was observed 5 days post spill, although small pools of oil remained and a persistent sheen was present throughout the mangroves. Oil remained visibly present 4 months post spill, and the mangrove forest substrate appeared oily and released oil sheen when lightly disturbed. This condition persisted through the 20 month post-spill survey, indicating significant amounts of oil retained in the surface sediments (Ballou et al. 1987).

At Site D, large clouds of dispersed oil and patches of undispersed oil were observed after the spill, which was distributed throughout the mangroves with the rising tide. At low tide, the substrate was covered with a thin film of oil, with small amounts of undispersed oil collected in depressions in the substrate 48 h after the start of dosing. Three days post-spill, sheen was present throughout, with an oil slick present in the mangrove prop roots. By 6 days post spill, less oil overall was observed, which largely disappeared by 4 months post-spill, with oil only observed in a pocket area where oil accumulated during dosing. Disturbed sediments continued to release small amounts of oil after 4 months, and oil sheen from 7 to 20 months post-spill (Ballou et al. 1987).

RESULTS AND DISCUSSION

The crude oil-only and dispersed crude oil releases resulted in significantly different exposure conditions and a starkly different range of environmental damages, effects, and concomitant recovery regimes at the respective sites.

Hydrocarbons

Aquatic concentrations were lower at Site O compared to Site D (Table 1) (Ballou et al. 1987). The crude oil-only treatment at Site O resulted in heavy oil contamination of mangroves and intertidal sediments. However, because fresh crude oil floated on the water surface and contains relatively few water-soluble compounds, there was relatively low aquatic hydrocarbon concentrations in the subtidal zone and little exposure of seagrass and coral to the oil and its constituents. Consequently, there was relatively little damage on subtidal seagrass and coral communities and habitats. At the dispersed oil Site D, concentrations in the water column were higher in the subtidal zone as pre-dispersed crude oil readily diffused and mixed into the subtidal water column, exposing seagrass and coral communities to the oil-dispersant aggregrate. This created a radically different set of damages and recovery regimes in the subtidal zone. However, sediment concentrations were lower compared to the crude oil-only site in both the subtidal and intertidal areas. This was likely due to both dilution of the oil-dispersant aggregate in the water column and the fact that dispersed oil droplets are stabilized by the surfactant in the dispersant and do not readily adhere or coalesce. Consequently, dispersed oil was released from the intertidal zone with the first few tidal inundations.

Table 1. Mean (±SD) aquatic hydrocarbon concentrations measured during the exposure period in different areas of each experimental site (data from Ballou et al. 1987).

Fluorometric samples collected from hours 0-49			
	Site O	Site D	Site R
Coral area	2.0 (±0.8) ppm (n=21)	15.2 (±9.8) ppm (n=51)	N/A
Seagrass area	2.1 (±0.6) ppm (n=19)	56.4 (±28.8) ppm (n=51)	N/A
Mangrove area	2.8 (±0.6) ppm (n=22)	38.1 (±19.3) ppm (n=40)	N/A
Discrete samples collected during dosing, GC/MS analysis			
Coral area	0.11 (±0.2) ppm (n=8)	5.5 (±4.6) ppm (n=10)	N/A
Seagrass area	0.05 (±0.02) ppm (n=9)	20.3 (±19.1) ppm (n=13)	N/A
Mangrove area	0.05 (±0.02) ppm (n=4)	72.9 (±103.5) ppm (n=6)	N/A

Sediment hydrocarbon concentrations over time are reported in Ballou et al. (1997) (exposure to 20 months post-spill), Dodge et al. (1995) (10 years post spill), Ward et al. (2003) (17-18 years post-spill), Baca et al. (2005) (20 years post-spill), DeMicco et al. (2011) (25 years post-spill), Baca et al. (2014) (30 years post-spill), and Renegar et al. (2016) (32 years post-spill). Briefly, high variability was evident at both sites with a more even distribution of slick oil at Site O and patchy pockets of slick oil at Site D. Liquid oil was still present at both oiled sites at 20 months post spill, with oil penetration likely due to tidal impacts and burrowing organisms. Oil was still present 10 years post-spill at Site O, as sheen was released by walking in the substrate; similar observations were not made at Site D (Dodge et al. 1995). After 32 years, although PAHs were detected, there was no indication of the original oil or degradation products of oil used in the experiment and were thus likely from small boat traffic (Renegar et al. 2016).

Mangroves

At Site O, oil migrated into the intertidal zone where it adhered to mangrove roots, likely causing suffocation and/or toxicity. Even after volatiles in the crude oil evaporated, the crude oil continued to adhere to mangrove roots, partially blocking aerial root lenticels necessary to meet mangroves' oxygen demands. Despite diurnal tidal flushing, weathered oil persisted in coating mangrove roots, compounding the initial acute exposure and resulting in significant mortality of mature mangrove trees in Site O (Figure 1). Additionally, crude oil entered into and remained entrapped in numerous crab, root, and other holes in the substrate during the initial tidal fluctuations after release of the oil. This oil then slowly leached from the substrate, resulting in chronic stress to remaining mangroves, lower repopulation by propagules, and reduced growth in juvenile and immature saplings for 20+ years. This ultimately resulted in a significant decrease in canopy cover (Figure 2) and an increase in the number of juvenile mangroves, although none of the experimentally planted juveniles survived to 4 months post-spill. The progression of mangrove damage and recovery therefore proceeded on the order of days, from initial defoliation to mortality and other sublethal effects over two years post-spill. Recovery of the mangrove community to pre-exposure levels of tree and root density and canopy cover has not occurred, as an approximately 7 m hole in mature mangrove trees still existed at Site O at the 32 year site visit. Overall, post experiment mortality resulted in a large decrease in living adult trees between 20 months and 10 years post spill. This was concomitant with a significant increase in the number of seedlings and juveniles present (from 13 to 89), primarily in the open area generated from the loss of adults at Site O (Dodge et al. 1995).

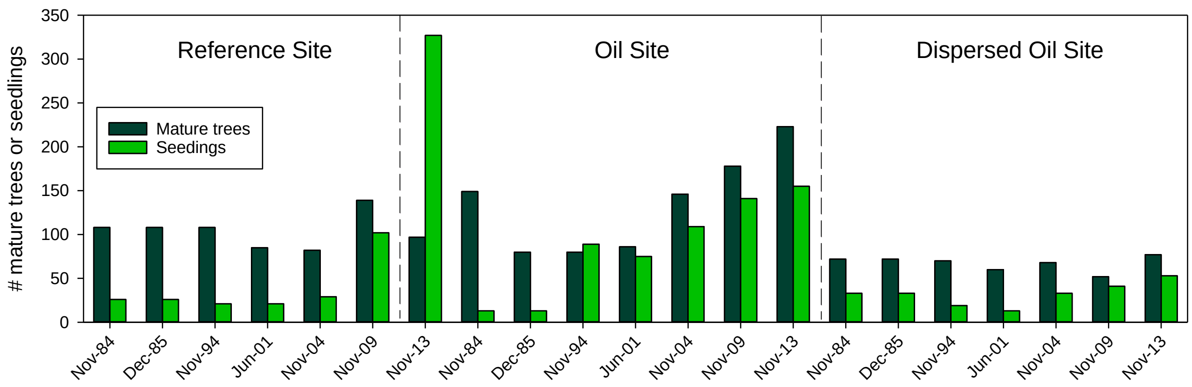

Figure 1. Counts of mature mangroves and seedlings over time at each treatment site.

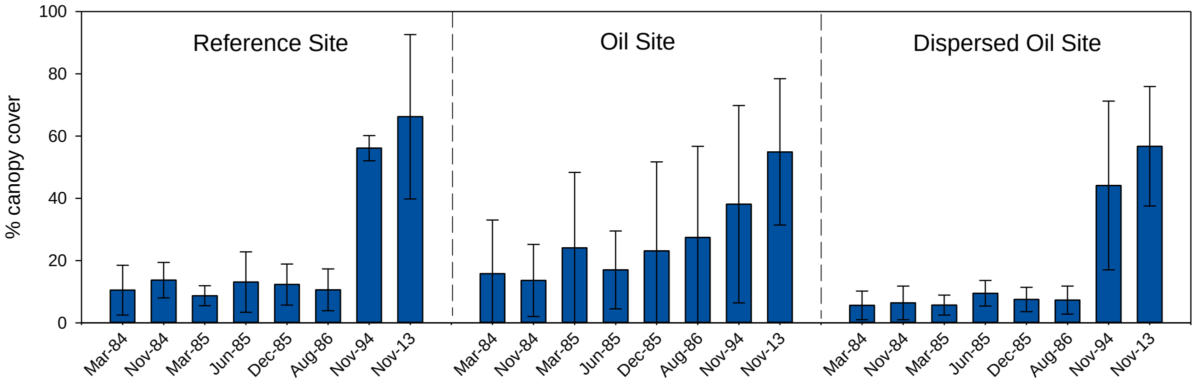

Figure 2. Percent mangrove canopy coverage over time at each treatment site.

A different pattern of exposure and effects was observed at the dispersed oil Site D. Hydrocarbon concentrations in the water column were higher in the subtidal zone, but sediment concentrations were lower compared to the crude oil-only Site O in both the subtidal and intertidal areas, There were no visually observed oil sheens at Site D as were observed at Site O. No significant effects on adult mangroves were observed, with no significant defoliation and no mortality. Neither short nor long-term effects on juvenile mangroves were apparent.

Mangrove fauna

Immediately after the exposure at Site O, many snails and tree crabs were coated with oil 3 days post spill, and the crabs showed no escape or defense response. At Site D, all crabs and snails were coated with oil, with an evident smell of both oil and dead animals. Attached sea anemones within the mangroves were covered in oil and fully distended, although they retained a tactile response. Both oiled sites had significant initial impacts on tree snails (Figure 3). Less significant impacts were observed in mangrove oysters, with high survival rates for all species (Figure 4). Hydrocarbon tissue concentrations at Site O and Site D increased to 679 and 507 ppm (respectively) 3 days post spill. By 4 months post spill, crab behavior at Site D, had returned to normal, and both crabs and snails were present throughout the site. Snail density was observed to increase at both sites but remained below baseline at both Site D and Site O. Oyster survival was more variable but remained relatively high. Tissue hydrocarbon concentrations decreased to 134 ppm at Site O and 161 ppm at Site D, and were 17 ppm at Site O and 31 ppm at Site D after 12 months, which was comparable to the pre-spill concentration (34 ppm) at Site R. A similar pattern was observed in the byssal threads.

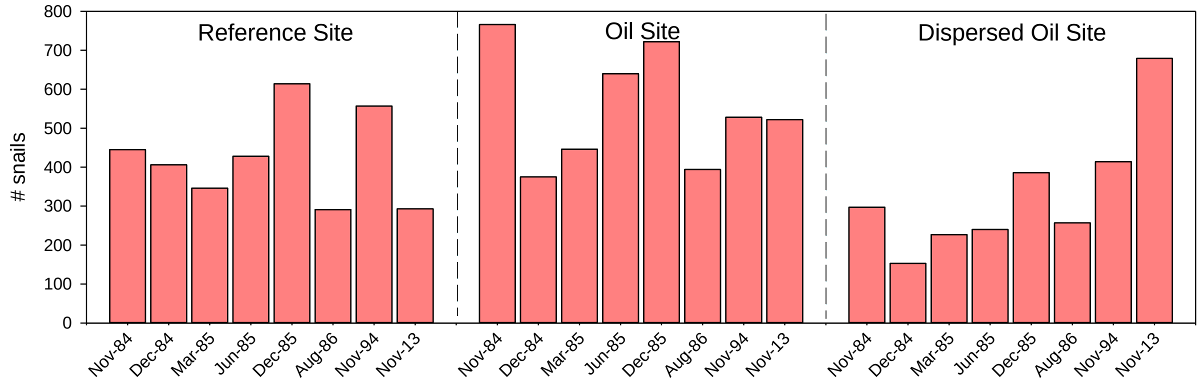

Figure 3. Counts of mangrove tree snails over time at each treatment site.

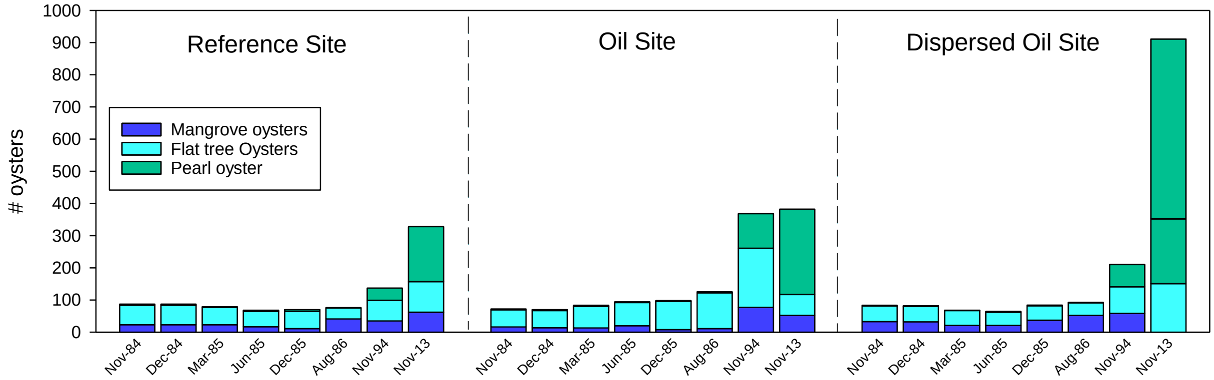

Figure 4. Counts of mangrove oyster species over time at each treatment site.

Corals

Overall, percent coral cover declined abruptly and significantly immediately following the exposure, and continued to do so for an entire year (Ballou et al. 1987). Growth of *P. porites* (or *P. furcata*) and *A. tennuifolia* (which dominated the reef community) was significantly reduced by dispersed oil. The short-term effects of dispersed oil on corals were clear, with coral cover remaining significantly lower for at least two years following exposure, with little indication of recovery. After ten years, parameters at all sites were indistinguishable and no significant changes in coral cover were found when comparing oil or dispersed oil sites to reference sites. Initial growth effects observed in some species, but not others were no longer evident (Dodge et al. 1995).

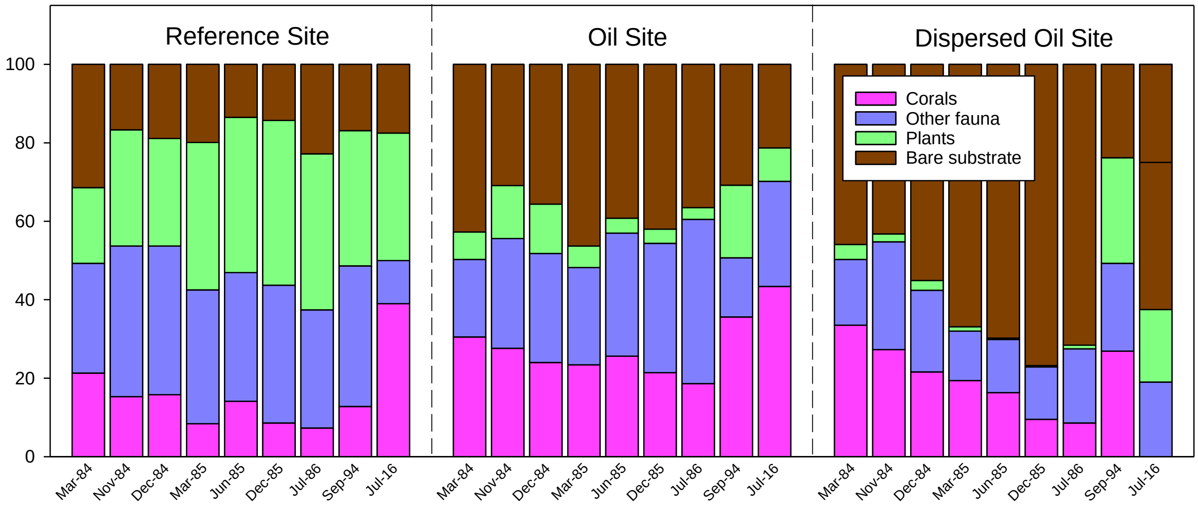

Figure 5. Percent cover of corals, other fauna (including sponges, zooxanthids, and anemones), plants (including algae and seagrass), and bare substrate (sand or rubble) over time at each treatment site.

Seagrass

No significant impacts of the treatments on seagrass growth rate were observed except for 20 months post spill, where mean growth rates were found to be significantly higher at Site D and Site R than at Site O; the higher growth rate was measured at Site R, but this was not significantly greater than at Site D. (Figure 6). Plant density (Figure 7) was difficult to interpret, as significant differences between each treatment site were found for both pretreatment and all post-treatment periods. After 17-18 years of recovery, the most obvious change observed was some loss of seagrass area due to encroachment of *Porites spp*. at Site O.

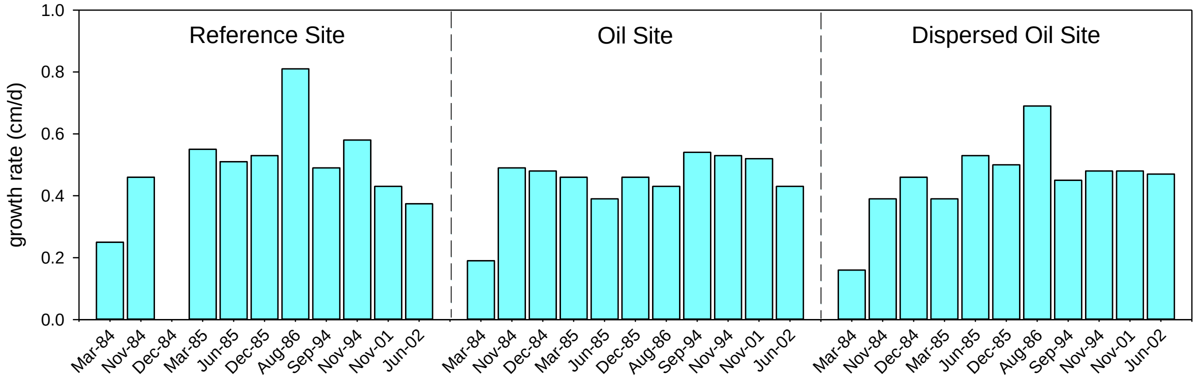

Figure 6. Seagrass growth rate (cm/day) over time at each treatment site.

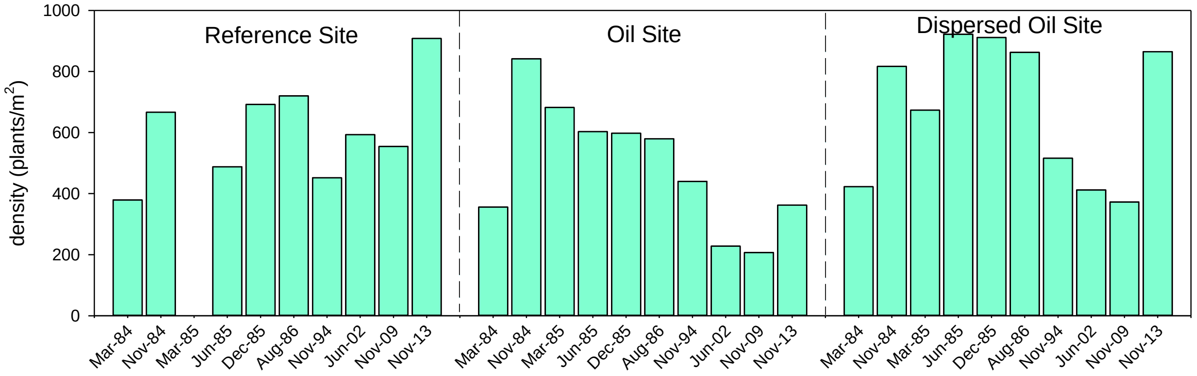

Figure 7. Seagrass density (plants/m2) over time at each treatment site.

Seagrass fauna

Sea urchin abundance (Figure 8) was severely reduced, with no surviving urchins immediately after the spill, although the population recovered by 1 year post-spill. Nine species of polychaetes and two species of bivalves were identified in the seagrass sediments, along with various amphipods, urchins, brittle stars, crabs, shrimps, sponges, isopods. Although not all were included in the analysis, there was no discernable differences in the abundance or diversity of these organisms as a result of the exposures, possibly due to a significant level of substrate heterogeneity.

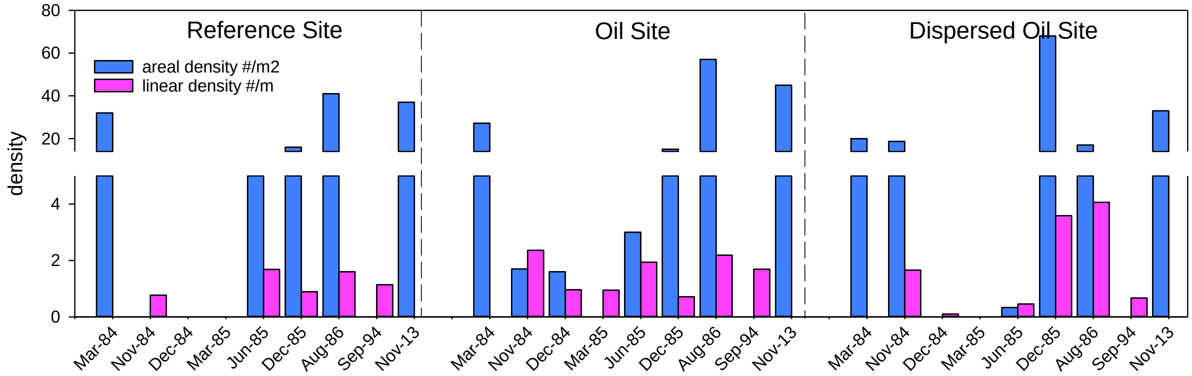

Figure 8. Linear and areal density of sea urchins over time at each treatment site.

COMPLEMENTARY RESEARCH

From the initial two-year experiment and evaluation of impacts, through a further 7 research site visits between 1994-2016, the ecosystems at the different treatment sites have exhibited significantly different recovery trajectories. The trade-offs associated with exposure to floating or surface oil compared to water column exposure from chemically dispersed oil were demonstrated by the significant variation in mangrove, seagrass, and coral reef environmental response, depending upon whether the sites were exposed to dispersed oil or oil only. Continuing oil contamination at the oil-only site remained an issue through the 30 year site visit, as does high erosion and sediment re-distribution that was not observed at the dispersed oil or reference sites.

The results of the 32-year TROPICS field study have broadly concluded that the impacts to mangrove communities from non-dispersed crude oil included significant adult tree loss, with long-term implications for substrate stability. In contrast, the impacts of dispersed crude oil to seagrass and coral communities nearby were less significant. Dispersed oil resulted in less impact to the mangroves, but significant short-term effects on coral cover and seagrass invertebrate communities, both of which recovered within 10 years. While the conclusions drawn from the TROPICS study were well justified, unequivocal interpretation of the results was challenging due to the non-replication of the experimental sites and previously limited parallel research to verify the observations and conclusions. Fortunately, a substantial amount of related research has been conducted over the past decades and it is now possible to examine the results of TROPICS within the context of this new knowledge.

Mangroves

Studies of oil impacts to mangroves are most commonly field studies of oil impacts, as well as laboratory studies. Observations have indicated a variety of acute and chronic effects (Duke 2016), and although interpretation is complicated by variability in methodology, species, and specific scenarios, there are a number of consistencies that allow some comparisons to be made. Initial acute impacts are related to physical intrusion of oil into the mangrove forest environment, with death of associated animals, defoliation of adult trees, and loss of seedlings and juveniles (Burns et al. 1993, Mackey and Hodgkinson 1996, Proffitt 1997; Hensel et al. 2010, Lewis et al. 2011, Santos et al. 2011). Over time, mature trees are lost (Duke and Burns 1999, Michel and Rutherford 2014, Duke 2016). The effects of oil spills in mangrove environments thus follow a pattern of short-term acute effects, with associated secondary and residual effects which ultimately lead to recovery or loss (Duke 2016). This pattern was generally followed by Site O in the TROPICS experiment, where long term recovery appeared to track the delayed loss of detectable hydrocarbons in the substrate and maturation of colonizing juveniles; the time frame thus far for recovery is still within the 10-50 years suggested by Lewis (1983) although complete recovery is not yet evident. Chronic effects, including root abnormalities and deformed propagules have been observed in several spill scenarios (Böer 1993), however this was not directly and consistently addressed in the TROPICS study.

It is well known that different types of oil cause variable impacts, as a result of differing toxicity. Thus lighter oils, or less weathered oils, are generally more acutely toxic than heavier or more weathered oils. Based on this, it might have been expected that the use of chemical dispersants (which increase the bioavailability of oils in the water column) may have had some impact associated with increased aquatic toxicity. Lighter weight oils have been found to have a more significant impact than heavier oils in mangroves (Duke et al. 2000), but this is not a consistent observation in actual spill scenarios (Jackson et al. 1989, Wardrop et al. 1996) and was not directly observed in the TROPICS study. In terms of associated invertebrate communities, studies are limited but results are unclear regarding if a greater impact results from dispersed vs whole oil (Lai 1986, Duke et al. 2000).

Seagrass

Like mangroves, seagrasses are considered environmental engineers, and serve a key role in the environment by modulating wave energy and binding and stabilizing substrate (Fonseca and Bell 1998, Duate and Chiscano 1999, van der Heide et al. 2012). Previous studies of oil and dispersed oil impacts to seagrasses have observed complete mortality, leaf exfoliation, metabolic impairment, and overall chronic and sublethal stress (Thorhaug and Marcus 1987, Jackson et al. 1989, Sandulli et al. 1998, Ralph and Burchett 1998, Peirano et al. 2005, Scarlet et al. 2005, Kenworthy et al. 2017). Effects, including mortality and impairment, on seagrass associated flora and fauna are an important secondary impact (den Hartog and Jacobs 1980, Carls and Meador 2009). Recent studies of seagrass impacts from exposure to a complex oiling scenario in the Chandeleur Islands, located south of Mississippi during the Deepwater Horizon spill were conducted by Kenworthy et al. (2017). Tissue and sediment samples indicated variable exposure, and analysis attributed seagrass losses to oil exposure. For general comparison, the maximum sediment TPAH concentration recorded was 3998 ppb, which is greater than the mean of 1.2 ± 0.7 ppm wet weight observed at Site O three days post-spill in TROPICS, and less than the 6 ± 4 ppm wet weight at Site O four months post spill. Thus the range of potential sediment contamination in the seagrass areas is comparable, however specific interpretations are challenged by the relative rarity of *T. testudinium* in the area considered by Kenworthy et al. (2017). The lack of catastrophic seagrass loss in the Chandeleur Islands in the short term was consistent with the lack of dramatic impacts to seagrass observed in TROPICS.

In contrast, significant effects were found in seagrass invertebrates, specifically sea urchins, from exposure to dispersed oil in TROPICS. Oil impacts to early planktonic life stages of sea urchins is well documented, but few studies have focused on adult populations. As in the TROPICS study, acute impacts to urchins have been observed in several field studies where oiling of nearshore habitats resulted in steep declines in urchin populations (Peterson et al. 1996; Barillé-Boyer et al. 2004, Moore et al. 1997, Edwards and White 1999). Sublethal exposures can also affect adult behaviors and contribute to ongoing mortality (Axiak and Saliba 1981).

Corals

The key endpoints for coral assessment at the TROPICS study sites was coral coverage, and mortality/growth rate of four species of *O. annularis*, *A. tennuifolia*, *P. porites (aka P. furcata)*, and *A. cervicornis.* A wide variety of lethal and sub-lethal effects of oil on corals has been reported, including but not limited to increased mortality, tissue distension and rupture, mesenterial filament extrusion, tentacle retraction, abnormal polyp behavior, reduced growth rate, decreased photosynthetic yield and symbiont density (Guzman et al. 1991, Downs et al. 2006, Shafir et al. 2007, Peter et al. 1981, Knap 1987, Guzman-Martinez et al. 2007, summarized in Turner and Renegar 2017). Result of past studies were challenging to interpret, however, based on differences in methodology, so consistent impacts were difficult to predict. Recent research (Renegar et al. 2017, Renegar et al. 2019) has attempted to clarify petroleum impacts to corals. This research included included single hydrocarbon exposures for 6 species of Atlantic scleractinian corals and oil only and dispersed oil exposures for 3 species, including the Endangered Species Act listed staghorn coral (*A. cervicornis)* and *Porites divaricata* (a related species to *P. furcata*). Experimental results have indicated the relative resilience of corals to oil exposure, due likely to coral's large tissue lipid reserves and ability to produce lipid-rich mucus. Specifically, exposure of *A. cervicornis*, *P. divaricata*, and *P. astreoides* to the water accommodated fraction of MC252 oil resulted in little to no mortality observed at the highest oil loading of 1250 mg/L used; this concentration fell within the range of GC/MS samples collected in the coral area at Site O during dosing. For the dispersed oil exposures, concentrations which resulted in coral mortality were within the range of the measured hydrocarbon concentrations for the dispersed oil treatment in TROPICS. The experiment results thus support the observations of impacts to scleractinian corals observed during and after the TROPICS exposures.

CONCLUSIONS

Overall, parallel research strongly supports the conclusions of the TROPICS study. However, applying experimental results, even from controlled field studies such as TROPICS, in order to predict real-world outcomes is challenging; The exposure conditions in actual spills are very complex, and replicating that and the individual nature of real spills is nigh impossible in even the best designed experiments. One of the most important considerations is that careful interpretation is key in translating research data to real-world spill response, and realizing that, in terms of application, what works in one scenario may not work in another. For example, variability in environmental stress factors and coral species-specific reproductive modes and population density can be significant factors influencing both impacts and recovery from disturbance, and may skew NEBA assessments towards opposite outcomes. Planners and responders should therefore be cautious applying TROPICS results without accommodating the nuances of the many factors that may affect resources of concern.

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