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TROPICS: 30-year Follow-up and Analysis of Mangroves, Invertebrates, and Hydrocarbons

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ABSTRACT 300307:

TROPICS (TRopical Oil Pollution Investigations in Coastal Systems) has been the seminal study on trade-offs for Net Environmental Benefit Analysis (NEBA) for dispersant use in tropical ecosystems. The study began in 1983/84 with the identification of suitable tropical island sites in Bahia Almirante, Bocas del Toro, Panama that contained mangrove, seagrass and coral habitats in close enough proximity to establish three 30m X 30m test sites. Controlled releases of Prudhoe Bay crude oil (dosed at 1L/m^2) and Prudhoe Bay crude oil pre-dispersed with Corexit 9527 (to maintain 50 ppm water soluble fraction), were introduced into the Non-dispersed oil (Site O) and the Dispersed oil (Site D) sites, respectively, for 48 hours. A nearby Reference site (Site R) was not treated with oil/dispersed oil. Treatments were designed to simulate a realistic oil spill in adjoining mangrove, seagrass, and coral habitats.

Following exposure and removal of oil, sites were studied periodically over 30 years for relative effects of dispersed and non-dispersed oil in coral, seagrass, mangrove, and invertebrate populations, as well as hydrocarbon presence. Early research focused on short- and mid-term effects compared to the Reference site (R), while later work focused on long-term effects and ecosystem recovery. In general, researchers found that Site O exhibited more overall long-term ecosystem disruption than Site D, and that Site D had recovered quickly to Site R and baseline levels.

In November 2013 (29 years after oil and dispersed oil exposure), the TROPICS sites were re-visited under a grant provided by Clean Caribbean & Americas. Researchers collected data on mangroves, mangrove invertebrates, and hydrocarbons. The density of mangrove trees at Site D had remained at Site R and baseline levels. Site O, which had experienced early die off of trees, followed by peak production at 10 years (far in excess of Site R and baseline levels), exhibited a decline dominated by small trees. Mangrove snails and oysters increased sharply at Site O after the spill, but declined over 10-20 years. Sites D and R maintained gradual invertebrate increases during this time.

This paper focuses on research from the November 2013 visit and draws on previous observations and TROPICS papers on overall ecosystem disruption and recovery as it pertains to the NEBA for nearshore dispersant use in tropical marine ecosystems.

INTRODUCTION:

Fate and Effects Studies on Tropical Environments

Few tropical oil spill studies have focused on long-term effects, most dealing with cleanup, restoration, and damage assessment. In the process, researchers have assembled a list of short- and medium-term effects (e.g., Lewis, 1983, RPI, 1987, Dodge *et al*., 1995). As shown in Table 1, details exist for acute and chronic, early stages, but not for long-term (10+ year) stages.

Table 1. Acute and chronic effects observed and reported by Lewis (1983)

Acute	
0-15 days	Death of birds, turtles, fish, and invertebrates (crabs, clams)
15-30 days	Defoliation and death of small (<1m) mangroves (e.g., often *Avicennia*); loss of aerial root community
Chronic	
30 days-1 year	Defoliation and death of medium (<3m) mangroves; tissue damage to aerial roots
1-5 years	Death of larger (>3m) mangroves; loss of oiled aerial roots with some re-growth (common deformities); re-colonization of oiled areas by new seedlings
1-10 years	Reduction in leaf litter, reduced reproduction, and mortality of seedlings; death and/or reduced growth of young trees

The TROPICS treatments were designed to simulate a severe, but realistic scenario of oil release in shallow, low energy coastal waters, and in close proximity to sensitive mangrove, seagrass, and coral habitats, explore the short-, mid-, and long-term effects (Figure 1).

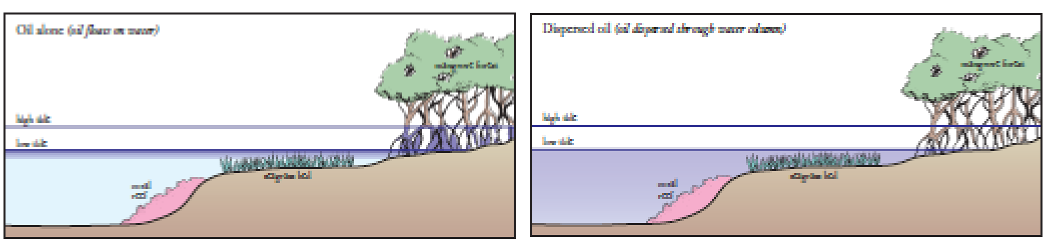


Figure 1. TROPICS created two exposure scenarios in marine tropical ecosystem habitats: left, Non-dispersed oil (Site O) and right, Dispersed oil (Site D) (IPIECA 1992).

The long-term duration of effects at the TROPICS oil spill in Panama was published through 25 years, as shown in Table 2. Descriptions of effects refer to percent changes in organisms over time, relative to baseline or previous years' data.

Table 2. Acute and chronic effects on mangroves and mangrove community at the non-dispersed oil site (Site O) (RPI, 1987, Dodge *et al*., 1995, Baca *et al*., 2005, and DeMicco *et. al*., 2011)

Year	Time Post Spill	Description of Effects
1984	72 hours	Roots and trunks coated; snails and tree crabs coated, no escape or defense responses; fish mortality and predation by predators (e.g., barracuda)
	5 days	Prop roots coated; tree crabs showed no escape or defense responses; tree snail numbers reduced by 49%
1985	30 days	Refer to Table 1 above for 0-15 and 15-30 days
	4 months	Substrate coated but no oil on prop roots; severe defoliation (25%) and mortality (35% dead or dying) of trees; canopy cover reduced (by 38%); tree snail numbers increased to 57%
	7 months	Sheen released from sediments; mortality "stabilized" at 15%, but defoliation averaged 45%; tree snail numbers increased to 84%
	12 months	Continued sheen released from sediments; seedlings increased by 8.7 times; tree snail numbers increased to 94% of original; but oysters showed largest reduction at 50%
1986	20 months	Same as 7 months but only 12% of trees showed no signs of defoliation; tree snails showed another drop, reduced to 52%
1994	10 years	Additional tree mortality occurred, now at 46% (54% live trees); significant reductions in mangrove characteristics were noted: trunk diameter, canopy cover, and leaf area; leaf thickness increased significantly, and leaf herbivory (insect damage) was significantly greater. Seedling count was 53% higher than pre-spill; tree snails increased by 14% over 1986; and tree oysters increased by over 5x original.
2001	17 years	Trees increased to 58% of original number due to seedling maturity; seedlings were 83% more than pre-spill but reduced to 84% of 10-year total; seedlings and small trees showed high rates of deformities; herbivory decreased to 50% of 10-year study
2004	20 years	Trees increased to 146% due to seedling maturity; seedlings increased to 109% more than pre-spill
2009	25 years	Trees increased to 178% due to seedling maturity; seedlings increased to 141% more than pre-spill. Note: the mangrove environment might be considered healed except for the presence of oil contamination in sediment and the unusually high density of trees and seedlings at the Oil Site.

Reports on the three years following the TROPICS spills were produced by RPI (1987) and Ballou *et al*. (1989). In the first year following the spills severe impacts were seen on mangroves at the non-dispersed oil site and invertebrates at the dispersed oil site. After two years the non-dispersed oil site showed severe effects on mangroves and associated sea life. Relatively minor effects were seen on seagrass and coral communities. Inversely, dispersed oil negatively affected sea life in tropical communities but had relatively few effects on their habitats: seagrasses and mangroves. Effects appeared to stabilize in 2.5 years and the study was discontinued. In contrast, Dodge *et al.* (1995) reported on research done ten years after the 1984 spills which showed an increase in Site O effects but apparent recovery at the Site D.

Petroleum Hydrocarbon Studies

The TROPICS studies contained intensive hydrocarbon sampling and analyses in the first 2.5 years and in the 10-year follow-up study (1994). Total petroleum hydrocarbons (TPH) were low or non-detectable after 10 years but changing forms of polycyclic aromatic hydrocarbons (PAH via EPA 8270, Florida Spectrum Environmental) were detected through 25 years (2009).

METHODS:

The present research was conducted at the same sites located on two islands in Bahia Almirante near Bocas del Toro, on the Caribbean coast of Panama. The original sites were chosen on the basis of presence and condition of mangrove forest, seagrass bed, and coral reef. Since these were experimental spills, baseline pre-spill studies of these sites were conducted numerous times in 1983 and 1984.

Three $900m^2$ sites were selected at separate locations: Reference (R), Non-Dispersed Crude Oil (O), and Dispersed Crude Oil (D). Three habitats were available for study within each 30m x 30m site ($900m^2$): mangrove forest, seagrass bed, and coral reef. However, since the focus of the present research was mangroves and component invertebrates, methods and detailed results are provided herein for mangrove forest (with invertebrates) only, as well as basic hydrocarbon sampling. The methods follow those used in 1984 and 1990, briefly as follows:

- Mangrove parameters – adult tree (>2m) height (m), seedling (<2m) height (m), tree diameter at breast height (DBH, 1.3 m high, in cm), canopy density (Forestry Suppliers™ crown densitometer, recorded in percent); all of these were taken at nine stratified (three tidal elevation strata: high, medium and low), random tree plots within each site.
- Invertebrates – mangrove tree snails (*Littorina angulifera* and other species) counted in vertical height classes and determined for nine stratified, random tree plots within each site.
- Invertebrates – mangrove oysters (*Crassostrea rhizophorae*), flat tree oysters (*Isognomon alatus*), and pearl oysters (*Pinctada margaritifera*), counted on five prop roots extending below mean high tide on each of three trees along the seaward edge (lowest stratum) of each site.

- Hydrocarbons - three sub-surface cores taken randomly from each mangrove zone (high, medium, and low elevations) at each site, using pre-cleaned glass containers provided by a certified laboratory. These were kept refrigerated and deposited in the laboratory two days after sampling, after which they were analyzed for PAH via EPA 8270 (Florida Spectrum Environmental).

RESULTS:

Mangrove Trees and Seedlings

Summaries of biological data collected over 30 years are given in Table 3 and Figures 1-3 for mangrove trees and seedlings. Statistical analyses are summarized in Table 7.

Table 3. Summary of mangrove counts before and after treatments over 30 years. Numbers represent percent of original population; actual counts are in parentheses. Highest counts over time are in bold, mostly in later years.

Sample Years	Parameter	Site R % (#)	Site O % (#)	Site D % (#)
Pre-dose (1984)	Mature Trees	100 (108)	100 (149)	100 (72)
	Seedlings	100 (26)	100 (13)	100 (33)
1 Year (1985)	Mature Trees	100 (108)	83 (80)	100 (72)
	Seedlings	100 (26)	100 (13)	100 (33)
10 Years (1994)	Mature Trees	100 (108)	54 (80)	97 (70)
	Seedlings	81 (21)	685 (89)	58 (19)
20 Years (2004)	Mature Trees	76 (82)	98 (146)	94 (68)
	Seedlings	112 (29)	838 (109)	100 (33)
25 Years (2009)	Mature Trees	**129 (139)**	120 (178)	72 (52)
	Seedlings	392 (102)	1085 (141)	124 (41)
29 Years (2013)	Mature Trees	89 (97)	**144 (223)**	**107 (77)**
	Seedlings	**1,258 (327)**	**1,192 (155)**	**161 (53)**

As shown, notable effects were detected at Site O: significant declines in trees and increases in seedlings (i.e., plants < 2m tall) were seen by year 10. The 1985 one-year data are included to show the rapid loss of trees which was believed to have stabilized by 7 months after treatment (RPI, 1987, Ballou *et al*., 1989). The 1994 (10-year) re-visit showed that this was not correct since a continuation or new "wave" of tree mortality had occurred. By 17 years trees had been essentially restored from seedlings at Site O. The opposite occurred at Sites D and R which experienced losses of mangrove trees before 25 years, dropping from baseline by 72% (25 years) and 76% (20 years), respectively. Tree counts at these sites have increased since then. Seedlings showed high recent increases over baseline at Sites O and R. It has been reported that seedling production peaks in October/November (the period sampled in 2013) and sometimes, researchers have avoided sampling then, and if they do sample, seedlings are scored (and counted) on the basis of node (joint) classes (e.g., Keller and Jackson, 1993). Due to time constraints, this method of viable seedling verification was not used in the present study.

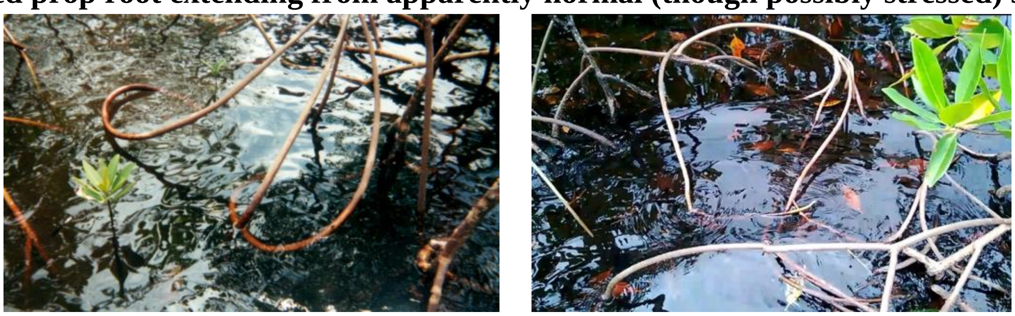
A breakdown of mangrove forest characteristics from baseline *vs*. long-term (10 years and 29 years) is given in Table 4 (statistics for mangrove measures and invertebrate counts are presented later in Table 7). Tallest trees were at Sites O and D; all trees showed highest diameter at breast height (DBH, 1.3m) in 2013, led by Site D; canopy cover was highest in 1984; most trees were at Sites O and D in 2013; and most seedlings were at all sites in 2013, led by Sites R and O.

Table 4. Mangrove parameters for baseline (1984), 10-year (1994), and 29-year (2013) sample periods. DBH (Diameter at Breast Height = 1.3m) results were significant (p<0.05) for year and site, and canopy cover data were significant for year only. Highest numbers per parameter are in bold.

Parameter	Sample Years	Site R Mean /SD	Site O Mean /SD	Site D Mean /SD
Tree Height (m)	Pre-dose (1984)	4.4/3.6	4.4/1.6	5.0/2.0
	10 Years (1994)	**4.7/4.1**	**5.0/2.9**	4.9/1.6
	29 Years (2013)	3.8/1.5	**5.0/3.2**	**5.2/0.8**
Tree DBH (cm)	Pre-dose (1984)	7.5/6.6	5.3/2.7	8.9/4.1
	10 Years (1994)	9.0/8.2	6.9/4.1	9.4/3.8
	29 Years (2013)	**10.5/3.4**	**8.4/4.3**	**14.7/5.2**
Canopy Cover (%)	Pre-dose (1984)	**84.4/6.2**	**90.8/7.5**	**78.9/14.7**
	10 Years (1994)	56.1/4.0	38.1/31.7	44.1/27.1
	29 Years (2013)	66.2/26.4	54.9/23.5	56.7/19.2

The issue of seedling and small tree deformities at Site O arose in 10 years and reached high levels of incidence in 17 years, continuing through 29 years (Fig. 2). Deformities seen were mainly curling and distortions of prop roots in small trees and seedlings. Likely causes relating to PAH effects are discussed later.

Figure 2. Deformities common at Site O from 17 years (2001, left) through 29 years (2013, right). Left shows distorted prop roots and small, stressed seedlings. Right shows contorted prop root extending from apparently normal (though possibly stressed) seedling.



Mangrove Invertebrates

Data for mangrove invertebrates (mangrove tree snails, mangrove oysters, flat tree oysters, and pearl oysters) were assembled for pre-spill (1984), spill study dates (1984-1986), 10 years (1994), and 29 years (2013). Mangrove tree snail (*Littorina angulifera*, etc.) results are given in Table 5 and Figure 3.

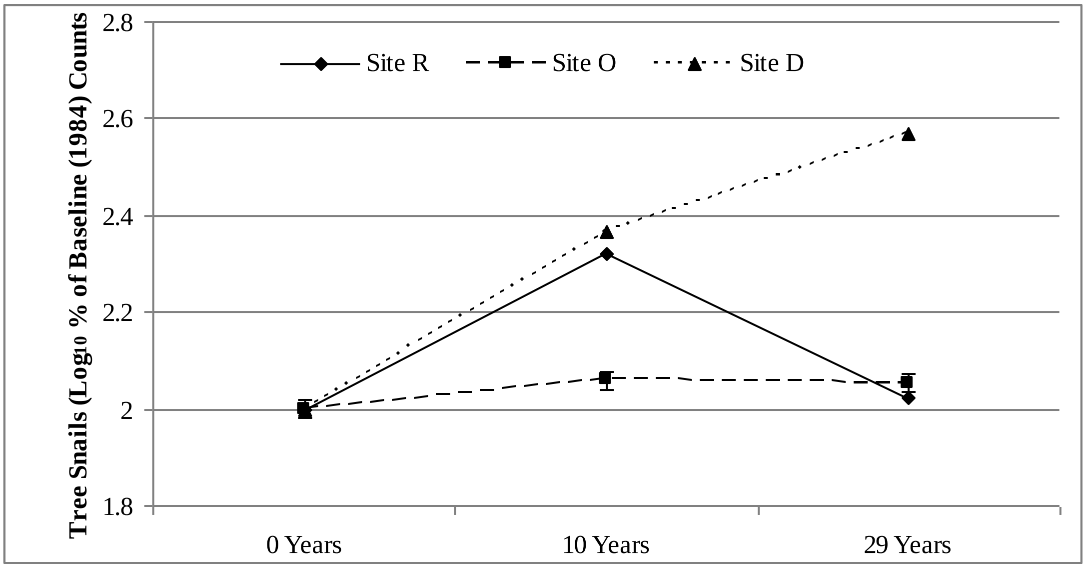
Table 5. Mangrove tree snail percent of 1984 baseline and actual counts for all dates in which they were sampled in detail. December 1984 data represent pre- (baseline) and four-day-post samples. Highest counts per site are in bold.

Sample Dates	Site R % (#)	Site O % (#)	Site D % (#)
Pre-dose (12/84)	100 (445)	**100 (766)**	100(297)
Post-dose (12/84)	91 (406)	49 (375)	52 (153)
1 Year (3/85)	78 (346)	58 (446)	76 (227)
1 Year (6/85)	96 (428)	84 (640)	81(240)
1 Year (12/85)	**138 (614)**	94(722)	130 (386)
2 Years (8/86)	65 (291)	51 (394)	87 (257)
10 Years (11/94)	125 (557)	69 (528)	139 (414)
29 Years (11/13)	66 (293)	68 (522	**229 (679)**
Overall Mean (#)	421	549	329
Overall SD (#)	118	147	158

As shown, all sites showed dramatic increases at the end of year 1 with upward trends at Sites R and D in 10 years post spill, and peaking at Site D in 29 years. Site O remained in downward trends, never reaching baseline.

Focusing on the three years of main collection efforts for tree snails simplifies the results, as shown in Figure 3. Data were log-transformed from percent of baseline. As shown, all sites showed an increase by ten years, although only Site D continued to increase.

Figure 3. Line graph of the three main years of tree snail study: 0 (baseline, 1984), 10 (1994), and 29 (2013).



Prop root bivalve (oyster) counts are given in Table 6 and Figure 4. Summaries are given for mangrove oysters (*Crassostrea rhizophorae*), flat tree oysters (*Isognomon alatus*), and pearl oysters (*Pinctada margaritifera*).

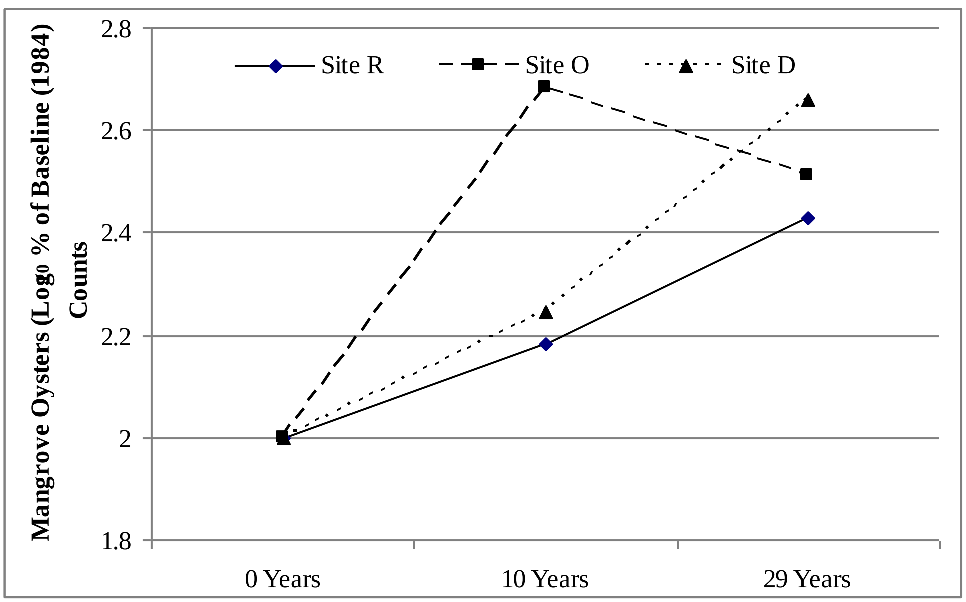
Table 6. Mangrove prop root oyster counts (mangrove oyster, flat tree oyster, and pearl oyster) are shown for periods that were sampled in detail. December 1984 data represent pre- and four-day-post samples. Counts are totals for each site taken in quadrats along transects at the seaward vertical stratum and below high tide level.

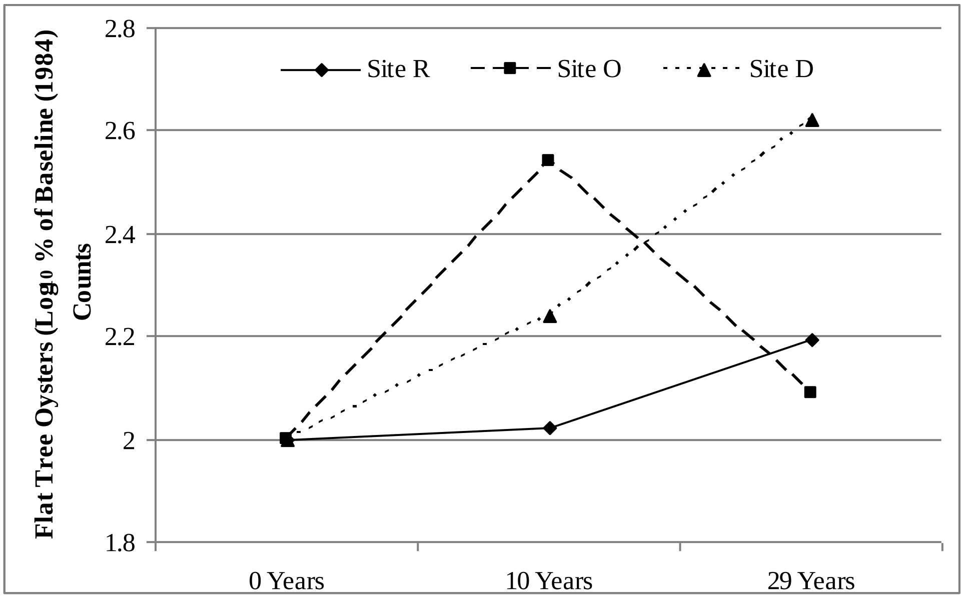
	Sample Dates	Site R	Site O	Site D
Mangrove Oysters	1 Year Pre- 1984 Dec	23	16	33
	1 Year Post- 1984 Dec	23	14	32
	1 Year 1985 Mar	23	13	21
	1 Year 1985 Jun	17	20	21
	1 Year 1985 Dec	11	8	37
	2 Years 1986 Aug	41	11	52
	10 Years 1994 Nov	35	77	58
	29 Years 2013 Nov	62	52	151
Flat Tree Oysters	1 Year Pre- 1984 Dec	61	53	48
	1 Year Post- 1984 Dec	61	53	48
	1 Year 1985 Mar	54	67	46
	1 Year 1985 Jun	48	72	41
	1 Year 1985 Dec	54	88	45
	2 Years 1986 Aug	34	111	39
	10 Years 1994 Nov	64	184	83

	29 Years 2013 Nov	95	65	201
Pearl Oysters	1 Year Pre- 1984 Dec	3	3	2
	1 Year Post- 1984 Dec	3	3	2
	1 Year 1985 Mar	2	3	1
	1 Year 1985 Jun	3	2	2
	1 Year 1985 Dec	5	2	2
	2 Years 1986 Aug	1	3	1
	10 Years 1994 Nov	38	107	69
	29 Years 2013 Nov	171	265	559

Prop root oyster counts for three main study years are illustrated in Figure 4. Summaries are given for mangrove oysters (*Crassostrea rhizophorae*, top) and flat tree oysters (*Isognomon alatus* bottom). Pearl oysters (*Pinctada margaritifera*) are not included because they were very rare in the early studies (pre- and 1984-1986 post-). As shown, both oysters had similar growth curves, for Site O: peaking 10 years after the spill and then declining (precipitously for flat tree oysters). In contrast, both oysters showed gradual upward trends with no declines at Sites D and R.

Figure 4. Abundance of two main oyster species observed on submerged prop roots at each site and sampling period. Abundances of pearl oysters were not included because they numbered <5 for each site until the 1994 survey.





Statistical Analyses

Comparisons were made between years and sites using two-way analysis of variance (ANOVA) and appropriate post-hoc tests (Sigma Stat ver. 3.1, Aspire Software, Ashburn, VA). The Holm-Sidak method was selected as the post-hoc test because of its power in analysis of two-way ANOVAs. Results are given in Table 7 for the main years 0 (1984), 1 (1985), 2 (1986), 10 (1994), 20 (2004), 25 (2009), and 29 (2013), for the three sites. As shown, mangrove tree counts, heights, and flat tree oysters were not significant. All other parameters were significant for years and/or sites.

Table 7. Statistical comparisons using two-way ANOVA, with significance at $p<0.05$. The Holm-Sidak method is the post hoc test (under Post-Hoc Significance).

HABITAT	PARAMETER	YEARS	SITES	ANOVA P-value	Post-Hoc Significance
Mangrove	# and % Live Trees	0 vs 10, 20, 25 10 vs 20, 25, 29	Oil vs Dispersed vs Reference	>0.05	No significant results
Mangrove	# and % Seedlings	0 vs 10, 20, 25 10 vs 20, 25, 29	Oil vs Dispersed vs Reference	0.028 (Site)	Oil vs Dispersed, Reference
Mangrove	Tree Height	0, 1, 2, 10, 20, 25, 29	Oil vs Dispersed vs Reference	>0.05	No significant results
Mangrove	Tree DBH	0, 1, 2, 10, 20, 25, 29	Oil vs Dispersed vs Reference	0.029 (Year) 0.028 (Site)	29 vs 0 years, and Dispersed vs. Oil
Mangrove	Canopy %	0, 1, 2, 10, 20, 25, 29	Oil vs Dispersed vs Reference	0.005 (Year)	0 vs. 10, 29
Mangrove	Tree Snails	0, 1, 2, 10, 20, 25, 29	Oil vs Dispersed vs Reference	0.005 (Date) 0.209 (Site)	10 vs. 0, 2 29 vs. 0, 2 Oil vs Dispersed
Mangrove	Mangrove Oysters	0, 1, 2, 10, 20, 25, 29	Oil vs Dispersed vs Reference	0.008 (Date)	29 vs. 0 (pre/post), 1
Mangrove	Flat Tree Oysters	0, 1, 2, 10, 20, 25, 29	Oil vs Dispersed vs Reference	>0.05	No significant results
Mangrove	Pearl Oysters	0, 1, 2, 10, 20, 25, 29	Oil vs Dispersed vs Reference	<0.001 (Date)	29 vs. 0 (pre/post), 1, 2, 10

Hydrocarbon Studies

Analytical results of all sites for the previous collections indicate that hydrocarbon levels as Total Petroleum Hydrocarbons (TPH) have continued to drop over the last 10± years until they are undetectable. Polycyclic Aromatic Hydrocarbons (PAH) peaked in 2009 (year 25), with the two-ringed naphthalenes making up 94 percent of the total. The change in PAH composition between 1994 (year 10) and 2009 shows a progressive molecule size reduction (seemingly the opposite of convention, discussed later) going from four-ringed chrysenes, fluoranthenes, and pyrenes, to three-ringed phenanthrenes and anthracenes, and ending with two-ringed (lightest) naphthalenes. However, no PAH was detected in 29 years (all components were undetectable at the lowest detection level).

DISCUSSION AND NET ENVIRONMENTAL BENEFIT ANALYSIS:

The effects of non-treated and dispersed crude oil at the TROPICS site, specifically the short- and long-term ecosystem disruptions, have been documented and continue to be short- and long-term for various parameters. While dispersant (Site D) showed serious and immediate effects on fauna, these effects were short-lived, and the site returned to pre-dose conditions, without long-term, ecological disruptions. In contrast, Site O has undergone considerable long-term changes as the oil contamination has resulted in ecological disruptions at that site. The Site O mangrove forest lost a significant portion of trees which were slowly replaced by “waves” of seedlings (early ones did not survive to produce trees). The seven-fold appearance of seedlings in year 10 (1994) was believed to be due to the effect of canopy opening as well as to nutrient production by the weathering oil (Dodge *et al.*, 1995). At 29 years, the Site O and Site D mangroves were restored by over 100% while Site O and Site R seedlings maintain their presence by approximately 1,200 percent of the original counts. The long-term (post-ten-year) affects on mangrove fauna at the sites have been explored and have raised questions about invertebrate productivity at Site O.

Pearl oysters were relatively new to the sites, having first appeared in high numbers 10 years after the spills, and increasing in much higher numbers at all sites such that percent of increase could not be graphed with trees. Since pearl oysters cannot be mistaken for other oysters it is unlikely that they were misidentified for 10 years, and their increased numbers appear to be a natural phenomenon.

Mangrove deformities have been seen and photo-documented at Site O (and no others) for many years. Recent incidents, such as deformed prop roots arising from otherwise normal looking plants, indicate that the situation is continuing. Since PAHs are known to be mutagenic, and since they have been present at Site O for some 25 years, it is likely that high levels found at Site O early in this study may be responsible. Mutagenicity of PAHs in mangroves has been documented and is the subject of environmental monitoring (e.g., Klekowski *et al.*, 1994;Proffitt and Travis, 2005). Since propagules are being produced at Site O it would be important to know if they might be transferring these deformities (i.e., mutations) to subsequent generations, on site and elsewhere.

The change in PAH appeared to go from heaviest to lightest compounds, culminating with two-ringed naphthalenes which were the last seen after 25 years, making up 94% of the PAH. This sequence is generally the reverse of what is commonly seen in spills, where light aromatics such as benzene and naphthalene are removed first and heavy PAH such as asphaltenes (e.g., tars) and resins remain the longest (NAP 1985). However, the anaerobic, tropical, low flushing, organically rich, marine sediments in the study sites have analogs in groundwater, landfill, laboratory bacterial studies, and creosote contamination sites which may apply; however, discussion of these is beyond the scope of the present research.

DeMicco *et al*. (2011) detailed the Net Environmental Benefits Analysis (NEBA) for nearshore dispersant use on mangroves, seagrass, corals, and hydrocarbons, based on a previous 25 years at the TROPICS sites. The present study focused on invertebrates, mangroves, and hydrocarbon presence. By analyzing the data collected during this study and combining it with information carried out at the sites previously, a number of observations confirm the NEBA for dispersant use at this site:

1) at 10 years, live mangrove trees suffered severe mortality at Site O (54% survival) but very little at Site D (97% survival)
2) earlier high seedling production (now over 1,000 %) resulting from open space provided by high mortality at Site O led to the present, albeit excessive re-growth of trees (now at 144%); in contrast is the near baseline tree count at Site D (107%).
3) mutations were seen on trees at Site O during the past 20 years but none were ever detected at Sites D or R
4) at 10 years, mangrove tree snail populations were near baseline (115%) at Site O but experienced natural increases at Sites O (232%) and R (208%), and this trend continued through the present
5) in contrast, 10-year mangrove oyster populations increased tremendously (481%) at Site O but were near baseline at Sites D (176%) and R (152%)
6) aromatic hydrocarbons were detected for 25 years (but not at 29 years) at Site O but were not detected after 3 years at Sites D or R
7) at 28 years, oyster populations receded (325%) at Site O but continued increasing at Sites D (458%) and R (297%)

CONCLUSIONS:

Almost thirty years have passed since non-dispersed and dispersed crude oil was released into the tropical ecosystem marking the beginning of the TROPICS study. Over this time, reports and papers have documented the trade-offs in dispersant use in shallow-water tropical ecosystems. Although the scale of the experiment or the failure to use replicates could be debated, there are some conclusive results of this study that should be taken into account for management of oil spills on water.

Relative to oil spills in mangroves, it is apparent that:

- Long-term (e.g., 10-30 year) negative effects of non-dispersed oil in a mangrove forest are real and measurable
- Long-term effects include keystone floral and faunal components of the ecosystem
- Medium-term (e.g., 10 years) and long-term, negative effects can be reduced by the appropriate use of dispersants in nearshore environments
- Medium- and long-term, dispersed oil spill effects are similar to conditions at the control site

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