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Assessing the potential for algal blooms in clear water phase tropical rivers

Project number: **UAD21**

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Assessing the potential for algal blooms in clear water phase tropical rivers

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1. Introduction

Algal blooms commonly occur in rivers across southern Australia and worldwide. Blooms and their associated biota cause taste and odour problems that are a constant source of complaints to water authorities. Blooms dominated by cyanobacteria or blue green algae are of economic and environmental concern because estimates suggest that 60-70% are toxic. The health risks associated with toxic blooms may lead to the closure of rivers for recreational use and disrupt water supplies for domestic, industrial and irrigation purposes. The formation of blooms, or dense algal populations, requires a supply of nutrients and energy so that the products of photosynthesis may be converted into algal biomass. The species composition, net rate of growth, final crop density all depend upon an interplay between temperature, nutrient availability and preference, thermal stratification and flow. Biological characteristics such as buoyancy regulation and susceptibility to grazing (eg size, taste) also play an important role. Factors leading to algal populations are reviewed by Oliver and Ganf (2000) who placed emphasis on a) the supply of two nutrients, phosphorus and nitrogen, and b) the depth of the surface mixed layer in relation to the depth of the euphotic zone. Their conceptual model was directed more towards turbid lakes and reservoirs than to clear, flowing rivers and they do not explore the interaction between algal growth rate, discharge and the potential for algal populations to persist in flowing rivers where downstream advection may exceed algal growth rates (Spiers and Gurney 2001).

The rivers of northern Australia and particularly those in the Top End of the Northern Territory are subject to major seasonal changes in flow and inter-annual variability. For example, the Daly River experiences dry season discharge rates of 2 to 80 m^3 s^{-1} (Webster *et al*. 2005). The ecological character of this river is shaped by the annual changes in discharge. High wet season flows reset the ecological clock (Webster *et al*. 2005) and can scour the river of macrophyte beds (Rea *et al*. 2003). During the dry season, spring water maintains flow with different water chemistry from the rainfall run-off that constitutes wet season flow. Based upon a number of biophysical observations, Rea *et al*. (2003) and Webster *et al*. (2005) suggest that the net accumulation of plant biomass in the river is limited by nutrient availability. Although dry season flows favour macrophyte and phytoplankton growth, low concentrations of available essential nutrients in the water and in the tissues of *Vallisneria nana*, suggest that growth at this time of year is constrained by the nutrient poor groundwater that keeps the river flowing. Blanch *et al*. (2005) identify river hydrology and chemistry as central to the significant conservation values of the Daly River, including fish and turtle, diversity and abundance.

Across the Top End, irrigated agriculture and the concomitant change in land use have been identified as a threat to the regions' clear water rivers (Erskine *et al*. 2003, Blanch *et al*. 2005). Evidence from southern Australia strongly supports the hypothesis that changes in catchment use will give rise to major water quality problems because of altered river hydrology, increased nutrient loads and decreased base flows. Such changes could give rise to algal blooms that would impact upon important commercial and recreational fisheries, alter the balance between the major primary producers (aquatic macrophytes, benthic and pelagic algae) and decrease the mobility and fecundity of icon species such as freshwater turtles.

This project built on the Daly River studies of Rea et al. (2003) and Webster et al. (2005), expanding the research to several other catchments and rivers in the Top End. An initial desk-top survey identified adjacent catchments that could be used to contrast the impact of different levels of land use on tropical rivers, in terms of algal concentrations and growth. Streams in the modified catchment of Darwin Harbour could be compared with those in the relatively unimpacted catchment of Bynoe Harbour: the rivers in both catchments are <100km in length. A similar difference between the Daly and Roper River catchments was identified as an opportunity to investigate potential impacts on longer and larger rivers. Despite the numerous rivers in both regions, there is very little published literature on algae and nutrient conditions outside the Daly River. Agriculture development and population growth is occurring across the Top End, especially in the Darwin Harbour and Daly River catchments. The Daly River catchment in the lower and upper sections is forecast to experience a significant increase in irrigated agriculture (Erskine *et al*. 2003). Although the middle reaches of the Daly River were the subject of environmental flow studies in 2000-2002, rivers further up the catchment, such as the Katherine, Edith, Cullen, Fergusson, which drain the Arnhem Land Plateau, have not received the same attention: the same applies to the King and Dry River's that drain pastoral lands to the south. The Katherine is of particular significance because it provides the drinking water for the township of Katherine. Rivers such as the Edith and Maude Creek may feel the impact of mining as well as agriculture. As with the Daly, the Roper River drains part of the Arnhem Land Plateau but flows eastwards, instead of westwards, to the Gulf of Carpentaria. The Roper catchment around Mataranka is also experiencing an emerging agricultural industry.

The factors promoting algal blooms are well known. In summary these are: an inoculum, available nutrients and sunlight that influence both species composition and growth rate. A major factor mitigating against the establishment and persistence of blooms in rivers is down stream advection. An algal population can neither establish itself nor persist if its discharge into a down stream receiving water body is greater than that populations intrinsic growth rate. Persistence of algae and blooms are a function of growth rate, discharge and river length. Growth rate determines how quickly a population expands, discharge determines how quickly the population is advected downstream and river length in combination with discharge reflects the length of time available for growth. Intuitively, the faster the growth rate, the slower the discharge and the longer the river, the greater the potential for the establishment and persistence of an algal bloom.

1.1 Aims

1. The first aim of this project was to identify whether or not the target rivers supported a viable inoculum of the major algal groups. The use of the classical microscopic enumeration of phytoplankton was discarded as being impractical for these remote locations and too time consuming. Instead, chlorophyll fluorescence was used as an index of phytoplankton biomass and four excitation

wavelengths were used to distinguish the three major algal groups (blue-greens, greens and browns). The viability of the populations was examined by measuring fluorescent yields (Schrieber 2004) and or the rate of electron transport (ETR). These measurements relied upon the portability and robustness of a Phyto-Pam (Walz GmbH) that permitted the analysis of samples in the field. This technique was used in preference to either the use of oxygen electrodes (Webster et al. 2005) or ^{14}C (Oliver and Ganf 2000) because it was anticipated that the chlorophyll concentrations were likely to be less than 5μg L^{-1} which would have required long incubations (hours v minutes). Metabolic dyes such FDA and Sytox (Brookes *et al*. 2002) also require access to a flow cystometer that was not available.

2. The Phyto-Pam in combination with bioassay experiments also provided a method for assessment of the growth response of algal populations to nutrient enrichment. This was the second aim of the project; to assess potential phytoplankton growth rates, differentiated by algal group, in response to enrichment with inorganic nitrogen and phosphorus. The ubiquitous distribution of phytoplankton led us to the hypothesis that all rivers would contain viable inocula of the three major algal groups. The hypothesis was that the phytoplankton of tropical rivers in the Top End would respond to enrichment because they are adapted to drainage from a nutrient poor, ancient landscape subject to persistent burning. The rule of thumb that rivers with a low conductivity (<50 μS cm^{-1}) are more susceptible to nutrient enrichment than rivers with higher conductivities (>1000 μS cm^{-1}) was also of interest, given this relationship has not been tested for tropical rivers, especially those fed by groundwater.

3. The third aim was to use these growth rates to assess whether or not algal populations were likely to persist in these tropical clear water rivers under a range of discharges and river lengths (Spiers and Gurney 2001). The model simulates the interaction between decreasing flow, as occurs throughout the dry season, and increasing growth rates, under chosen river lengths. The objective was to combine biology with hydrology to derive critical or target levels of the forcing functions that would indicate the potential for the development of algal blooms.

4. The use of the Phyto-Pam permitted an analysis of the response of populations to a range of irradiances in the form of Light Response Curves (LRC, Ralph and Gademann 2005). The use of fluorescent techniques to assess photosynthetic activity in response to a variable light climate is well documented (Ralph and Gademann 2005). However, not so well documented is the fluorescent response of phytoplankton to the removal of a nutrient stress (ie enrichment with limiting nutrients). Based upon measurements of photosynthetic activity, Webster et al. (2005) suggested that the biota of the Daly River was likely to be limited by nutrient availability. The aim here was to investigate whether the parameters defining the pseudo P/I curve responded to the alleviation of a nutrient stress. The following parameters were investigated for their response: a) alpha the

slope of the initial linear portion of the ETR v PAR curve, b) ETR_{max} the maximum rate of electron transport via photosystem II and c) the light intensity that signifies the onset of light saturated electron transport (E_k).

5. A small study was conducted in collaboration with staff of the Environmental Research Institute of the Supervising Scientist with the aim of testing the utility of the Phyto-Pam for rapid assessment of algal response to increasing uranium concentrations. Cultures of the unicellular *Chlorella* were used in these experiments.

This report summarises the main findings of the project and will be followed by the publication of results in international journals.

2. Study sites

The rivers visited and the locations of the sampling sites are given in Table 1 and Figures 1,2 and 3. Land use in the catchments are summarised in Tables 2 and 3.

Table 1. Location of sites sampled. Refer to Gregory's Map of Darwin and Central Australia 4th Edition 2005.

River	Road Reference	River	Road Reference
Darwin Harbour Catchment		**Daly River Catchment**	
Howard R 1	Gunn Point Rd	Cullen R	Stuart Highway
Howard R 2	Hicks Rd	Fergusson R	Stuart Highway
Howard R 3	Hillier Rd	Edith R 1	Stuart Highway
Howard R 4	Pioneer Dr	Edith R 2	Edith Falls Rd
Elizabeth R 1	Gulnare Rd	Katherine R 1	Katherine Gorge
Elizabeth R 2	Stuart Highway	Katherine R 2	Donkey Camp Weir Pool
Blackmore R 1	Cox Peninsula Rd	Katherine R 3	Boat ramp Railway Bdg
Blackmore R 2	Meade Rd	Katherine R 4	Low Level Weir
Darwin R 1	Cox Peninsula Rd	Katherine R 5	Galloping Jacks
Darwin R 2	Reedbeds Rd	King R	Victoria Highway
Darwin R 3	Darwin River Rd	Daly R 1	Oolloo Crossing
Berry Ck	Cox Peninsula Rd	Daly R 2	12km d/s Oolloo Crossing
Bees Creek	Bees Ck Rd	Daly R (1-7)	Sites between Site 1 & 2
Bynoe Harbour Catchment		**Roper River Catchment**	
Charlotte R East	Cox Peninsula Rd	Elsey Ck	Roper Highway
Charlotte R West	Fog Bay Rd	Elsey Ck@ Warloch ponds	18km south Mataranka
Annie R	Fog Bay Rd	Roper R Site 1	Elsey National Park (u/s)
		Roper R Site 2	Elsey National Park (d/s)
		Bitter Springs	Elsey National Park

3. Regional site hydrology and land use

3.1 Darwin and Bynoe Harbour Catchments

The Catchment's of Darwin Harbour and Bynoe Harbour are adjacent, with the former reasonably well developed and the latter relatively undeveloped. As such they provide an opportunity to compare tropical streams that lie within modified and populated areas with streams that lie in near-pristine catchments. In the NT at least, these streams are the most impacted in terms of being in the most densely settled region, yet there is very little, if any, published data on their ecology or hydrology.

The streams that drain these catchments are typical of short first order streams across the Top End. Both catchments are relatively small with low relief. The undulating to flat topography means there are a number of streams often quite close to each other. The distance between the source of these streams and the Harbours is relatively short. The rivers and streams chosen for study are the major systems that discharge to the respective Harbours. Additional small creeks occur, but most of the other 'arms' are tidal.

Most of these systems nearly cease to flow during or toward the end of the annual dry season. Only a few actually do fragment into pools. All appear to have some spring input, although these spring areas have not been documented. It is evident from the just flowing and clear water that groundwater from localised sedimentary aquifers continue to discharge into these watercourses well into the dry season.

The nature of these springs is probably near surface small localised unconfined aquifers that fill during the wet season and then discharge back through stream channels during the dry seasons' low flow. Their contribution to stream flow is small, but significant given they maintain flow well after the wet season storms have ceased. Berry Springs and Howard Springs are two notable exceptions that are the expression of confined bodies of water in the deeper dolomite aquifers. The underlying geology differs between the two catchments despite their close proximity. The ionic character of the water is likely to differ because of the different geology and this may support a different aquatic flora and subsequent food web.

The terrestrial vegetation is similar and comprised of open woodland, with patches of monsoon thickets and dense riparian vegetation adjacent watercourses. A patchwork of wetlands exists in this region, resulting from the intense monsoons coupled with the flat topography where water sits on the surface forming Melaleuca swamps as well as circular wetlands after subsidence of the dolomite beneath and build up of organic matter and clay. Most of these wetlands are not thought to be spring fed, but would play a role in the slow recharge of rainfall and cycling of water back to surface streams. The role of the regions wetlands in the ecology and health of tropical streams is not well understood, although their wide distribution and number suggests it would not be insignificant.

Land use in their sub catchments also separates all these streams across a gradient from highly modified to near pristine. Darwin Harbour Catchment (Table 2) is more developed than the Bynoe Harbour region. Most of the catchments consist of rural blocks from 5-80 acres, with varying degree's of land clearing and development. The region is a patchwork of bush blocks for rural amenity, mango farms, other horticulture (cut flowers, citrus, banana's, vegetables), horses and other domestic animals and farmed crocodiles, chickens and pigs. Reserves, wildlife parks, schools, ovals and golf courses also occur. Given the flat topography, water historically was slow to drain from the land. Diffuse recharge across the broad savannah accounts for most of the groundwater recharge. Today, wide shallow drains criss-cross the region, quickly channelling the water away, providing access and 'dry blocks' for development purposes. The impact of this landscape drainage is thought to be responsible for the Howard River and Howard Springs ceasing to flow in late 2005, a rare event not precipitated by drought conditions.

Table 2. Land use of sampled river in the Darwin Harbour and Bynoe Harbour Catchments.

River	Key characteristics and modification of catchment
Darwin Harbour	
Howard River	Medium –modification: Patchwork of rural lots (1-5 ac), quarries, horticulture, fire, septics, horses, reserves and bush (north side pastoral lease). Spring fed in part. Can cease to flow in some sections.
Bee's Creek	Medium-modification: Mainly small 5 –20ac rural lots (pasture, horses, septics, horticulture, bushland, fire). Ceases to flow.
Elizabeth River	High modification: Mainly 10-80ac lots: Large cleared areas plus areas of bushland. Large mango farms, live cattle depots, chicken farms, fire. Ceases to flow.
Berry Creek	Semi-modified: Mainly rural lots (some pasture, horses, horticulture, bushland, cattle, reserves for wildlife and recreation, fire). Perennial Creek from major spring – dolomite water.
Darwin River	Semi-modified: Mainly 20-80(320) ac rural lots (pasture, horticulture, bushland, horses, fire). Dammed in the headwaters; receives regulated flow 5ML/day.
Blackmore River	Low modification: Mainly 20-80(320) ac rural lots (pasture, horticulture, bushland, horses, fire). Cease to flow only in some sections.
Bynoe Harbour	
Charlotte River	Very low modification: Rural blocks 80-2000 ac: grazing, fire and reserves
Annie River	Very low modification: Rural blocks 80-2000 ac: grazing, fire and reserves

Regional recharge and discharge has also been modified by the increase in bores and groundwater use. In Darwin Harbour Catchment, the number of bores has increased from approx. 3000 to 15,000 (1981-2001) with water use showing parallel increases (D. Hardy pers. comm.). In the Howard River Catchment, additional and significant groundwater use occurs for town water from the major borefields into McMinns aquifer and the adjacent Howard East Borefield in the vicinity of where Gunn Point Rd crosses the Howard River. Development and use of this Borefield for Darwin's water supply, will increase markedly in stages over the next decade.

Bynoe Harbour Catchment (Table 2) on the other hand has not been sub-divided to the same extent, although some of the properties are starting to be divided into lots in the 100's of acres. The catchments of the Annie and the Charlotte Rivers are largely uncleared. Both catchments experience considerable burning from the late wet season to the early wet season (April-November). For example, the majority of Darwin River Dam Catchment is burnt each year in uncontrolled fires. The effects of fire on the ecology of these streams is likely to impact on the major factors that underpin algal growth.

3.2 Daly and Roper River Catchments

The Cullen, Edith, Fergusson and Katherine Rivers (Table 2) flow into the upper middle reaches of the Daly River. These are the major tributaries on the east side of the river. Comparable streams on the other side are extremely difficult to access due to limited and unsealed roads and private property. Similarly, the major tributaries to the North of the Upper Roper are difficult to access. On the south side of the Roper River, the Roper Highway intersects Elsey Creek and Salt Creek.

Both river systems are underlain by major aquifer systems that keep these rivers flowing year round. The Tindall Aquifer feeds the headwaters of both systems, while the upper Roper is also fed in part by Mataranka and Bitter Springs that tap deeper aquifers.

Although regions of both these Rivers and their tributaries are spring fed at some stage, there are many systems which are not perennial and may receive only small spring flows or which cease to flow. The selected river systems also provide a wide range of tributary types in the upper reaches of both these major river systems (Table 2). Some cease to flow, while others are perennial.

As with the comparison between the catchments of Darwin Harbour (modified) and Bynoe Harbour (unmodified), the catchments of the Daly (Table 3) are considered semi-modified with about 10% cleared. Most of this clearing is on the eastern side of the river. On the other hand, the adjacent Roper River Catchment is considered unmodified, with only minimal recent clearing for horticulture in the Mataranka district. Cattle grazing dominates, and as with all areas of the Top End and Northern Australia, fire is ubiquitous.

Table 3. Land use of sampled river systems in the Daly and Roper River Catchments.

River	Key characteristics and modification of catchment
Daly River Catchment	
Cullen River	Medium modification: Pastoral properties and horses. Extensive grazing and fire. Ephemeral river - ceases to flow in early dry season above Hwy bridge; input from Copperfield Ck below bridge maintains low flow.
Fergusson River	Low modification: Pastoral and other leases with low grazing pressure and annual fire. Ceases to flow mid dry season.
Edith River	Semi modification Pastoral and other leases with low grazing pressure and annual fire. Mt Todd Gold Mine and associated mine runoff (Cu). Some horticulture at Edith Farms. Almost ceases to flow upstream Tindall aquifer input and Edith Farms.
K1atherine River	Semi-modified to medium modification: Katherine Gorge – catchment all reserve and Indigenous owned and managed. 15 km u/s and d/s Katherine - Mainly rural lots (20-320 ac) pasture, horses, mangoes, citrus, peanuts, bushland, parks and gardens, accommodation, tourism, fire. Perennial river with major spring inflow in specific reaches and from different aquifers. Donkey Camp Weir regulates the river upstream Katherine causing river to almost cease to flow in the dry season downstream until Tindall aquifer input.
Roper River Catchment	
Bitter Springs	Low modification: Aboriginal Land Trust covers most of Catchment, fire common.
Elsey Creek @ Roper Hwy	Low modification: Light grazing and fire.
Warloch Ponds @ Elsey Creek	Low modification: Light grazing and fire.
Roper River @ Elsey Nat. Park	Low modification: Pastoral land, grazing Aboriginal Land, horticulture, fire.

4. Methods

Sample collection

Water and phytoplankton were collected in acid washed containers. To avoid errors associated with small-scale variation three independent 1 litre samples were collected at each site and combined. This was repeated three times to give three independent composite samples. Conductivity was measured and corrected for temperature on the composite samples. Samples were stored in the dark in an ice-cooled container. Measurements using the Phyto-pam were conducted as soon as possible after sample collection, usually within 2-3 hours but on occasions this was extended to overnight.

4.1 Phyto-Pam measurements

Chlorophyll calibration

Chlorophyll calibration was undertaken using concentrates of the natural plankton community extracted in 90% methanol using the equation of Talling and Driver (1963). Additional calibrations used unicellular algal cultures of *Chlorella* and *Microcystis* grown at 28°C at a light intensity of between 75 and 105 μmol m^{-2} s^{-1}. Neither of these calibrations procedures was optimal but overcame the difficulties of sampling rivers with unknown species compositions. The majority of the chlorophyll data reported are based upon calibrations obtained from the natural phytoplankton that occurred in the rivers.

Chlorophyll concentrations

Chlorophyll concentrations are reported for the main algal groups, blue-green, green and brown as determined by the fluorescence readings at four wavelengths (470, 520, 645 and 665nm).

Quantum Yield

Yields for phytoplankton samples were determined in triplicate using the Phyto-ED attachment of the Phyto-Pam. Samples were continuously stirred and yields were determined on dark-adapted samples (minimum dark adaptation time 30 min) according to the procedures outlined in Oliver et al. (2003) and Kolber and Falkowski (1993). Samples were filtered through 0.45μm filters to obtain background fluorescence that was estimated via the Zoff adjustment at gains equivalent to the fluorescence obtained from the unfiltered sample. The duration of the saturation pulses used were optimized for F_0 and F_{max} via a series of trials. Saturation pulses of 2600 μmol quanta m^{-2} s^{-1} were used. Yields were determined at temperatures that approximated the river water temperatures.

Electron Transport Activity

Electron transport activity (ETR) was determined on freshly collected dark-adapted samples. It was determined as Yield x PAR x 0.5 x 0.84 (μmol electrons m^{-2} s^{-1}). No attempt was made to correct for variations in the absorption cross section. It was assumed that the factor of 0.84 found for higher plants was applicable to phytoplankton and aquatic macrophytes, although it is recognised that due to their more translucent nature, it is likely to be less.

Light response curves were generated from actinic light intensities of 4, 8,16, 65, 96, 135, 174, 247, 320, 395, 537, 681, 752 and 874 μmol m^{-2} s^{-1}. Internal light calibration was determined using a spherical micro quantum sensor using the routine procedure outlined in the Phyto-Pam handbook. Phytoplankton were exposed for 20s at each irradiance. These light response curves permitted calculation of the characteristics of the ETR / light curve: ETR_{max}, E_k and alpha. These were used to compare and contrast the activity of material from different locations with and without nutrient enrichment.

Nutrient enrichment experiments

Nutrient enrichment experiments were carried out in the laboratory in growth cabinets at 28^{0}C and 85 μmols m^{-2} s^{-1}. Clear plastic culture vessels were filled with 50ml of the natural river water. Four acted as controls, 4 had nitrogen (KNO_3) added, 4 were enriched with phosphorus (KH_2PO4) and four had both N and P added. The final concentrations used were 80μg N and 20μg P L^{-1}. These experiments ran for between 3 to 6 days. The following measurements were determined: total chlorophyll concentration; chlorophyll associated with the major algal groups; electron transport activity; and the parameters defining the light response curve. Three or four replicate measurements were taken on the initial samples. Similar measurements were made on the controls and nutrient enriched samples at the start and finish of the experiments, although in some instances a complete set of measurements was taken at daily intervals. Growth rates were calculated from the chlorophyll data and used to estimate the growth rates of the algal groups. Growth rates were assumed to follow the exponential equation $N_t = N_o e^{\mu t}$ where N_0 is the chlorophyll concentration at time zero and N_t the final chlorophyll concentration at time (t), μ is the specific growth rate (day^{-1}).

Photo-chemical and non-photochemical quenching

These stress related characteristics were calculated as defined by Oliver *et al.* 2003 and Kolber and Falkowski (1993).

Uranium toxicity

Uni-algal cultures of Chlorella were incubated in 50mL tissue culture flasks on a 12:12 hr light dark regime at 28^0C at a light intensity of ca. 100 μmol m^{-2} s^{-1}. Uranium sulphate was added to four replicate flasks at final concentrations of 0, 5, 10, 20, 40, 80 and 160 μg L^{-1}. The bioassay experiments were run for 72 hr. Cell counts and light response curves were measured on dark adapted samples at 0, 24, 48 and 72 hr. Regressions were made using the statistical Excel package after appropriate transformation. Light response curves were fitted using the equation of Ralph and Gademann (2005).

Analysis

Means and standard errors were calculated on three to four replicates after testing for homogeneity of variances (Microsoft Excel Stats Pack 2004). Differences between measurements were assessed by one way analysis of variance.

5. Results

5.1 Total Chlorophyll and its distribution across blue green, green and brown algae

Darwin and Bynoe Harbour tributaries

Conductivity of these rivers was < 75μS cm^{-1} throughout February and April (Table 4). By July, conductivities in the Elizabeth and Howard Rivers had risen to 185 and 332 μS cm^{-1}, respectively, but the other rivers remained below 55 μS cm^{-1}. The exception was the Blackmore where the conductivity had risen to 33,900 μS cm^{-1} a conductivity that indicated a salt water intrusion (Table 4).

The shallow fast flowing nature of these river during the transition from the wet to dry season suggests that there is little discernable difference in chlorophyll concentrations between longitudinal sites. For example, at several sites in the Howard River throughout March and April the phytoplankton community was dominated by brown algae and total chlorophyll concentrations did not exceed 10 $\mu g\ L^{-1}$. There was no significant difference between the four sites ($p<0.001$ Fig 3). Chlorophyll fell to < 2 $\mu g\ L^{-1}$ in mid April, after a local rain event, but recovered quickly and by April 20 the chlorophyll had risen to 11.4 $\mu g\ L^{-1}$ ($\pm$ 0.5), which was not significantly different from the results obtained earlier.

From February to August 2005 the chlorophyll concentrations in the rivers of the Bynoe and Darwin Harbour catchments ranged from <2 to > 35 $\mu g\ L^{-1}$ (Table 5, Fig 4). These algal communities were dominated by brown algae (diatoms) although in most cases there were small communities of blue greens and traces of green algae (Fig 4).

Total chlorophyll in the East Charlotte River was 10 $\mu g\ L^{-1}$ and there were detectable concentrations of all the major groups. The other rivers had average chlorophyll concentration of < 10 $\mu g\ L^{-1}$ and in all cases populations of blue green algae were detected (Fig 4).

The Blackmore River had similar chlorophyll concentrations at the up and downstream sites during March (9.5 and 8.1 $\mu g\ L^{-1}$, respectively.Table 5) but the conductivity of the upstream site was significantly lower than the downstream (18.8 v 78.7$\mu S\ cm^{-1}$). As river flow in July fell the upstream site had a chlorophyll concentration of 8.3 $\mu g\ L^{-1}$ and a conductivity of 28$\mu S\ cm^{-1}$ whereas the conductivity of the down stream site had a chlorophyll concentration of 35$\mu g\ L^{-1}$ and a conductivity of 33,900 $\mu S\ cm^{-1}$ (Fig 4). The algal community was dominated by brown algae, greens were not recorded but there was a significant population of blue green algae.

A similar high conductivity and chlorophyll concentration was observed in the lower reaches of the Howard River where it discharges into Shoal Bay. This indicates a discontinuity in tropical rivers where tidal upstream flow meets discharge, effectively decreasing river length and creating a freshwater pool that abuts sea water. Chlorophyll concentrations in the upper Howard (in the vicinity of Howard Springs) in early March were ca. 10$\mu g\ L^{-1}$ whereas in the previous week in late February chlorophyll concentrations in the lower Howard were between 100 and 200 $\mu g\ L^{-1}$. The algal composition of the river water in the upper catchment was dominated by brown algae whereas in the lower section it was dominated by dinoflagellates and blue green algae.

Daly and Roper Rivers and tributaries

Compared with the Bynoe and Darwin Harbour Rivers in April 2005 the conductivity of the Roper River and Elsey Creek was an order of magnitude higher (Table 4). Conductivity of the Katherine River progressively increased downstream from the Katherine Gorge (21 $\mu S\ cm^{-1}$) to167 $\mu S\ cm^{-1}$ at Galloping Jacks (Table 4) related to discharge from the tindall limestone aquifer between these sites. This increased ionic concentration was not correlated with the increase in chlorophyll concentration across the five sites on the Katherine River (6 and 12 $\mu g\ L^{-1}$, Fig 5). The King River had average chlorophyll of 7 and the Edith River only 2 $\mu g\ L^{-1}$.

Chlorophyll in the Roper River had a mean of 10 $\mu g\ L^{-1}$, and in Elsey Creek < 5 $\mu g\ L^{-1}$. Warloch Ponds in upper Elsey Creek had begun to dry and the chlorophyll was variable and ranged between 2 and 18 $\mu g\ L^{-1}$ (Fig 5). Blue green, greens and brown algae were present in all the rivers and sites (Fig 5) at concentrations of < 5 $\mu g\ L^{-1}$ and often less than 3 $\mu g\ L^{-1}$.

Chlorophyll concentration at seven sites between Daly River Site 1 and Site 2 (Table 1; Aug 2) was never more than 1.5 $\mu g\ L^{-1}$. As in the other rivers the three major groups of phytoplankton were present but at very low concentrations (Fig 6).

The general conclusion drawn from these and additional data (Table 5) is that the rivers sampled all had relatively low chlorophyll concentrations. The exceptions are where tidal forces do not permit the unrestricted discharge of freshwater into the sea: i.e. the Blackmore River during July when there was a marine water intrusion and the lower Howard River during February / March.

The rivers of the Bynoe and Darwin Harbour catchments were dominated by brown algae but the other algal groups were present. Rivers associated with the Roper and Daly Rivers generally had the lowest chlorophyll concentrations, especially the Daly River during August when the river was approaching base flow. Nevertheless, all three algal groups were present at nearly all sample sites. Multiple sample sites within river systems did not indicate significant variation between sites, except as mentioned above. For example, seven samples across a 12 km reach of the Daly River all had total chlorophyll concentrations of about 1$\mu g\ L^{-1}$ and there was no significant difference in the composition of the seston between sites.

5.2 Algal response to nutrient enrichment

A frequent response to the development of catchment areas is a deterioration of water quality. When this is combined with flow restrictions algal blooms may occur and cause environmental problems. The data on the composition of the phytoplankton communities suggest there is an inoculum that could give rise to algal blooms. However, the presence of an inoculum does not indicate that it is viable and or how it will respond to nutrient enrichment both in terms of total chlorophyll and by algal group. To test the viability and the response of the three algal groups to nutrient enrichment a series of bioassay experiments were conducted. These are summarised below and a statistical analysis is given in Table 6.

Howard (March / April)

The initial enrichment experiment (March 7) was designed to test whether the simultaneous addition of N and P to river water from the upper catchment stimulated algal growth and whether it was possible to detect a differential response between algal groups. Water was sampled from sites 1 and 4 (Table 1). No difference was detected between the control and initial samples (Table 6, Fig 7) indicating that there was insufficient ambient nutrient to support further algal growth in the original water sample. However, the addition of N and P resulted in chlorophyll concentrations in excess of 50 μg L^{-1}. There were also substantial population of blue-greens, greens and brown algae (Fig 7a).

The enrichment experiment (March / April Fig 7b) was designed to test which of nitrogen or phosphorus was limiting population growth. The results showed that the ambient nutrient availability was not sufficient to support growth and there was no response to the addition of nitrogen. Phosphorus addition stimulated growth, mainly due to an increase in the chlorophyll associated with the brown algae. With the addition of N and P, substantial populations of the three algal groups developed.

These data suggest that the current land use in the upper catchment of the Howard River during the transition from the wet to the dry season in March and April is not adversely influencing the nutrient status of the River. Nevertheless, the addition of phosphorus did stimulate algal growth and the development of a significant community of blue green algae. This suggests that there was sufficient biologically available nitrogen to support a total chlorophyll concentration of 30-40μg L^{-1}. In other words, the Howard River at this time is susceptible to phosphorus enrichment and the development of algal blooms.

Elizabeth (March 2005)

There was no evidence that ambient nutrient availability could support further algal growth (Fig 8b, Table 6). There was no response to the addition of phosphorus and the addition of nitrogen only marginally stimulated algal growth above the control. These treatments were dominated by brown algae but green algae were undetectable. The addition of both N and P caused the total chlorophyll to rise to >40μg L^{-1}. Although brown algae still dominated the algal community both green and blue green algae reached concentrations of 9 –11 μg L^{-1}.

At this time of year (late wet season) there was no evidence to suggest that activities within the catchment of the Elizabeth River upstream of the sampling site (Table 1) were unduly influencing its nutrient status. Unlike the Howard River the addition of both nitrogen and phosphorus was needed to stimulate algal growth. This indicates that there was little or no unused biologically available nitrogen and or phosphorus.

Blackmore (March 2005)

The initial total chlorophyll concentration did not differ from the control indicating that the ambient nutrient concentration was unable to support further algal growth (Fig 8a Table 6). Comparisons of the control with addition of nutrients suggest that the algal community was P-limited. The blue greens and browns were P-limited but the greens were not detected except when both N and P were added and the total chlorophyll concentration increased to between 60-70 μg L^{-1} made up of substantial populations of all algal groups. The concentration of blue greens was between 16 and 19 μg L^{-1}.

The response of the Blackmore is similar to the Howard. Phosphorus is indicated as the limiting nutrient. The growth response to phosphorus suggests that there is a pool of biologically available nitrogen and thus the river is susceptible to phosphorus enrichment and potential algal blooms.

Katherine (April 2005)

Nutrient enrichment bioassays were carried out on samples from the Katherine Gorge and from Central Katherine boat ramp (Table 1). Comparison of the initial and control treatments for Gorge water samples showed that the total chlorophyll concentrations in the controls were significantly above those in the initial (Fig 9, Table 6). This was mainly due to the response of green algae and indicates that the ambient nutrient concentrations were sufficient to support growth. Comparisons of the control with the other treatments show that the total chlorophyll responded to the addition of nitrogen but not to phosphorus. The addition of both nitrogen and phosphorus produced a contrary result because the increase in total chlorophyll concentration was substantially less that the response associated with the addition of phosphorus alone and not significantly different from the control (Fig. 9, Table 6). The blue green and the brown algae responded to the addition of nitrogen but not to either phosphorus or to the combined addition of N and P.

Comparisons of the controls with the initial samples of water from the river in central Katherine showed that total, blue green and green chlorophyll in the control sample were significantly above the initials. However, no response from the brown algae was detected (Fig. 9, Table 6). This suggests that the ambient nutrient concentrations were sufficient to stimulate the growth of greens and blue greens, but not brown algae.

The addition of nitrogen stimulated the growth of total chlorophyll via the response of the blue green and brown algae. The addition of phosphorus caused total chlorophyll to substantially increase above the control and this was due to the positive response of the brown algae. It is unclear why the total chlorophyll was less in the N and P treatment than when these nutrients were added singularly.

Total chlorophyll concentration was substantially higher for samples from central Katherine than for water sampled from the Gorge. The Gorge samples responded to nitrogen addition but not to phosphorus, whereas, both nitrogen and phosphorus were implicated as the limiting nutrient in water from central Katherine, but for different algal groups. These results suggest that nutrient addition to the river in central Katherine would result in a significant algal bloom dominated by diatoms but there is no evidence for high concentrations of blue green algae.

Daly (May / June 2005)

The response of the algal community from the Daly was followed at two-day intervals (Fig 10) but the statistics (Table 6) refer to differences between the initial and final values. The community responded to the addition of phosphorus ($p < 0.001$) within 48 hr, mainly through the growth of chlorophyll associated with the blue greens and the greens. Comparisons between the initial and final control chlorophylls (day 6) showed that the control chlorophyll concentrations were substantially above the initials for all algal groups. Although total chlorophyll did not respond to the addition of nitrogen, the green algae did respond, but not the other two algal groups. Total chlorophyll via the green and blue green algae responded to the addition of phosphorus, but there was no response by brown algae to phosphorus addition.

The algal community did not respond as strongly to the addition of N and P compared with when one or other of the nutrients was added alone. In contrast to the Katherine River the Daly River had much lower chlorophyll concentrations but the response of the algal community from both rivers to the combined addition of N and P was similar. There is no obvious explanation of why both rivers should respond in this manner.

Charlotte (July 2005)

A comparison of total chlorophyll for the initial and control samples showed that there were insufficient ambient nutrients to allow further growth (Table 6). This result is inconsistent with the statistical analysis that suggested that the three algal groups had higher concentrations in the controls compared with the initials (Table 6). It was only with the addition of both N and P that chlorophyll concentration showed a significant increase above the controls (Fig. 11). Although the data in Fig. 10 suggests that the community was responding to the addition of phosphorus, the variability between replicates was too great to identify a positive response. Substantial populations of both blue green and green algae did develop with the addition of N and P (Fig.11).

Darwin (July 2005)

The data for total chlorophyll suggests that the ambient nutrient concentrations were unable to support growth of the initial samples (Table 6). However, the statistical analysis suggested that all three algal groups showed significant increases (Table 6) although these were not reflected in the total chlorophyll. There were no positive responses to the addition of either N or P by any of the algal groups. Only the combined addition of N and P caused a significant increase in the total chlorophyll concentration (Fig 11) via positive responses from all three algal groups. That the blue green algal concentrations were >30μg L^{-1} suggests that Darwin River may be susceptible to blue green algal blooms. Similarly, final total chlorophyll concentrations of >150μg L^{-1} are likely to cause significant diel fluctuations in oxygen concentrations below the Darwin River dam that could be detrimental to fish and other biota.

Elizabeth (July 2005)

There was an adequate supply of available nutrients to significantly increase the chlorophyll concentration in the controls above the initials (Table 6). The addition of nitrogen stimulated the growth of the three algal groups but the addition of phosphorus produced no significant response (Fig.12). Very high chlorophyll concentrations (total >200 μg L^{-1}) resulted from the addition of both N and P with a significant proportion of the total chlorophyll attributed to the blue green algae.

The results of this experiment contrast sharply with those obtained earlier (March). Biologically available nutrients had accumulated in the river water and permitted chlorophyll in the controls to increase above the initials. In July, nitrogen was identified as the limiting nutrient for all three algal groups whereas in March it did not stimulate the growth of any of the algal groups. The final concentrations of total chlorophyll were three times greater in July compared with March. Thus the potential for algal blooms had increased. Changes in chlorophyll and algal populations spatially and temporally are well documented for rivers. In the wet dry tropics, there may be a relationship between the predictable flow regime (high wet season flows, transitional recessional flows and dry season base flows) and algal growth and nutrient availability.

Howard (July 2005)

Available nutrients were not sufficient to increase the chlorophyll concentrations of the controls above the initials (Table 6), while the control concentration of brown algae decreased below its initial value. The addition of nitrogen produced a positive growth response in all three algal groups with the total chlorophyll reaching >50 $\mu g\ L^{-1}$ (Fig. 13). Unlike the samples taken in March and April (Fig. 7) there was no response to the addition of phosphorus but the addition of both nutrients resulted in very high (>200 $\mu g\ L^{-1}$) total chlorophyll that was dominated by brown and blue green algae (>50 $\mu g\ L^{-1}$).

Daly (Aug 2005)

The enrichment experiments on water from the two sites on the Daly River (Table 1) produced similar results and the results are combined in Fig.14. The statistical analyses (Table 6) suggested that there were sufficient available nutrients to increase the control chlorophyll above the initials; however, this should be viewed in the context of the very low initial concentrations (<0.3 $\mu g\ L^{-1}$) that are at the limit of detection. The addition of nitrogen did not stimulate algal growth above the controls but the addition of phosphorus did. The addition of both nutrients resulted in total chlorophyll concentrations of >50 $\mu g\ L^{-1}$ that were dominated by the chlorophyll associated with blue green algae.

Katherine (Aug 2005)

Site 1 water samples were from Donkey Camp Weir pool (Katherine water supply) and Site 2 samples were from the boat ramp under the Railway Bridge in central Katherine. Both nutrient enrichment experiments produced similar responses (Table 6, Fig. 15). There were sufficient available nutrients to support an increase in the controls above the initials. The addition of phosphorus stimulated the growth of the three algal groups but nitrogen alone did not. The addition of both nutrients stimulated growth and total chlorophyll concentrations reached 60 $\mu g\ L^{-1}$ at site 2 but only 40$\mu g\ L^{-1}$ at site 1. All algal groups had higher concentrations at site 2 (central Katherine boat ramp) compared with site 1 (Donkey Camp Wier Pool). Addition of both nutrients gave a total chlorophyll concentration of >60 $\mu g\ L^{-1}$ associated with substantial and equivalent populations of blue green, green and brown algae.

Roper (August 2005)

The two sites sampled on the Roper River (Table 1) produced similar results (Table 6, Fig.16). There was a sufficient concentration of ambient nutrients to support the growth of the initial samples. The addition of nitrogen did not stimulate the growth of any of the three algal groups whereas the addition of phosphorus did (Fig. 16). The addition of N and P resulted in high concentrations of total chlorophyll: 100 $\mu g\ L^{-1}$ at site 1 and 60$\mu g\ L^{-1}$ at site 2. The final chlorophyll concentrations associated with the three algal groups were significantly greater at site 1 compared with site 2.

5.3 Growth Rates and River Discharge Rates

Growth rates, calculated as the difference between the initial and final chlorophyll concentrations (N and P treatment), for the three algal groups and the total chlorophyll for the major rivers sampled during the transition from the wet to the dry season (Table 7) show that maximum specific growth rates can exceed 1 day^{-1}. Individual algal groups have growth rates that vary from 0.1 to >1.0 day^{-1}.

Whether or not an algal bloom will develop is not only dependent upon growth enhancing factors (nutrient availability, light and temperature) but also upon the losses that a population is subject to. The persistence and establishment of riverine populations is a function of the growth rate (r), downstream advection (V_r) and the length of the river (L) (Spiers and Gurney 2001). The factor ε indicates the degree of vertical discontinuity (thermal stratification) and here is set at 1, indicating the rivers are uniformly mixed, as Webster et al. (2005) found for the Daly River.

The critical value of the term $\varepsilon*V_r/L*r$, that if exceeded will not permit the persistence of a population, is 0.434. The influence of these three factors illustrates that as the river length decreases, so the potential for persistent populations increases (Fig 18, 19, 20). Similarly, as the growth rate increases at a standard discharge rate the potential for an algal bloom increases. For combinations of river length, discharge and growth rate, washout will occur at values above the critical value (ie downstream losses exceed growth rate). The potential for an algal community to persist and therefore become established increases as the critical values falls below 0.434 and growth rates exceed the rate of washout. These conditions are exacerbated by increasing river length, as illustrated in Figures 17, 18 and 19.

5.4 Algal growth response to light and nutrients

During the sampling period the rivers were clear and light penetrated to the sediments. Rapid light curves (RLC; Ralph and Gademann 2005) were used to investigate the response of algal communities to combinations of irradiance and nutrient enrichment. Of particular interest was whether or not RLC were influenced by nutrient enrichment and hence could detect nutrient stress.

Total chlorophyll showed a significant response to the addition of N and P in July 2005 for samples from the Elizabeth River (Fig. 12a). At the same time as the chlorophyll measurements were made the dark adapted yields of the algal community were measured and converted to rates of electron transport (Fig.12b) and the parameters defining these curves (ETR_{max}, α and E_k) estimated. The ETR_{max} of the N and P enriched samples was 41 μmol electrons m^{-2} s^{-1} whereas that for the initials was 21 and for the control 28μmol electrons m^{-2} s^{-1}. Furthermore, the N and P treatment showed no evidence of photo-inhibition at the higher irradiances whereas the other treatments did. The dark adapted initial samples had yields that fell below 0.1 at moderate irradiances and the yields became progressively more variable and unreliable. Hence the ETR of the initial samples are only reported for irradiances up to 210 μmol m^{-2} s^{-1} (Fig. 12b).

Additional evidence comes from the nutrient enrichment experiment conducted on the Howard during March (Fig. 20). The ETR_{max} for the enriched algal community was 55μmol electrons m^{-2} s^{-1} compared with the control value of 22μmol electrons m^{-2} s^{-1}. The corresponding alpha and E_k values were 0.288 and 195μmol m^{-2} s^{-1} for the enriched community, and 0.178 and 124μmol m^{-2} s^{-1} for the control community.

The dark-adapted yield response of the three algal groups from the Katherine River (August 2005. Fig. 21) differed in magnitude, although the shape of the yield v. irradiance curves is similar (exponential decline as irradiance increases). Comparisons between the controls and the nutrient enriched (N and P) samples show that the maximum dark-adapted yields increase with enrichment and higher yields are maintained across a wider spectrum of irradiances.

Although the results given above are clear cut examples of the response of algal communities and individual algal groups to nutrient enrichment the response was not always obvious. The reasons for this are unknown and would profit from additional research as the use of RLC and yields may prove rapid and reliable indicators of the growth potential of phytoplankton communities: i.e. whether they were nutrient stressed (senescent cells) or not (young healthy cells).

5.5 Response of Chlorella to uranium

Chlorella growth rates estimated via cell counts and changes in chlorophyll concentration via the Phyto-Pam (Fig. 22) showed a similar response although the PAM results tended to give lower growth rates at the higher uranium concentrations. A possible explanation is that microscopy could not distinguish between live and dead cells and thus over-estimated the number of cells and hence the growth rate.

The electron transport rate (Fig. 23) clearly illustrates the influence of increasing uranium toxicity on the maximum rate of electron transport. The lower uranium concentration and the control had maximum rates up to six times faster than the rates for the samples exposed to 160μg L^{-1} of uranium. The parameters defining the ETR irradiance curve suggest (ETR_{max}, alpha, E_k) that the critical uranium concentration was about 40 μg L^{-1} (Fig. 24); above this level the growth rate of *Chlorella* declined.

6. Discussion

6.1 Chlorophyll as an index of river health

The draft Queensland Water Quality guidelines (May 2005) and the Australian and New Zealand guidelines (Table 8) suggest acceptable average chlorophyll concentrations for various freshwaters, hazard concentrations for blue green algae and classify water bodies from oligotrophic to hypereutrophic. On the basis of these guidelines the only rivers that could be classified as oligotrophic are the Annie, Daly and Elsey (Table 9). The Blackmore stands out as supereutrophic and the other rivers as either mesoeutrophic or eutrophic (Table 9).

Although chlorophyll is a useful indicator of the trophic status of a water body and has been used widely since the introduction of the nutrient loading models pioneered by authors such as Sakomoto, Vollenweider, Dillon and Rigler, and Cullen, it is a blunt instrument to tackle a complex question. The simple application of a specific chlorophyll concentration does not take into account that some types of chlorophyll are more desirable than others. For example, a water authority would not be too concerned with a chlorophyll concentration of 20μg L^{-1} if it was composed entirely of diatoms or green algae. However, the same chlorophyll concentration that was composed entirely of blue green algae would cause concern.

Technology has provided a tool that distinguishes between the major groups of algae. There are uncertainties and problems such as encountered here. For example, this study explored some of the more remote rivers of the Northern Territory and there was no background information about the likely composition of the algal community and hence chlorophyll calibration of the Phyto-Pam was problematic. Nevertheless, it did demonstrate that the rivers of the Darwin and Bynoe harbours were dominated by brown algae and although, the chlorophyll concentrations were consistently about 10 μg L^{-1} this did not pose a water quality problem. The Roper and Daly Rivers and their tributaries had relatively low total chlorophyll concentrations but of more significance is that there were only traces of blue green algae and hence the potential hazard associated with toxic blooms is low.

6.2 Predicting potential river health using chlorophyll

Measurements of chlorophyll, even when partitioned between the major algal groups, only indicates current trophic state. It does not explore the potential for algal blooms. One way of assessing potential is to artificially enrich water samples and measure the response. The bioassay protocol used in this study may be open to criticism; the samples were incubated under standard conditions in the laboratory, and the replenishment of nutrients via fluxes between sediments and open water, as well as between biota, were not considered. Despite these valid criticisms the results do provide an overview of the potential affects of nutrient enrichment that may arise if there are major changes in the land use of the catchments (ie irrigated agriculture that results in reduced flow and increase nutrient run-off). For example, enrichment of rivers from the Bynoe and Darwin regions in March with both nitrogen and phosphorus resulted in total chlorophyll concentrations in excess of 50μg L^{-1}. For the Darwin, Howard and Elizabeth Rivers in July total chlorophyll concentrations >100μg L^{-1}. These chlorophyll concentrations are unacceptable even if no blue green algae are present because night time respiration is likely to significantly lower the oxygen concentration of the river water resulting in adverse effects to fish and other biota.

The response of the Roper and Daly river phytoplankton to enrichment was less pronounced than observed for the Bynoe and Darwin rivers. Nevertheless, the potential for unacceptable chlorophyll concentrations in both the Katherine and Ropers Rivers is substantial. Even the Daly that had low ambient concentrations of chlorophyll has a potential to support significant algal populations if enrichment occurred.

Based upon the natural (unenriched) chlorophyll associated with blue-green algae (i.e. the inoculum), the only river that has a medium blue green algae hazard potential is the Blackmore. The others have low potentials. However, if the hazard potential is based upon the response of the enriched samples, the Daly (June) and the Katherine (April) are the only rivers that have a low potential, while the Blackmore, Elizabeth (July) and Howard (July) Rivers have a high potential hazard. The other rivers have a medium potential hazard for developing blue-green algal blooms (Table 9).

6.3 Biologically available N and P

Much of the information gathered during this project was based upon estimates of chlorophyll. The amount of available nitrogen and phosphorus that could give rise to these chlorophyll concentrations can be calculated from the stoichiometric relationships between chlorophyll, nitrogen and phosphorus as reviewed by Reynolds and Maberly (2002). They suggest that 1μg of chlorophyll has a requirement for 9μg of biological available nitrogen (BAN) and 1.2μg of biologically available phosphorus (BAP). The nutrient enrichment experiments on the Howard and Charlotte Rivers (July 2005) showed that the Howard was nitrogen limited and the Charlotte phosphorus limited. The addition of the limiting nutrient increased the chlorophyll concentration above the control. Calculations suggest that there was 36 μg L^{-1} of BAP in the Howard and 135μg L^{-1} BAN in the Charlotte. Similar calculations for the Katherine (August 2005) and the Roper (August 2005) indicated that there was 20μg L^{-1} BAP in the Katherine and 630μg L^{-1} BAN in the Roper. These suggested values for BAN and BAP were not verified by chemical analysis and are based upon the assumed stoichiometric relationships of Reynolds and Maberly (2002). They indicate that there are substantial quantities of BAN and BAP at various times of the year and it only requires the addition of the limiting nutrient to release the phytoplankton from nutrient limited growth. The stoichiometric relationships between chlorophyll, nitrogen and phosphorus in these tropical rivers by tissue nutrient analysis would be a profitable extension of the current work.

6.4 Target nutrient concentrations

The concentrations of inorganic nitrogen and phosphorus added in the bioassay experiments were 80 and 20μg L^{-1}, respectively. These nutrient concentration were sufficient to allow chlorophyll concentrations of > 50μg L^{-1} to develop within six days. The Australian and New Zealand water quality Guidelines (Table 8) suggest that chlorophyll concentration of >50μg L^{-1} indicate a supereutrophic water body. Therefore at the very minimum concentrations of inorganic nitrogen and phosphorus should never be allowed to reach these levels.

Oligotrophic and mesoeutrophic waters have a chlorophyll concentration of 2 - 5μg L^{-1}. If the stoichiometric relationships of Reynolds and Maberly (2002) are applied this would suggest that to maintain chlorophyll levels of < 5μg L^{-1}in these rivers inorganic nitrogen levels should not be > 45μg L^{-1} and phosphorus not > 6μg L^{-1}. However, many of the rivers in the Bynoe and Darwin catchments had chlorophyll concentrations of 10μg L^{-1}. If 10μg L^{-1} is set as the upper chlorophyll level this would suggest that nitrogen should not be allowed to rise above 90μg L^{-1} and inorganic phosphorus above 12μg L^{-1}.

Although target nutrient levels are often given as ambient concentrations of oxidised nitrogen (NO_x) and filterable reactive phosphorus (FRP) these maybe misleading. A continual supply of inorganic nitrogen and phosphorus of 90 and 12μg L^{-1} may well lead to an algal bloom. Therefore, it would be more realistic to set target concentrations for total particulate nitrogen and total particulate phosphorus of 90 and 12μg L^{-1}.

6.5 Light as limiting factors for algal blooms

The light response curves and the dark-adapted maximum quantum yields of the planktonic communities from the various rivers suggest that maximum yields occur at light intensities of between 4-8 μmol m^{-2} s^{-1} and the maximum rate of electron transport at irradiances of between 700 and 800 μmol m^{-2} s^{-1}. All the rivers sampled were clear and light reached the sediments. Therefore, under the current conditions it is unlikely that light would inhibit primary productivity. For light to become limiting turbidity levels caused by an increase in sediment loads due to erosion caused by land clearance would have to rise substantially.

For an average river depth of 2m nephelometric turbidity would have to rise to between 100 NTU's which would give an down-welling light extinction coefficient of 4 m^{-1} and a light intensity at 2m of close to zero with an incident irradiance of 1500 μmol m^{-2} s^{-1}. Extinction coefficients of 1, 2 and 3 m^{-1} would give light intensities at 2m of 4, 27 and 203 μmol m^{-2} s^{-1}, respectively. During the clear water phases of these rivers the down-welling light attenuation coefficient should not be permitted to rise above 1m^{-1}. Preliminary data (Fig. 25) collected for Spirogyra, Myriophyllum and a filamentous, benthic, green algae from the Katherine River showed that the maximum rate of electron transport occurred at an irradiance of 300μmol m^{-2} s^{-1}.

Thus an attenuation coefficient of 1m^{-1} would allow sufficient light for benthic algal populations (such as those that occur in the Daly River).

6.6 River length and discharge

Whether or not algal blooms will develop depends upon the nutrient interactions described by Spiers and Gurney (2001). The analysis presented here suggests that for equivalent growth rates and discharges the potential for algal populations to persist increases as the river length increases. Conversely, for equivalent growth rates and discharges the potential for algal populations to persist decreases as the river length decreases. Longer rivers such as the Katherine/Daly River system and the Roper River, allow greater time for algal populations to increase, and therefore would theoretically have a higher algal hazard potential. However, larger rivers also have higher discharge that reduces the time available for algae to grow. Shorter rivers such as the Annie, Charlotte, Elizabeth, Howard, Darwin, Blackmore and Bee's Creek, conversely allow less river habitat/length for algae to grow (unless constrained by blockages caused by tidal water in estuarine reaches) but the lower discharges on the other hand would increase the time available for algae to grow. Given that river length is constant, and an inoculum of algae is always present in the sampled tropical rivers, the key variables are discharge and nutrient availability. Decreases in discharge and/or increases in the availability of the essential nutrient N and P is predicted to increase the hazard potential for algal blooms in most tropical rivers.

In theory the longer rivers such as the Roper and the Daly are more likely to support algal blooms than the shorter rivers such as the Annie, Elizabeth and Howard. However, the advection model makes the assumption that the discharge into the terminal water body is uninterrupted. This is unlikely for rivers that discharge into areas with a large tidal movement that restrict the discharge of freshwater and thus increase the residence time. The salt water intrusion into the Blackmore River may be indicative of an increased river residence time that resulted in high chlorophyll concentrations.

An additional assumption of the advection model is that the characteristics of the river are more or less uniform throughout its length. The discharge of sewage into lower reach of the Howard River is an example of a point source pollution that alters the nature of the river. Spot measurements of the chlorophyll in the Howard estuary and Buffalo Creek during February 2005 gave concentrations of between 100 and 200 $\mu g\ L^{-1}$, much of which was associated with blue green algae. It is likely that these high concentrations are a result of an increased river residence time due to tidal movements and increased available nutrients from the point source.

Concluding remarks

This project has identified the potential for algal blooms in clear water phases of some tropical rivers. Although chlorophyll concentrations are relatively low at most times, the presence of an inoculum and biologically active essential elements has shown that the algae can respond with high growth rates leading to blooms. The conditions under which this could occur cannot be predicted from a single indicator or target. Algal growth rate and composition, biologically active N and P, and river discharge and length are in combination the relevant indicators for algal blooms. Specific targets for water quality monitoring programs need to use this suite of variables as part of predictable models for meaningful results. Further information on the longitudinal characteristics of the rivers, nutrient sources and cycling, as well as slack water zones are needed to refine the predictions of the model used in this study.

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