Net Environmental Benefit Analysis (NEBA) of Dispersed Oil on Nearshore Tropical Ecosystems: Tropics – the 25th Year Research Visit

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ABSTRACT

The TROPICS (Tropical Investigations in Coastal Systems) field study began in 1983/84 near Bocas del Toro, Panama. The study was designed to examine the relative short and long-term effects of dispersed crude oil versus non-dispersed crude oil on tropical marine ecosystems. After baseline studies (1983), two 900m^2 sites composed of intertidal mangrove and subtidal seagrass-coral zones were dosed (1984) with untreated Prudhoe Bay crude oil and Prudhoe Bay crude oil dispersed with Corexit® 9527. At periodic intervals over 25 years, the sites were monitored and effects were compared to a nearby reference site. A number of papers were published during the study period.

In the short term, mortality to invertebrate fauna, seagrass, and corals was observed at both the dispersed oil and non-dispersed oil sites. In the long-term (10-25 years), as compared to the reference site, there was little to no oil detected and the ecosystem appeared to have returned to pre-dosing condition at the dispersed oil site. At the non-dispersed site, substrate core samples revealed the continued presence of oil. Mangrove, primarily *Rhizophora mangle*, repopulation was impeded and substrate erosion at the non-dispersed site. In addition, seagrass beds of *Thalassia testudinum* at the non-dispersed site had been overrun by finger coral (*Porites porites* a.k.a. *P*. *furcata*), a condition not found at the dispersed site or reference site. Core samples indicated an elevated levels of aromatic hydrocarbons (naphthalene) at the non-dispersed site. The dispersed site exhibited recovery to near reference conditions by year 10 whereas long-term disruption has been observed at the non-dispersed site through 25 years.

These results provide baseline scientific data for addressing Net Environmental Benefit Analysis (NEBA) for dispersant use decision-making in near-shore tropical ecosystems. Dispersants appeared to prevent long-term contamination to mangrove forests and the resulting absence of oil in the substrate, made possible by advantageous properties of dispersed oil, avoided long-term exposure to toxic compounds and provided the conditions for ecosystem and habitat recovery. Most significant, after 25 years, components of non-dispersed crude oil,

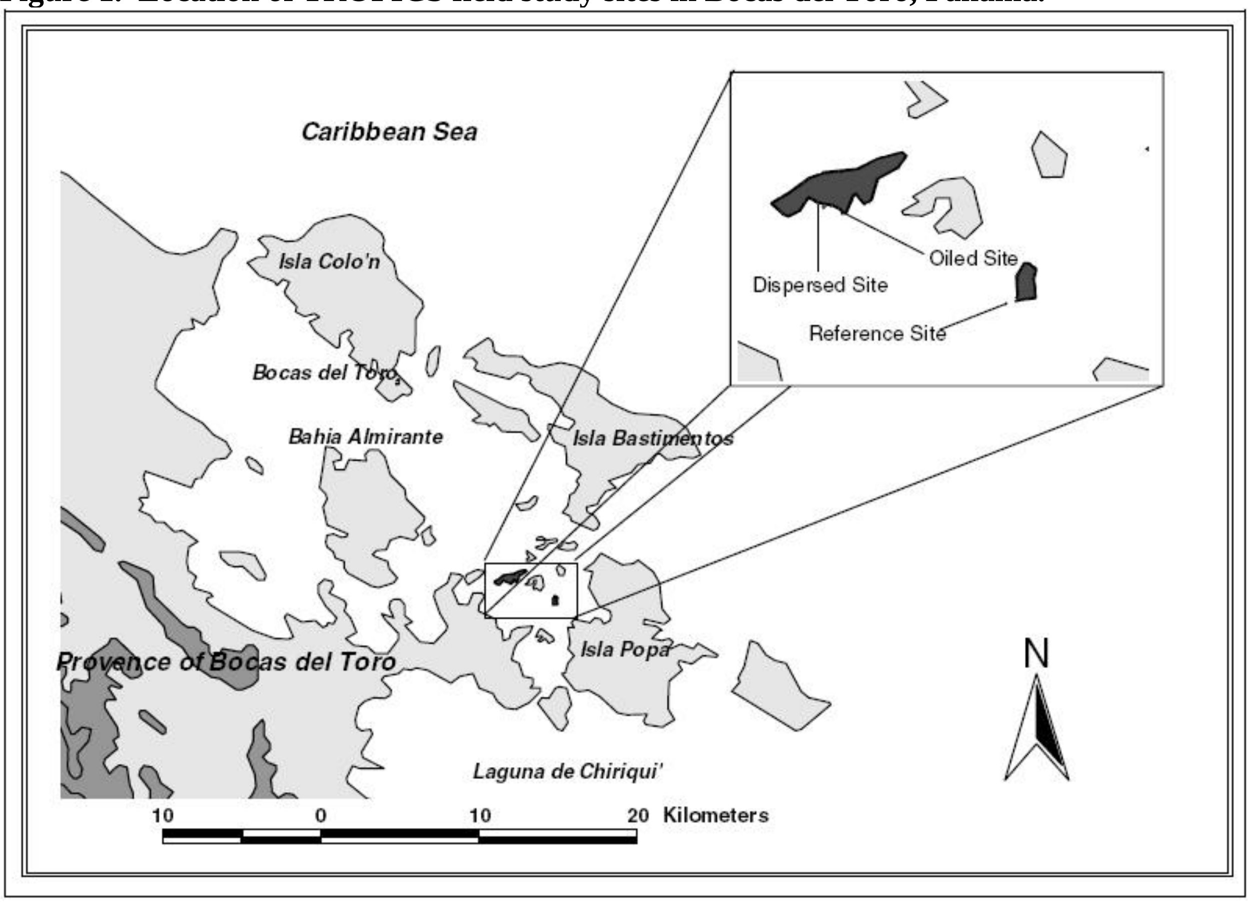
specifically aromatic hydrocarbons, remain in the mangrove substrate in the non-dispersed site, where chronic exposure continues to inhibit recovery and repopulation.

INTRODUCTION

Previous Biological Studies

A number of oil spills have occurred in tropical Atlantic/Caribbean waters which affected mangrove, seagrass and coral habitats; however there have been few long-term studies that have exceeded 10 years. Reports on the 3 years following the initial TROPICS dosing in Panama (Fig. 1) were produced by Research Planning, Inc. (1987) and Ballou *et al.* (1989). In the first year following the dosing, severe mortality was observed on mangroves at the non-dispersed oil site and invertebrates at the dispersed oil site. After 2 years, mangroves and associated fauna continued to exhibit severe effects at the non-dispersed oil site. Relatively minor effects were seen on seagrass and coral communities. Conversely, dispersed oil negatively affected fauna in tropical communities but had relatively few effects on their habitats: seagrasses and mangroves. Effects appeared to stabilize in 2.5 years.

Figure 1. Location of TROPICS field study sites in Bocas del Toro, Panama.



Later Dodge *et al.* (1995) reported on research done 10 years after the 1984 dosing which showed an increase in non-dispersed oil effects but apparent recovery at the dispersed oil site. Mortality of mangroves at the non-dispersed site went from 17% to 46%, while the mortality at the dispersed oil and reference sites was 3% and 0%, respectively. Seagrasses experienced short-term increases at all sites prior to 1994: 123% at the non-dispersed oil site, 122% at the dispersed site, and 120% at the reference sites. In the years prior to 1994 coral cover increased (118%) at the non-dispersed oil site but declined at the dispersed and reference sites, 81% and 61%, respectively.

In 2003 Ward published observations from the 18-year study (Ward *et al.* 2003). Results continued the trends and helped explain what occurred in the 10-year study. Mangrove seedling population rose to 838% over the original, partially as a result of the large canopy opened by mangrove mortality. The abundance of seedlings versus mature mangrove trees reflected an overall decline in the non-dispersed site forest. Seagrass declined to 64% of its original cover at the non-dispersed oil site, primarily due to an invasion of finger coral (*Porites porites* a.k.a. *P. furcata*). Seagrasses also maintained density coverage of 97% at the dispersed site, while the reference site had an increase to 158%. Increased coral (mostly *Porites)* cover results at the non-dispersed oil site (221%) were correlated with seagrass reduction. Coral cover at the dispersed and reference sites decreased to 46% and 79%, respectively.

Petroleum Hydrocarbon Studies

The TROPICS studies contained intensive hydrocarbon sampling and analyses in the first 2.5 years and in the 1994 10-year follow-up study. Lesser intense albeit relatively complete hydrocarbon data were collected in 2004 (20 years) and 2009 (25 years). Analyses of hydrocarbons collected from the mangrove forest at the non-dispersed oil site, were reported in Ballou *et al.* (1989). A brief survey and sediment sampling were made in April 2004, the 20th year, and the results showed reduction, but continued presence, of total petroleum hydrocarbons at the non-dispersed oil site (Baca *et al.* 2005). This latest survey marks the 25th year following the experimental dosage of non-dispersed crude oil and dispersed crude oil at the TROPICS sites. Samples were collected from mangrove forest in three central locations, from the seaward to the landward areas of each of the three experimental sites.

RESULTS

Biological

Biological results of the last 15 years of studies were similar to those seen in previous 10 years, except negative effects were exacerbated; primarily the loss of seagrass, takeover of seagrass beds by finger coral, and the increase in trees (formerly seedlings) at the non-dispersed oil site. Summaries of biological data collected over 25 years are given in Tables 1-3 for mangroves, seagrass, and corals, respectively.

Table 1. Summary of mangrove counts between the three treatment sites over 25 years. Numbers represent percent of original population; actual counts are in parentheses.

Sample Dates	Parameter	Non-Dispersed % (number)	Dispersed Oil % (number)	Reference Site % (number)
Pre-dose (1984)	Mature Trees	100 (149)	100 (72)	100 (108)
	Seedlings	100 (13)	100 (33)	100 (26)
1 Year (1985)	Mature Trees	83 (80)	100 (72)	100 (108)
	Seedlings	100 (13)	100 (33)	100 (26)
10 Years (1994)	Mature Trees	54 (80)	97 (70)	100 (108)
	Seedlings	685 (89)	58 (19)	81 (21)
20 Years (2004)	Mature Trees	98 (146)	94 (68)	76 (82)
	Seedlings	838 (109)	100 (33)	112 (29)
25 Years (2009)	Mature Trees	120 (178)	72 (52)	129 (139)
	Seedlings	1085 (141)	124 (41)	392 (102)

As shown, notable effects were detected at the non-treated oil site: significant declines in trees and increases in seedlings (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 new "wave" of tree mortality had occurred. By 17 years trees had been essentially restored from seedlings at the non-treated oil site. The opposite occurred at the dispersed and reference sites which experienced losses of trees prior to 2009, dropping from baseline by 72% (2009) and 76% (2004), respectively. Seedlings showed increases during this period for these two sites, ending at 124% and 392% (respectively), presumably a response to recent tree losses.

Tree and seedling counts over time are further illustrated in Figure 2, where the disparity between trees and seedlings is clear. As indicated, the non-dispersed site had major increases in seedlings over the last 15 years. Of the other sites, only the present year of the reference site showed high increases in seedlings, presumably because of recent (i.e., 2001/2002) tree mortalities at that site.

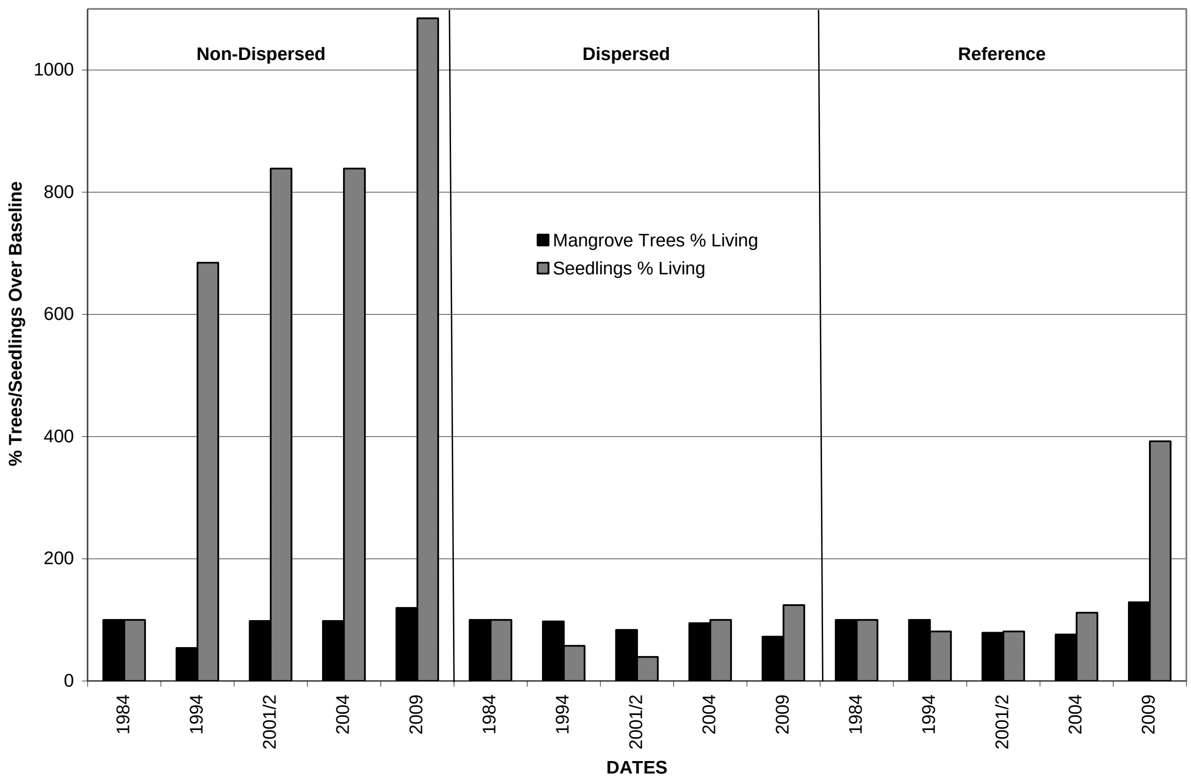


Figure 2. Percents of original baseline counts for trees (>2m) and seedlings (<2m) at the TROPICS sites over the past 25 years.

Seagrass results over the years are given in Table 2. Growth measures were not taken in 2009 and seasonal corrections for growth measurements were not factored in for the studies. The density data are also graphed in Figure 3, showing standard errors (SE) and measures used in statistics. As discussed with coral results, the overall trend was loss of seagrass and invasion by finger coral at the non-dispersed site.

Table 2. Summary of seagrass results during the 25 years of the TROPICS project. Numbers represent percent of original measures; mean original population size (per m^2) and mean growth rates (cm/da) are given in parentheses for baseline studies (1984).

Sample Dates	Parameter	Non-Dispersed	Dispersed Oil	Reference Site
Pre-dose (84)	Density	100 (357)	100 (423)	100 (523)
	Growth rate	100 (0.49)	100 (0.43)	100 (0.43)
1 Year (85)	Density	105	135	113
	Growth rate	90	111	115
10 Years (94)	Density	123	122	86
	Growth rate	111	106	107
18 Years (02)	Density	64	97	158
	Growth rate	89	111	87
25 Years (09)	Density	58	88	106

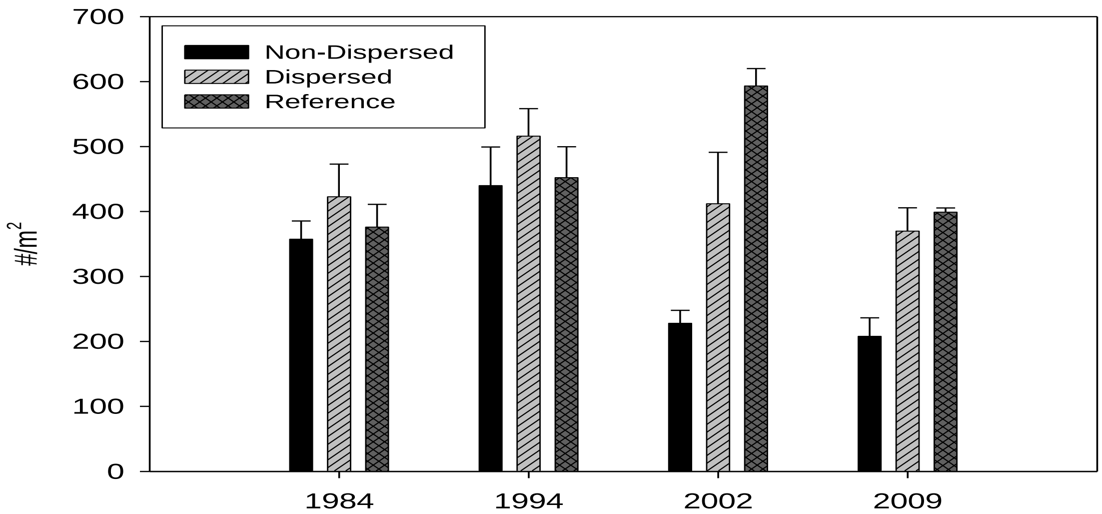


Figure 3. Graph of seagrass density data using actual counts for analysis, with standard error bars.

Coral habitat cover results are given in Table 3. The percent cover data are also graphed in Figure 4, showing standard errors (SE) and measures used in statistics. The short-term effects were readily apparent at the dispersed site, but the coral recovered to pre-dosing/reference levels within ten years. Conversely, the coral cover at the non-dispersed site was at its lowest level at 1994, but this was reversed in the next ten years.

Table 3. Summary of coral cover results during the 25 years of the TROPICS project. Numbers represent percent of original measures; original percent cover data are given in parentheses for baseline surveys (1984).

Sample Dates	Parameter	Non-Dispersed	Dispersed Oil	Reference Site
Pre-dose (1984)	Coral Cover	100 (27.6)	100 (21.6)	100 (21.3)
	Total Fauna Cover	100 (55.6)	100 (50.3)	100 (49.3)
	Total Flora Cover	100 (13.5)	100 (3.8)	100 (19.3)
1 Year (1985)	Coral Cover	77.5	43.9	40.3
	Total Fauna Cover	97.8	45.5	88.8
	Total Flora Cover	26.7	7.9	217.6
10 Years (1994)	Coral Cover	35.6	81	60.0
	Total Fauna Cover	50.8	97	98.3
	Total Flora Cover	18.5	710	178.8
18 Years (2002)	Coral Cover	221.3	45.5	78.9
	Total Fauna Cover	158.4	106.0	75.7
	Total Flora Cover	85.7	815.8	217.8
25 Years (2009)	Coral Cover	260.7	210.1	353.5
	Total Fauna Cover	173.2	157.3	162.9
	Total Flora Cover	184.3	550.0	102.1

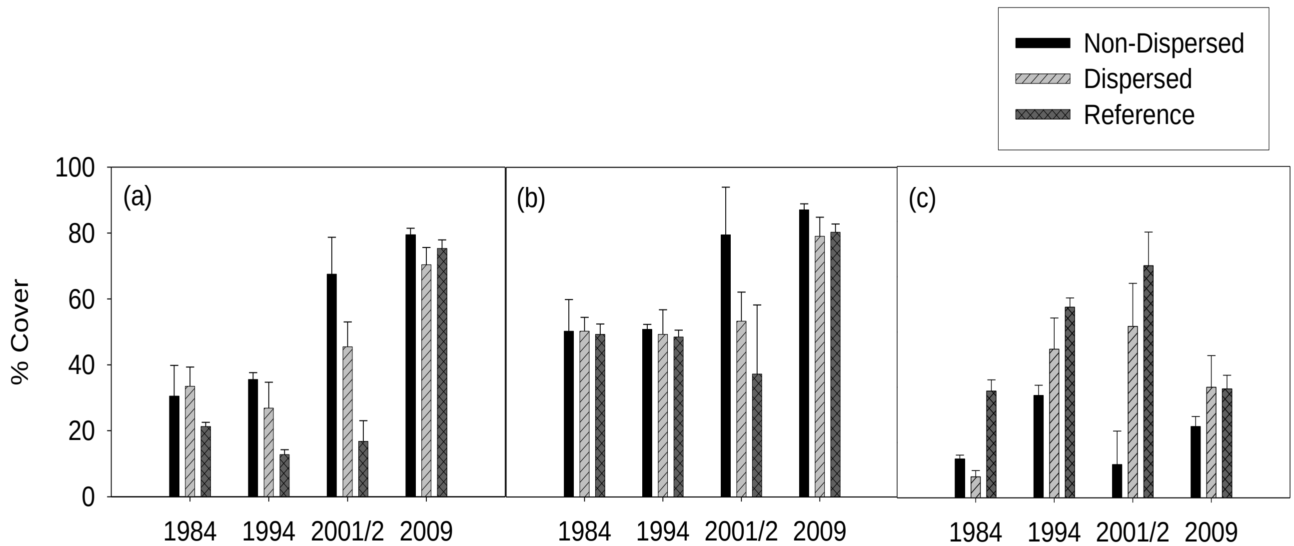


Figure 4. Percent cover data of the three main coral habitats: (a) % coral, (b) % all fauna, and (c) % flora, with SE bars.

Hydrocarbon Studies

Analytical results of all sites for the June 2009 sediment collections, as compared with 1995 and 2004, are given in Table 4. A quick glance would indicate that hydrocarbon levels as Total Petroleum Hydrocarbons (TPH) have continued to drop over the years. However, Polycyclic Aromatic Hydrocarbons (PAH) have apparently stabilized after an increase in 2004 and a closer examination of the PAHs which make up this mean of 0.05mg/kg reveal startling trends. Comparisons of the main aromatic compounds and groups between 1995, 2004, and 2009 samples at the non-dispersed oil site are given in Table 5. As shown, 2009 levels are almost twice that of 2004, and this is primarily due to a large increase in naphthalenes. This is more obvious in Figure 5 where naphthalenes dwarf all other hydrocarbons, and where information about the transformation of the PAH groups can be supposed: the top PAH groups in 2004 have dropped in levels and given rise to a formerly rare group, the naphthalenes. As stated here and previously, the PAH levels are very low and may be considered inconsequential at this time, were it not for their toxicity (discussed later).

Table 4. Hydrocarbons analyzed from sediment samples taken in 1995, 2004, and 2009. Units in mg/kg (=ppm). NR = Not Reported.

Parameters	1995 Ref.	2004 Ref.	2009 Ref.	1995 Non-Disp.	2004 Non-Disp.	2009 Non-Disp.	1995 Disp.	2004 Disp.	2009 Disp.
Mean TPH	NR	1.14	0.00	15.0	1.61	0.05	10.0	0.74	0.00
SD TPH	NR	0.17	0.00	25.7	0.63	0.04	12.8	0.10	0.00
Mean Alkanes	NR	1.12	0.00	NR	1.56	0.00	NR	0.74	0.00
SD Alkanes	NR	0.25	0.00	NR	0.05	0.00	NR	0.10	0.00
Mean PAH	NR	0.02	0.00	0.01	0.05	0.05	NR	0.01	0.00
SD PAH	NR	0.01	0.00	0.01	0.07	0.04	NR	0.01	0.00
% Alkanes	NR	98.25	0.00	NR	96.89	0.00	NR	99.66	NR

Table 5. Comparisons of PAH compounds and groups of PAH compounds between the 1995, 2004, and 2009 sediment sample dates (mg/kg=ppm) at the <u>Non-dispersed Oil Site.</u>

PAH Compounds	1995 levels mg/kg	2004 levels mg/kg	2009 levels mg/kg
Replicates per site	2	14	3
Naphthalenes	0.00	0.05	0.77
Phenanthrene/Anthracene	0.02	0.15	0.03
Pyrenes	0.05	0.08	0.01
Naphthenes	0.00	0.06	0.01
Fluoranthene	0.04	0.02	0.01
Fluorene	0.00	0.03	0.02
Chrysenes	0.02	0.02	0.00
Dibenzothiophene	0.00	0.04	0.00

Perylenes	0.00	0.00	0.00
TOTAL	0.13	0.45	0.85
MEAN	0.01	0.05	0.09
SD	0.02	0.04	0.25

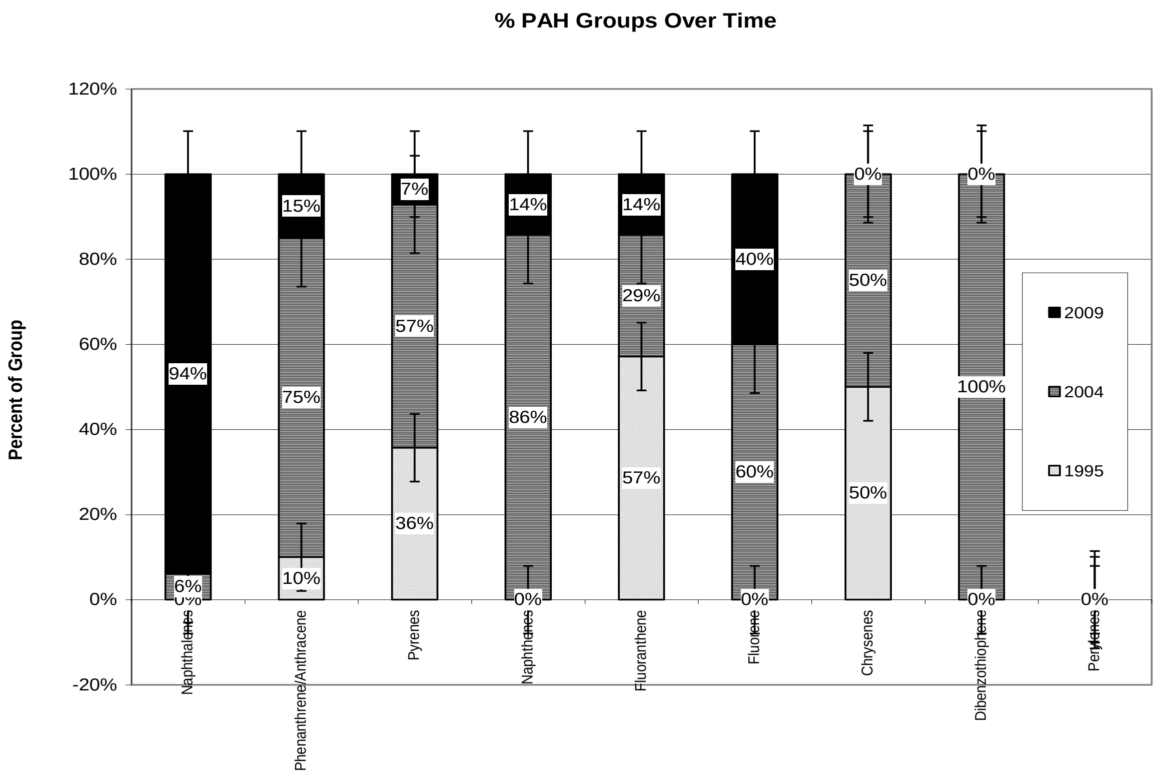


Figure 5. Percent of PAH groups over time, from overall highest percent occurrence to lowest (left to right).

RESULTS AND DISCUSSION

The effects of non-dispersed and dispersed crude oil at the TROPICS site have been documented and determined to be short- and long-term for various parameters. While dispersed crude oil showed serious and immediate effects on fauna, these effects were short-lived. In contrast, the non-dispersed crude oil site has undergone considerable long-term changes. The mangrove forest lost a significant portion of trees which were slowly replaced by "waves" of seedlings that never reached maturity, presumably due to the long-term exposure to toxic petroleum compounds that remained trapped in the substrate.

The long-term (post-ten-year) affects on mangrove fauna at the sites have not been extensively studied.

Seagrass density declined at the non-dispersed site, apparently being replaced by finger corals. However, seagrass declined overall at both sites, ending at 58% (non-dispersed) and 88% (dispersed) of original coverage. With the exception of Ward (2003), other seagrass metrics besides density were not pursued after 1994 due to time and funding constraints. Reviewing the TROPICS field notebooks there are various measures of area and depths which indicate that the subtidal shelf off the non-dispersed site became narrower and deeper over time. For example, the average width of the non-dispersed site was 7.8m in 1984 while the dispersed site was 6.9m (Baca unpublished). In contrast, measures recorded by Ward in 2001 (unpublished) showed widths of 1.5m and 6.5m for the non-dispersed and dispersed sites, respectively. This would indicate a loss of 6.3m at the non-dispersed site, a probable measure of impacts.

Coral cover increased at all sites, culminating at approximately 200% over baseline at non-dispersed and dispersed sites, and almost 400% at the reference site. However, through 2001/2002, replacement by flora (seagrass and algae) was apparently a cause at the dispersed and reference sites, but not at the non-dispersed site. By contrast, percent flora in coral habitat increased at the non-dispersed and dispersed sites, while dropping to baseline at the reference site. These changes in the marine environment may reflect natural trends which require further investigation.

Finding a drop in total petroleum hydrocarbons but a spike in toxic naphthalene was an unexpected result of this 25 year study. Rationale for this large increase in the naphthalene components of PAH and the drop in other groups may be due to such concepts as:

- Natural degradation of PAH from one form to another. This is commonly seen in the degradation process (e.g., Young and Phelps 2005) although naphthalene and other groups such as phenanthrene enter the process (e.g., via carboxylic acid formation) differently and would not necessarily result in the disappearance of one group and the increase of another.
- Systematic relationships between similar (i.e., molecular weight, solubility, specific gravity, and/or melting point) groups exist which favor degradation of one group over another. For example, plots of occurrence can show that phenanthrene is closer to pyrene than it is to naphthalene (USGS 2002), and the comparative degradation rates and times may vary between these dissimilar groups.
- Other factors can influence relative abundance of different PAH groups such as patchy distribution, different collection depths, different sample numbers, post-sample treatment, timeliness of analysis, analytical methods, etc.

As stated here and previously, the PAH levels are very low and may be considered insignificant. However, seven PAHs are on the EPA's Priority Chemical List (EPA 2008):

1. Acenaphthene
2. Acenaphthylene
3. Anthracene
4. Benzo(g,h,i)perylene
5. Fluorene

6. Phenanthrene
7. Pyrene

Besides the PAHs listed on the EPA's Priority Chemical List, there is a larger group of 21 (mostly Benzo- and Dibenzo- forms) which are defined for Toxic Release Inventory reporting (EPA 2000). PAH exposures of between 300-900 ppm in short- and long-term animal studies result in health problems and birth defects, and they seem to be associated with cancer in humans (EPA 2008). Relevant to the TROPICS work, phenanthrene and anthracene are common contaminants in the environment.

According to EPA (2000), naphthalene has numerous uses and routes for exposure such as mothballs, cigarettes, and insecticides. The lowest observed adverse (human) effect level is 52 ppm, which is over 50 times the average level found at the non-dispersed oil site. Chronic (non-cancer) effect levels are much lower but have only been determined for laboratory animals.

CONCLUSIONS

By observing the long-term impacts of non-treated crude oil entering the nearshore and tropical ecosystem in comparison to the short-term impacts of dispersed crude oil, there is more support for the Net Environmental Benefit for the nearshore use of dispersants in tropical ecosystems, as summarized in Table 6.

Table 6. Net Environmental Benefits (NEB) for dispersant use based on 25+ years of research. Data are percent of original 1984 taken for given years, comparing Non-dispersed and Dispersed sites only.

Habitat	Parameter	Non-Dispersed	Dispersed	NEB?
Sediment	Hydrocarbon persistence	25+ years	3 Years	Yes
Mangrove	# Live Trees	54% 1994	97% 1994	Yes
		120% 2009	72% 2009	Yes
	# Seedlings	684% 1994	100% 1994	Yes
Seagrass	Density	25% 2009	45% 2009	Yes
	Growth	90% in 2001/2	124% in 2001/2	Yes
Coral	% Coral Cover	118% 1994	81% 1994	No
		261% 2009	354% 2009	Yes
	% Fauna Cover	101% 1994	81% 1994	No
		173% 2009	210% 2009	Yes
	% Flora Cover	257% 1994	710% 1994	Yes
		184% 2009	550% 2009	Yes

As has been the case in the first 20 years of the study, three principal conclusions evidently continue in the 25th year:

- Oil contamination remains at the non-treated crude oil dosing site but is non-detectable at the dispersed crude oil and reference sites,
- *Porites* coral have overrun the seagrass bed at the non-treated crude oil site, a situation which occurs nowhere on the island nor at the dispersed crude oil or reference sites, and
- Erosion and sediment re-distribution have apparently occurred at the non-treated crude oil site, but not at the dispersed crude oil and reference site.

A disturbing discovery resulting from the core samples collected during the field visit in 2009 showed that yet another detrimental component continues to hinder recovery at the non-dispersed site with levels of naphthalene at fifteen times what they were in 2004, just five years earlier. Effects from years of the loss of habitat, erosion, slow release of toxic compounds, and potential slow release of fertilizing substances (minerals, metals, and organics) continue to keep the non-dispersed site environment in a constant state of flux.

In conclusion, dispersed oil did not become trapped in the substrate and consequently allowed for short-term recovery at the dispersed oil site. Conversely, at the non-dispersed crude oil site, oil penetrated the mangrove forest substrate, adhered to and became trapped in the substrate, where it remains, albeit in small quantities, despite tidal flushing over 25 years. In addition, the recent spike in PAHs at the non-dispersed site raises the specter that oil trapped in the substrate may naturally degrade into more, versus less, toxic compounds. These observations underline the importance of considering the nearshore use of dispersants in tropical ecosystems.

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