



Chlorophyll-deficient propagules of *Avicennia marina* and apparent longer term deterioration of mangrove fitness in oil-polluted sediments

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Abstract

A correlation between petroleum hydrocarbon concentrations in sediments and chlorophyll-deficient mutations in mangroves may occur also in Australian mangroves. Earlier reports of such mutations in the Caribbean area were evident in viviparous propagules of the common mangrove genera, *Rhizophora*, borne on otherwise normal trees. These mutant propagules were termed 'albinos' since they lacked chlorophyll and normal green coloration, leaving them white, yellow or red. The mutation was considered lethal since newly established albino seedlings appeared unable to survive more than a few months. Our preliminary investigation of mangroves in SE Queensland found a similar mutation in another common mangrove genus, *Avicennia*, and this was apparently also correlated with oil concentrations in sediments. Although, more evidence is required, an apparently similar relationship shows that whatever caused the mutations may act commonly across a diverse range of plant types in quite separate locations. How widespread might this mutation be in mangroves? How many genera and species are affected? Are all occurrences correlated with oil in sediments? Does oil cause the mutation? We discuss these important questions and the potentially serious implications to coastal management where high mutant densities may be indicative of longer term genetic deterioration of mangrove habitat in oil-polluted wetland environments.

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1. Introduction

Mangrove habitats and individual trees are highly sensitive to changes in coastal water quality, especially from the impacts of large petroleum spills (e.g., Wardrop, 1987; Thorhaug, 1992; Grant et al., 1993; Volkman et al., 1994; Dodge et al., 1995; Connell, 1995; Proffitt et al., 1995; Duke et al., 1999a,b, 2000). Although mangroves are found in a wide range of climatic and physiological conditions, the species present in these areas vary both in type and dominance. Where tidal wetland habitats are impacted with large amounts of noxious compounds, like petroleum oil, some plants die, but others survive and have possible sublethal responses (e.g., Duke et al., 1997). Two alternate hypotheses may explain the occurrence of albino-bearing trees. First, the

more sensitive plant species remaining might change in genetic makeup by direct mutation. Or, they might change by genetic selection over many generations for individuals more suited to chronically polluted conditions. In either case, mangroves polluted over longer periods are expected to have relatively low biodiversity, and possible high levels of genetic abnormalities. In such instances, ecosystem function may decline and even collapse in extreme cases if establishment success deteriorates further. In such cases, the benefits and services mangrove habitats provide would be expected to be lost also (Ewel et al., 1998).

Mangroves typically have few species, ~70 in the world, but they are genetically diverse being derived from 20 plant families and they have developed common morphological and physiological adaptations in a convergent and shared evolution (see Duke et al., 1998). They also occupy a narrow ecological range, constrained mostly between mean sea level and highest tidal levels between 1 and 2 m elevation, or considerably less in

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some regions. Despite such restrictions, mangroves are well adapted to their tight ecological niche although they are at risk when conditions change rapidly during coastal development projects and severe storms, and generally when additional stresses such as pollutants are applied. Around the world, people utilise mangrove ecosystems particularly for food and forest products (e.g., Field, 1995). In conjunction with the reduced benefits with habitat loss, there has been a serious decline in the capacity of mangroves to protect shorelines from erosion and in trapping sediment (e.g., Duke and Wolanski, 2001) and disruption of trophic relationships affecting both estuarine and nearshore fisheries (e.g., Lee, 1995; Robertson and Alongi, 1992). Coupled with the range of pressures on mangroves, the presence of albino propagules represents an additional and unquantified aspect of general deterioration in habitat fitness and survival of coastal wetland habitats around the world.

1.1. Genetic mutants and petroleum pollution

Along the south-western coast of Puerto Rico, Caribbean Sea, observations were made of sediment hydrocarbon concentrations and frequencies of chlorophyll-deficient alleles in mangroves (Handler and Teas, 1983; Klekowski, 1988; Klekowski et al., 1994b,c). A positive correlation was found between the concentrations of polycyclic aromatic hydrocarbons (PAHs) and the frequency of nuclear mutations in the mangrove trees, *Rhizophora mangle*, growing in contaminated sediments (Klekowski et al., 1994c). Although these results require refinement to account for biogenic hydrocarbons, they nevertheless are indicative of the influence of oil on plant growth and development.

In *Rhizophora* species, young new plants attached to parent trees germinate when their embryos rupture through the stigma end of the ovary, and the hypocotyl, or first root, extends down 20–90 cm in length. Mutant individuals were characterised by their lack of normal green coloration, leaving them either yellow, pinkish or red (Klekowski et al., 1994b). Mutant propagules are chlorophyll deficient and they are often referred to as ‘albinos’. *Rhizophora* albinos can easily be observed whilst attached to the parent tree since they contrast with the green foliage and normal sibling propagules. Their presence further possibly signifies that albino-bearing parent trees have a mutant recessive gene while these trees otherwise appear normal.

1.2. Genetic abnormalities and vivipary in mangrove plants

Vivipary is common in mangrove plants (Duke et al., 1998) and it has allowed for relatively easy screening of wild populations for genetic abnormalities in young

seedlings, especially for some members of the mangrove family Rhizophoraceae. In marked contrast with most plants which enclose their developing embryos within dormant seed capsules, mangrove mutant offspring become visible soon after germination and whilst they remain attached to the parent tree. Albino propagules may be biologically defective but they usually do not die until well after abscission, dispersal and establishment. While the propagules are attached they are apparently nourished by the parent tree and they are easily visible. After detachment, the young plants initially utilise food reserves stored in the propagule, but after this reserve is depleted, normal green seedlings would depend upon exogenous influences and their own ability to fix carbon by photosynthesis (e.g., Pannier, 1962). In this way, albino progeny might survive for considerable amounts of time, notably for as long as their parent-derived reserves last.

As a number of progeny can be observed at some time on the same parent tree, families of progeny can be scored for the mutant trait. Segregation ratios for mutant and wild-type embryo phenotypes can be determined. For example, an observed ratio of 3:1 for wild-type (green) to mutant (not green) propagules would indicate the tree was a mono-hybrid and that self-fertilisation had probably predominated. In any case, an albino-bearing tree (i.e., the heterozygous parent with the mutant recessive gene) will have both progeny in some measurable ratio of frequencies. Consequently, vivipary and self-fertilisation have allowed field recognition and quantification of the chlorophyll-deficient gene (allele) in natural populations of at least one mangrove species (Klekowski and Godfrey, 1989; Lowenfeld and Klekowski, 1992; Klekowski et al., 1994a,b,c).

The apparently nuclear-inherited, chlorophyll-deficient genotype is presumably due to a mutant allele at any one of a suite of nuclear genes that control photosynthesis in the chloroplast. In flowering plants, approximately 300 nuclear gene loci control the presence of chlorophyll in the chloroplasts (Corredor et al., 1995; Klekowski, 1992). Chlorophyll-deficient mutations therefore represent a diagnostic character by which to monitor relatively small populations, around 1000 individuals (e.g., Klekowski et al., 1994b).

1.3. Albino mutants in other species and other regions

References cited above refer to mutations present in *R. mangle* in the Caribbean Sea. However, similar albino mutations have been observed in several other mangrove species and in other regions of the world. For instance, in Central America, albino species include: *Avicennia germinans* and *Pelliciera rhizophorae* as well as *R. mangle* (Duke, pers. obs.). In Brazil, non-albino mutations were also recorded for *A. germinans* (da Silva et al., 1997). In south-east Asia, mutation rates have been



Fig. 1. Propagules of *A. marina* showing different colour morphs of cotyledons from left to right, as 'brown' (both red and green pigment), 'white' (pale yellow), 'red', and 'green' (normal condition). Those propagules without any green pigment at all, i.e., 'white' and 'red', were collectively called 'albino' forms.

reported for albino (= chlorophyll deficient) *Kandelia* (Chen et al., 1996).

In eastern Australia, observed albino genera include: *Rhizophora*, *Ceriops* and *Avicennia* (Duke, pers. obs.). The mutation was observed in several other Queensland and New South Wales locations but previously only as isolated rare trees. Curiously, however, there are some areas where the presence of mutants were more frequent. For example, albino-bearing trees of *Rhizophora stylosa* were observed in unusually large numbers in Port Curtis, Central Queensland, Australia, during experimental studies assessing the impacts of large oil spills on mangroves (Duke and Burns, 1999; Duke et al., 1999a,b). In New South Wales, Australia, albino-bearing trees of *Avicennia marina* are reportedly quite common, particularly around the Homebush Bay area (S. Paul, pers. obs.).

Similarly, albino propagules of *A. marina* (Fig. 1) were observed in high numbers along the foreshores of Moreton Bay (Fig. 2), a region which has recently been the subject of intense ecological study with important implications for local coastal management (e.g., Denison and Abal, 1999). Mutant albino propagules of *A. marina* have not been reported elsewhere in the world. For this mangrove species, mutant progeny attached to the parent tree are covered in a soft husk, the pericarp. This feature makes identification of albino-bearing trees more difficult compared to survey methods described for *Rhizophora* (e.g., Klekowski et al., 1994b). For *Avicennia*, identification of mutant bearing trees involves an extra step. In the first instance, newly fallen albino propagules must be located on the ground during a low tide period. Once the presence of these mutant propagules has been established then the area must be searched to locate the source tree. In Moreton Bay, albino-bearing trees were found adjacent to the busy port area, a site subject to relatively frequent small spills of fuel and other oils.

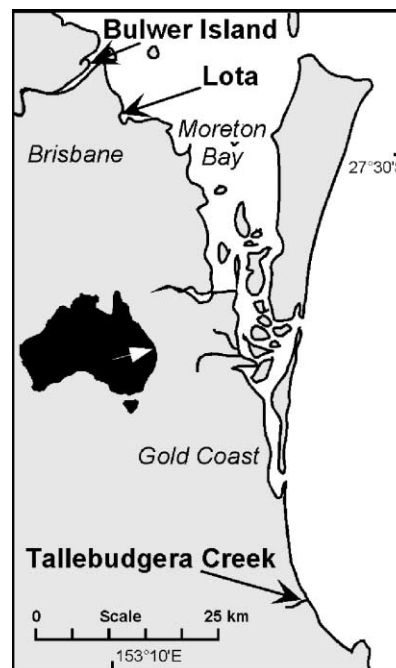


Fig. 2. Map of the three mangrove site locations surveyed in this investigation.

In this preliminary survey, we investigated the occurrence of albino propagules of *A. marina* and the seemingly normal, albino-bearing trees in Moreton Bay. Our chief objectives for this investigation were to:

1. Derive preliminary site estimates of the frequency of albino genes of *A. marina* growing in Moreton Bay, south-east Queensland, Australia; and
2. Collect sediment surface samples (0–2 cm depth) in the same sites for hydrocarbon analysis, including: total petroleum hydrocarbon (TPH); and PAH concentrations and composition.

2. Methods

2.1. Field survey and collections

Field work was conducted over 2–3 days during mid July 1999. Sampled areas were mostly fringing forest stands of *A. marina* extending from the waters edge to the upper intertidal limit. Tree heights varied from 3 to 8 m, and stem densities varied depending on tree age and topographic position. All sites were located within the Moreton Region of south-east Queensland, Australia. Three sites were assessed (Fig. 2) including: one at the north-east end of Bulwer Island in the Brisbane River, a second along the foreshore at Lota in the mouth of Tingalpa Creek, and a third within Tallebudgera Creek Environmental Reserve in the Gold Coast area. The Bulwer site had apparent high levels of established mutant-bearing (heterozygous) trees, based on earlier observations.

The chief aim was to investigate the likelihood of a relationship between gene mutation and PAHs, the most likely mutagenic agent. PAHs were expected to accumulate in sediments of mangrove forests close to possible sources of chronic oil pollution. Survey work was chiefly conducted for collection of data on gene frequencies (chlorophyll-deficient genes), particularly based on the frequency of albino-bearing, parent trees.

The survey strategy used at each site was to walk within the mangrove forest at low tide and to locate detached albino propagules either on the sediments generally, or along the high water mark in beach debris. Albino propagules were defined as those completely lacking green pigment in cotyledons, or any other part. These propagules ranged in colour, from bright yellow, to red, and white (see Fig. 1). In practice, propagules had not been carried far from where they had fallen. In this way, it was possible to easily locate albino-bearing, parent trees nearby. When a tree was confirmed to be albino-bearing, by checking for attached albino propagules, it was labeled with a permanent tag for future reference. Such identification was not always possible however since access to upper branches was not safe or easily achievable during this investigation where taller

inner forest trees reached >5–8 m in height. In these cases, likely trees were tagged for future reference.

Studies were conducted at each field site to determine the number of mutant bearing trees of *A. marina* in defined plots of mangrove forest. In contrast with assessments of Bulwer and Lota sites, no mutant bearing trees were located at Tallebudgera Creek despite the survey area being three times that of the other locations. For Bulwer and Lota, areas of around one hectare were surveyed in each case.

2.2. Sediment samples and hydrocarbon analyses

Surface sediment samples were collected from each location surveyed (Fig. 2). Three to five replicate samples were gathered systematically from each study location, and each consisted of four to five pooled sub-samples. A total of 12 samples were analysed for total hydrocarbon and PAHs. Samples were analysed by the chemical laboratory of MAFRI in Victoria. The methods used for hydrocarbon analyses closely followed Burns (1992).

3. Results

3.1. General observations

Some characteristics of the study area and sites are presented briefly in Table 1. Land use adjacent to the sites varied considerably. The Bulwer site was surrounded by heavy industry, oil refineries, and it was next to a busy port. By contrast, the sites at Lota and Tallebudgera were more residential but the Lota site was near to a small boat harbour and there was light industry nearby. These land use differences had an important bearing on the amount of hydrocarbons present in mangrove sediments.

In general, propagules with albino cotyledons often also had albino leaves. These seedlings appeared to become established in the normal way and all produced at least their first leaf pair before dying after around 2 months whether in full sun or shaded locations. From field observations, normal green seedlings persisted

Table 1
Results of field collections at the three study locations

South-east Queensland location	Survey area (ha, dimensions, km)	Frequency of heterozygous trees (ha)	Sediment samples collected	Land use
Bulwer Island mouth of Brisbane R.	1.0 (0.50 × 0.02)	9	5 (A5 to A9)	Heavy industry, refineries and major port area
Lota foreshore, mouth of Tingalpa Creek	0.8 (0.40 × 0.02)	5	4 (A1 to A4)	Residential, light industry, small boat marina
Tallebudgera Creek, Gold Coast	3.0 (0.30 × 0.10)	0	3 (A11 to A13)	Residential, canal estates and environmental habitat reserve

much longer and produced 3–4 leaf pairs before dying when growing in shaded locations.

It was discovered also during the survey that the proportion (number) of fallen propagules with respect to each individual parent tree was indicative of tree size. In this way, larger mutant bearing trees dropped more mutant propagules than smaller trees. The Bulwer site was notable for the number of larger mutant bearing trees compared with the Lota site. This observation was important also since it implied that albino bearing trees had become established more recently at the Lota site.

3.2. Sediment samples and hydrocarbon analyses

Results of chemical analyses on sediment samples from the three sites are shown in Table 2. All samples had significant amounts of biogenic hydrocarbons. These were distinguished by large odd carbon numbered *n*-alkane peaks in chromatograms of the saturates fraction. All samples had considerable amounts of or-

ganic matter (root matting and small fibrous roots) in them and this may be the source of biogenics.

Samples from Tallebudgera (A11–A13) were notable because they had little aromatic hydrocarbon components and it was assumed these samples contained biogenics with only traces of petroleum. The total hydrocarbon concentration in these three samples was relatively uniform. It is possible that the other samples had approximately the same concentration of biogenics in them.

All samples showed UV fluorescence which indicated the presence of traces of petroleum, but the samples with the lowest UV max were A4 from Lota and A11 from Tallebudgera. This was in agreement with the low aromatic hydrocarbon content of these samples. Samples A12 and A13 were not done since total hydrocarbon levels were low. Overall, most samples from Bulwer and Lota contained petroleum hydrocarbons, but all contained biogenic hydrocarbons as well. The hydrocarbon concentrations in the samples were all quite low (total hydrocarbons range 18–94 µg/g dry weight) and approximately 20 µg/g of this was likely to be due to the biogenic component.

Levels of parent PAH compounds are shown in Table 3. While there are differences between samples (e.g. samples from Lota vs. Tallebudgera) the concentrations were not particularly high. These parent PAHs were indicative of combustion sources, as their concentrations in oil were not particularly high. The alkylated

Table 2
Results of chemical analyses of sediment samples from the three field locations

South-east Queens-land location	Sample code	Saturates (µg/g dry wt.)	Aromatic (µg/g dry wt.)	Total hydrocarbons (µg/g dry wt.)	Type
Bulwer	A5	65	13	78	Mostly petroleum
	A6	59	11	70	Mostly petroleum
	A7	66	28	94	Mostly petroleum
	A8	35	6	41	Mostly biogenics
	A9	57	35	92	Mostly petroleum
Mean ±1SE		56 ± 6	19 ± 6	75 ± 10	
Lota	A1	24	7	31	Mostly biogenics
	A2	53	20	73	Mostly petroleum
	A3	47	17	64	Mostly petroleum
	A4	16	3	19	Mostly biogenics
Mean ±1SE		35 ± 9	12 ± 4	47 ± 13	
Tallebudgera	A11	18–19	1–2	20	Biogenics
	A12	22	1	23	Biogenics
	A13	17	1	18	Biogenics
Mean ±1SE		19 ± 1	1 ± 0	20 ± 1	

Table 3
PAHs in mangrove sediments (ng/g dry weight of sediment) at three sites (values are mean estimates from four surface samples each)

PAH compounds	Bulwer	Lota	Tallebudgera
<i>Parent</i>			
Naphthalene	<5	<5	<5
Acenaphthylene	<5	<5	<5
Acenaphthene	<5	<5	<5
Fluorene	<5	<5	<5
Phenanthrene	12	19	<5
Anthracene	83	54	8
Fluoranthene	30	52	<5
Pyrene	32	46	<5
Benzo[<i>a</i>]anthracene	32	33	<5
Chrysene	16	22	<5
Benzo[<i>b</i>]fluoranthene	52	74	<5
Benzo[<i>k</i>]fluoranthene	12	12	5
Benzo[<i>a</i>]pyrene	26	38	<5
Indeno[1,2,3- <i>cd</i>]pyrene	68	49	<5
Dibenz[<i>a,h</i>]anthracene	20	<5	<5
Benzo[<i>ghi</i>]perylene	43	35	<5
<i>Alkylated</i>			
C1 Naphthalene	<5	<5	<5
C2 Naphthalene	<5	<5	<5
C3 Naphthalene	<5	<5	<5
C1 Phenanthrene/anthracene	23	42	<5
C2 Phenanthrene/anthracene	40	26	<5
C3 Phenanthrene/anthracene	58	12	<5

PAHs were present in several of the samples from Bulwer and Lota, confirming the presence of chronic oil contamination in these samples.

In consideration of the alkylated PAH (C1–C3 naphthalenes and C1–C3 phenanthrenes/anthracenes) fractions, the results showed that the naphthalenes were in all cases below the detection limit. However, some alkyl phenanthrenes/anthracenes were found at low concentrations in most of the samples—except A11–A13 (Tallebudgera). The results suggest some petroleum contamination of the samples. The alkyl phenanthrene/anthracene PAH concentrations in samples A1 to A5 (Lota) were unusual in that concentrations were expected to increase from C1 to C3 compounds. However, in these samples the concentrations decreased from C1 to C3. This may be due to some co-eluting compounds or some other unspecified interferences. The pattern of alkyl PAH concentrations for samples A6–A9 (Bulwer) were more of what is expected in typical oil samples—although the concentrations are relatively low. This is the pattern expected for sediments subject to chronic oil contamination.

3.3. Comparing mutation frequency with hydrocarbons in sediments

Data on mutation frequencies and hydrocarbons in sediments are summarised in Fig. 3. The increased levels of mutation frequency were correlated with the concentration of total hydrocarbons ($P < 0.01$, noting that $n = 3$ sites weakens the outcome of the regression analysis in this preliminary study). Furthermore, the amount of biogenic components appeared relatively constant. Therefore, the kind of hydrocarbons affecting this apparent correlation were almost certainly petroleum based. This was indicated by the apparent significant relationship ($P < 0.01$) also between mutation frequency and the aromatic fraction, shown in Fig. 3.

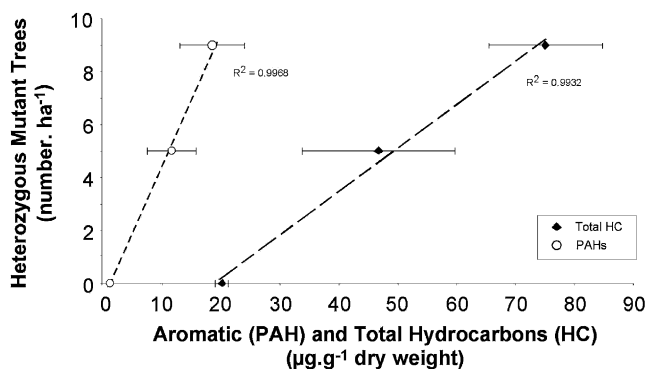


Fig. 3. Relationship between sediment hydrocarbons and the presence of albino-bearing trees (= heterozygous mutants) of *A. marina* in Moreton Bay mangroves. Standard error bars shown for hydrocarbon concentrations.

4. Discussion

We present the results of our preliminary investigation into the occurrence of the apparently lethal genetic mutation in the common mangrove tree, *A. marina*, in Moreton Bay, south-east Queensland. The mutation was manifest as albino propagules and seedlings lacking all green coloration in cotyledons and leaves, a characteristic which was expected to reduce the regenerative capacity of the local mangrove habitat. The lack of green coloration in mutant propagules shows these individuals lack chlorophyll pigment leaving them unable to photosynthesize. Newly established albino seedlings therefore were expected to survive for only so long as their food reserves lasted, possibly up to around 2 months based on personal observations in the field. Our results further show a possible relationship between the presence of albino-bearing trees (which appeared otherwise normal) and petroleum hydrocarbons in sediments, particularly PAHs. It was considered important to report this occurrence and to encourage detailed investigations of the cause.

These observations are compelling support for the proposal that petroleum hydrocarbons are responsible for causing, or favouring, the occurrence of lethal mutations in mangrove plants, including *A. marina* and other species, in south-east Queensland and elsewhere. Our results show mutant genes (determined as albino-bearing trees) of *A. marina* were more frequent in sites with sediments having higher levels of both total hydrocarbon and the petroleum-based PAHs. This apparent relationship was comparable with the one shown earlier for *R. mangle* (Klekowski et al., 1994b). However, for *A. marina*, the levels of total hydrocarbons in sediments were lower in south-east Queensland and there were apparently lower levels of mutant gene frequencies—a feature in keeping with the relationship described above for *R. mangle* in the Caribbean area (see Fig. 4).

This apparent relationship however differed in the comparison with PAHs for *R. mangle* and *A. marina* (Fig. 5). For this oil fraction, the trends differed for each species. At the same concentration of PAH, the frequency of mutant genes was approximately an order of magnitude less for *A. marina* in south-east Queensland. Therefore, although relationships between increasing PAH concentrations and increasing mutant frequencies were comparable, the relationships between species differed. All our observations, however, are largely tentative and should be treated with caution since they are based only on three sample sites in this preliminary investigation.

These current findings do identify potential environmental management issues which need to be addressed, concerning the persistence of petroleum products in marine intertidal environments and their possible impacts

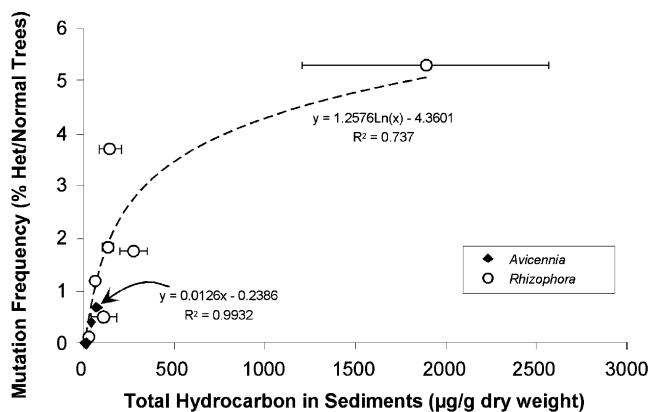


Fig. 4. Relationship between sediment total hydrocarbons and the frequency of albino-bearing trees (= heterozygous mutants) of *A. marina* in Moreton Bay in Queensland, and *R. mangle* in Puerto Rico. Standard error bars shown for hydrocarbon concentrations.

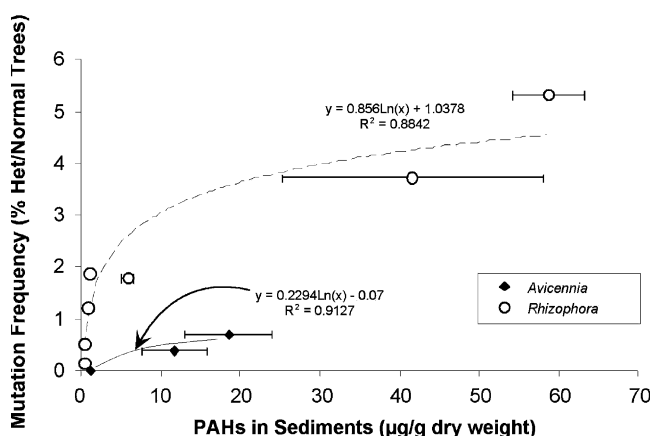


Fig. 5. Relationship between sediment PAHs and the frequency of albino-bearing trees (= heterozygous mutants) of *A. marina* in Moreton Bay in Queensland, and *R. mangle* in Puerto Rico (Klekowski et al., 1994b). Standard error bars shown for hydrocarbon concentrations.

on dependant flora and fauna. It is of great concern, for instance, that valuable mangrove habitat may be threatened further by a loss of genetic fitness in the presence of petroleum hydrocarbons in sediments. Petroleum hydrocarbons are known to persist in mangrove sediments for several decades (Burns et al., 1993), and trees take a similar time to mature (Duke, 2001), so there are several factors which might influence mutant gene frequencies and cause mutations. In either case, albino gene frequencies may be considered indicative of genetic deterioration of mangrove habitat.

In view of such observations, we offer three recommendations for further investigations. (1) Validate local effects. To confirm current observations in the Moreton Bay area of the apparent relationship between mutant genes in *A. marina* populations and the presence of hydrocarbons, notably by including a greater number of

sites. (2) Quantify wider effects. To identify albino mutants elsewhere and to investigate possible relationships between mutant gene frequencies (albino-bearing trees) and sediment oil concentrations in other locations worldwide, and for all viviparous or cryptoviviparous species. (3) Investigate the cause. To discover whether hydrocarbons cause albino mutations, or whether the albino-bearing individuals might be favoured over normal individuals growing in oiled sediments. Making this distinction may help to correctly identify the true cause, and to refine the direction of future research.

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