"The Impact of Tourism on Dune Lakes on Fraser Island, Australia."

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ABSTRACT:

In view of the increasing tourism to Fraser Island, Queensland, a Tourist Pressure Index (TPI) was developed to assess the potential threat of tourism to 15 of the most accessible dune lakes on the island. TPI scores indicated that the two clear lakes on the island, Lake McKenzie and Lake Birrabeen, are most threatened by tourist activities, owing to their accessibility, facilities and prominence in advertising campaigns.

In addition, limnological investigations of the same 15 lakes were conducted in February 1999, to determine their current trophic status and potential susceptibility to adverse impacts from tourism, particularly in reference to eutrophication. On the basis of nutrient and chlorophyll *a* concentrations, the two water-table window lakes, Ocean Lake and Lake Wabby , were classed as mesotrophic and oligo-mesotrophic, whilst all of the perched dune lakes were oligotrophic. Lake McKenzie and Lake Birrabeen, the two most threatened lakes according to TPI scores, had the lowest nutrient concentrations of all of the lakes examined and we consequently suggest that nutrient additions may elicit rapid algal growth responses in these systems.

Comparisons between current data and historical date from Arthington *et al.* (1990) indicate that increases in planktonic chlorophyll *a* concentrations were not always directly mirrored by increases in total phosphorus concentrations. We found that whilst chlorophyll *a* concentrations were significantly higher in the 1999 samples than in the 1990 samples for all lakes, total phosphorus concentrations were higher in Ocean Lake, lower in Lake Jennings and similar in Lakes McKenzie, Birrabeen and Wabby.

Key Words: tourism, impacts, eutrophication, dune lakes, Fraser Island

Introduction

Tourists can adversely effect the ecology of pristine aquatic ecosystems through the addition of nutrients and other chemicals into the water column (King & Mace 1974; Butler *et al.* 1996) and by direct physical disturbance to sediment and vegetation (Liddle & Scorgie 1980). In oligotrophic systems, additions of nitrogen and/or phosphorus typically elicit strong algal growth responses (Dodds & Priscu 1990; Butler et al. 1996; Burns & Schallenberg 1998). Butler et al. (1996) found unnaturally high nutrient concentrations and algal biomass in rock pool swimming holes of pristine streams in North Queensland. These unnaturally high concentrations were attributed to the activities of tourists, most likely in the form of consequences of sediment re-suspension and urine inputs (Butler *et al.* 1996). Whilst the long-term consequences of these comparatively small-scale nutrient additions in oligotrophic systems are unknown (Butler *et al.* 1996), there is some evidence to suggest that they may lead to undesirable shifts in primary production and proliferation of nuisance algal communities (Welch *et al.* 1988; Hawes & Smith 1993; Havens *et al.* 1996a).

It has been suggested that the physical and chemical attributes of oligotrophic perched dune lakes on Fraser Island may make them particularly susceptible to adverse ecological consequences from nutrient additions from tourist sources (Bowling & Tyler 1984; Outridge *et al.* 1989; Arthington *et al.* 1990). Perched dune lakes are hydrologically unique, as they form in basins where organic matter and sand become cemented together to form an impermeable B-horizon soil known as "coffee rock" (Bayly 1966; James 1984; Timms 1986). This unique mode of origin ensures that perched lakes are not connected to the regional aquifer (Timms 1986), and as such, added nutrients accumulate in these systems over time (Outridge *et al.* 1989; Arthington *et al.* 1990). With ambient total phosphorus and chlorophyll *a* concentrations rarely exceeding 5 μg/L and 1 μg/L respectively (Arthington *et al.* 1990), the consequences of ongoing nutrient additions may be ecologically and aesthetically undesirable (Outridge *et al.* 1989; Arthington *et al.* 1990; Butler *et al.* 1996).

The threat that tourism poses to the ecological health of perched dune lakes in South-East Queensland has long been known (Outridge et al. 1989). For the lakes on Fraser Island, where visitor numbers have risen by almost 300% since gaining World Heritage status in 1992 (Anon. 1993; Sinclair 2000; Fullerton 2001; UNESCO 2001), the threats have similarly increased (Fullerton 2001; UNESCO 2001). Because perched dune lakes on Fraser Island lie in nutrient poor catchments, natural nutrient inputs are low (Bayly 1964; Timms 1986; Arthington *et al.* 1990; Greenway 1994). It has also been suggested that the algal flora in these oligotrophic systems is well equipped to respond to additions of nutrients (Outridge *et al.* 1989). Together these factors ensure that nutrient additions, regardless of their sources, will potentially lead to rapid increases in algal biomass (Outridge *et al.* 1989; Arthington *et al.* 1990; Butler *et al.* 1996).

In view of the threats that tourists may have on the health of the dune lakes on Fraser Island, this study was undertaken to assess the following questions:

1. Which lakes are most under threat from tourist activities?
2. Do the nutrient, chlorophyll *a* or physicochemical parameters in any of the lakes on Fraser Island make them particularly susceptible to adverse impacts from tourism?
3. Are there any significant differences in nutrient and chlorophyll *a* concentrations between the current study and that of Arthington et al. (1990)?

Methods

Study Site

Fraser Island lies within an ancient sequence of sand dunes located off the Queensland coast between 24° 35' - 26° 20'S and 152° 45' - 153° 30'E (Fig. 1; Anon 1999). Comprising an area of approximately 166 283 hectares it is widely acknowledged as the largest sand island in the world (Barson 1997; Anon 1999; UNESCO 2001). Rainfall on the island is high, with in excess of 1800 mm falling on the highest dunes each year. The subtropical climate is strongly influenced by the Pacific Ocean to the east, with mean daily temperatures ranging from 14.1°C in winter, to 28.8°C in summer (Anon 1999).

With in excess of 40 named lakes on the island, the Fraser Island region has been referred to as one of the few lakes districts in Australia (Bayly 1964, 1966). Furthermore, the lakes are unique on the basis of their numbers, their modes of origin, their biological diversity, their shallow depths, their oligotrophic status and for the perched lakes, their elevation (Anon 1999; UNESCO 2001). Over half of the world's known perched lakes occur on Fraser Island and sediment cores suggest that some are in excess of 300 000 years old (Longmore 1986, 1997; Anon 1999).

Fraser Island was inscribed on the World Heritage list in 1992 by satisfying natural area criteria ii. (be outstanding examples representing significant ongoing ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals), and iii.(contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance) of the World Heritage Area Convention (UNESCO 2001). The lakes on the island, in conjunction with the wide diversity of vegetation types that fill their catchments, played an important role in the World Heritage nomination and today they form the focus of a rapidly expanding tourist market to the region (Sinclair 2000; UNESCO 2001).

Lake selection

In February 1999, 15 Fraser Island dune lakes were chosen for a broad limnological survey. Lake selections were based on data from previous studies (Bayly 1964; Bayly *et al.* 1975; Arthington *et al.* 1986; Bowling 1988; Arthington *et al.* 1990), recommendations from Queensland National Parks and Wildlife staff, ease of accessibility and perceived visitation levels. An effort was made to include a wide and representative range of lakes.

Two water-table window lakes, which are connected to the water table (Lake Wabby and Ocean Lake) and 13 perched lakes (Lake Boomanjin, Lake Benaroon, Barga Lagoon, Lake Birrabeen, Lake Jennings, Lake McKenzie, Basin Lake, Lake Garawongera, Coomboo Lake, Lake Boomerang South, Lake Boomerang North, Lake Allom and White Lake) were selected (Fig. 1).

Tourist Pressure Index

To determine the relative pressure of tourism on each of the 15 study lakes, factors relating to accessibility, publicity and the provision of facilities were used to calculate a Tourist Pressure Index (TPI) as follows:

$$\mathrm{TPI} = \{(P + R + A) \,/\, [(\textbf{lowest of } B \textbf{ or } S) + C + T)]\} \times 100$$

Where: **B** = distance to nearest barge landing (kms)

S = distance to nearest settlement (kms)

C = distance to nearest camping area (kms)

T = distance to nearest toilet facilities (kms)

P = publicity surrounding site (0=unknown, 1=on postcards, QNPWS flyers etc, 2=extremely well known)

R **= road quality – relates to ease of travel (0=closed road, 1=used road, 2=scenic drive)**

A = accessibility of lake to parking facilities (0=no track, 0.5=long track, 1=medium length track, 2=short track)

Since day visits to lakes by tourists are strongly influenced by the ease of access from the mainland (access via barge only) or from settlements on the island (4WD vehicular access only), the lower of B or S was used to calculate the TPI score for each lake. S was primarily used for the lakes in the northern part of the island, where distances to the nearest barge landings suggest that day-trips are logistically prohibited.

High TPI scores relate to higher potential pressure from tourism. Low values for B (or S), C and T are likely to attract tourists to a lake, as they represent the accessibility and comfort afforded to tourists whilst at the lake. In contrast, low values for P, R and A have a negative effect on potential impacts, as each has the potential to reduce tourist motivations to visit lakes.

Limnological Investigations

From February 15 to March 3 1999, a limnological survey was conducted to determine baseline physicochemical measurements, nutrient concentrations and chlorophyll *a* concentrations in each of the 15 lakes. With reference to the TPI scores calculated for each lake, this investigation aimed to assess the potential susceptibility of each lake to effects from human activities.

Physicochemical Parameters

Dissolved oxygen, conductivity and pH were measured using a Greenspan® meter and probes in each of the study lakes. All measurements were taken at a depth of 1 metre and in two haphazardly selected epilimnetic sites.

Nutrient and Tannin Concentrations

All water samples were collected in reverse osmosis washed polyethylene bottles from epilimnetic collection points within each of the lakes. Unfiltered samples were taken for samples of total nitrogen (TN) and total phosphorus (TP) concentrations, whilst water samples filtered through a 0.45 μm filter were taken to assess concentrations of ammonium (NH_4^+) and nitrogen oxides (NO_x^-). In addition to nutrient analyses, unfiltered water samples were collected from each lake for analysis of tannin concentrations (μg/L). In all instances, samples were immediately placed on ice, frozen within 5 hours and transported to the Scientific Services division of Queensland Health for analysis.

Chlorophyll a Concentrations

A hand pump and filter apparatus was used to filter two replicate water samples through 0.7 μm glass-fibre filter papers at both epilimnetic sites. Each filter paper was stored in a centrifuge tube wrapped in aluminium foil and samples were immediately put on ice and frozen.

Analysis of chlorophyll *a* concentrations followed the standard methods described for aquatic samples (Parsons *et al.* 1984). Chlorophyll *a* on filter papers was extracted overnight at 4°C in 90% acetone, sonicated for 1 minute and centrifuged for 3 minutes at 3000*g*.

Sample absorbances were measured using a 'Shimadzu UV-1601' spectrophotometer with acidification for phaeophyton corrections. All chlorophyll *a* concentrations are expressed as μg/L and were standardised according to the volume of lake water filtered to attain the sample.

Statistical Analyses

Multivariate Analysis

A multivariate approach was adopted to identify baseline patterns for each of the variables measured in the 15 lakes. Lakes were classified according to their dissolved oxygen measurements, conductivity measurements, pH measurements, nutrient concentrations, tannin concentrations and chlorophyll *a* concentrations.

The multivariate analysis used an ordination technique (multi-dimensional scaling) within the computer package PATN (Belbin 1995). The raw data matrix was standardised to remove the bias of zeros and very large numbers in the data set. The data was then converted into an association matrix using the Bray-Curtis measure of similarity (Bray & Curtis 1957). Semi-Strong-Hybrid (SSH) multidimensional scaling was used to generate the ordination plots from the matrix (Belbin 1991). Vectors representing the subset of variables which best describe the pattern displayed in the ordination plot were determined using the Principle Axis Correlation (PCC) procedure and the significance levels for each of the vectors were calculated using a Monte Carlo Randomisation Test (Manly 1991). Only the vectors that were found to contribute significantly ($p < 0.05$) to the patterns in the ordination plot are presented.

Total Phosphorus – Chlorophyll a Relationship

Arthington *et al.* (1990) found a strong positive linear relationship between log total phosphorus and log chlorophyll *a* concentrations, which enabled the prediction of chlorophyll *a* concentrations in response to anticipated increases in total phosphorus concentrations. For the current data set, regressions of total phosphorus *versus* chlorophyll *a* concentrations were conducted to determine whether there has been a shift in the relationship observed by Arthington et al. (1990).

Comparative Analyses

Total phosphorus and chlorophyll *a* concentrations from the current data set were compared against those of Arthington et al. (1990) for the five (Wabby, Ocean, McKenzie, Birrabeen and Jennings) lakes common to both studies. Concentrations were compared statistically using thenovel ANOVA model designed by McKone and Lively (1993), enabling a powerful analysis of temporal changes within lakes rather than focussing on between lake differences.

Results

Tourist Pressure Index

Calculation of TPI scores revealed that the clear lakes, Lake McKenzie and Lake Birrabeen, and the small stained lake, Lake Allom, are currently under the most pressure from tourist activities (Table 1). With TPI scores of 61.22, 34.29 and 35.71 respectively, these lakes represent some of the most heavily visited systems on the island.

The other lakes with relatively high TPI scores were Ocean Lake and Lakes Jennings, Boomanjin, and Garawongera. The higher scores for most of the lakes from the central series (see Fig. 1) reflect the density of tourist activities between Central Station and Lake Boomanjin. Conversely, and with the exception of Lake Allom (which has toilets and camping facilities), most of the lakes in the northern section of the island had relatively low TPI scores (Table 1).

Physicochemical Parameters

Values for tannin concentrations, pH, conductivity and dissolved oxygen fell within the ranges expected for perched dune lakes on Fraser Island. All of the perched lakes were acidic, with pH values ranging from 4.15 in Barga Lagoon to 5.34 in Lake Allom. In contrast, the two window lakes (Ocean Lake and Lake Wabby) had neutral pH values of 6.81 and 6.72, respectively (Table 2). Ocean Lake (343.7 μS/cm) and Lake Wabby (155.6 μS/cm) also had substantially higher conductivity values than the perched dune lakes (range from 54.7 μS/cm in Barga Lagoon to 107.2 μS/cm in Lake Boomanjin). . On the basis of surface dissolved oxygen concentrations (ranging from 9.60 in Ocean Lake to 11.37 in Lake Allom), all of the lakes studied were at or near saturation.

Water Quality Parameters

Total phosphorus

Total phosphorus concentrations were generally below 5μg/L, suggesting that the majority of the systems were oligotrophic (Fig 2a). Only White Lake and the two window lakes, Wabby and Ocean, had total phosphorus concentrations approaching those more typical of mesotrophic conditions (> 10 μg/L).

Total Nitrogen, Ammonium and Nitrogen Oxides

Some of the lowest ammonium and nitrogen oxide concentrations recorded were for the water table window lakes (Ocean and Wabby), despite the fact that they had some of the highest total nitrogen concentrations (Fig. 2b). In contrast, the two clear perched lakes (McKenzie and Birrabeen) had relatively high levels of ammonium and nitrogen oxides (up to an order of magnitude greater than most of the other perched lakes). Basin Lake and Boomerang Lake North also had comparatively high concentrations of inorganic nitrogen.

Chlorophyll a

Chlorophyll *a* concentrations in the window lakes (Ocean and Wabby) were more than an order of magnitude higher than samples taken from the majority of the perched dune lakes sampled (Fig. 2c). For most lakes, concentrations fell within the range from 0.08 μg/L (Lake McKenzie) to 0.35 μg/L (Lake Allom) and across all lakes there was a strong (R^2=0.84) positive relationship between epilimnetic total phosphorus and chlorophyll *a* concentrations.

Multivariate Analysis

As expected, the higher total phosphorus concentrations, higher chlorophyll *a* concentrations, higher pH's and higher conductivity of the window lakes (Wabby [9] and Ocean [5]) ensured that they were isolated from the perched dune lakes in ordination space (Fig. 3a). In addition to this partitioning, the clear lakes (McKenzie [1] and Birrabeen [3]) fell to the left of the main cluster of perched lakes, due to their comparatively high nitrogen oxide concentrations (Fig. 3b).

On the whole there was very little difference among most of the perched dune lakes sampled. However, Barga Lagoon [10] was slightly removed from the main cluster due to comparatively low dissolved oxygen concentrations and White Lake [15] sits closest to the window lakes in two dimensional ordination space owing to its high total nitrogen, total phosphorus and chlorophyll *a* concentrations (Fig. 3b). Basin Lake [8] also sits removed from the main cluster, due to its inexplicably high total nitrogen (and ammonium) concentrations (Fig 3b).

Comparative Analyses – February 1990 versus February 1999

Total phosphorus

Total phosphorus concentrations in the 5 Fraser Island dune lakes sampled in February 1999 and February 1990, showed significant yet lake-specific temporal variability ($p=0.0001$, Fig. 4a). For the water-table window lakes, samples from the current study (February 1999) had significantly higher total phosphorus concentrations than those from 1990 in Ocean Lake ($p=0.0066$, Table 3), whilst the increases in Lake Wabby total phosphorus concentrations were not quite statistically significant ($p=0.0537$, Table 3). Conversely for the perched dune lakes, differences reflected no change in total phosphorus concentrations in Lake McKenzie and Lake Birrabeen, whilst Lake Jennings total phosphorus concentrations fell significantly from 4 μg/L in 1990, to 2 μg/L in 1999 ($p=0.0001$, Table 3).

Chlorophyll a

Chlorophyll *a* concentrations were at least an order of magnitude higher in 1999 than in 1990 in all five lakes (Fig. 4b). These large increases in chlorophyll *a* concentrations represented statistically significant differences in all lakes (Table 4).

Total phosphorus versus Chlorophyll a.

A positive relationship was observed between log (x+1) total phosphorus and log (x+1) chlorophyll *a* concentrations in both the 1990 (data from Arthington et al. 1990) and 1999 sample periods (Fig. 5).

Despite both representing strong positive relationships between total phosphorus and chlorophyll *a* concentrations, statistical comparisons of the 1990 and 1999 regression lines found that they were significantly different from each other (p= 0.0001). This difference is most likely due to the elevated chlorophyll *a* concentrations in Lake Wabby and Ocean Lake in 1999 and the subsequent influence they have over the slope of the regression line.

Discussion

Tourist Pressure Index

TPI scores calculated for the 15 dune lakes examined in this study supports the commonly held belief that the clear lakes on Fraser Island are some of the most threatened by tourist activities (Sinclair 2000). In a recent survey of tourists at Lake McKenzie (Hadwen & Arthington in prep), 70% of those censused nominated clear lakes as the favoured swimming location, highlighting the appeal of lakes McKenzie and Birrabeen. In addition to highlighting the focus of tourist attention on these systems, this result suggests that the TPI index developed here adequately predicts threatened systems owing to its incorporation of logistical and attraction-based variables.

Based on TPI scores Lake McKenzie, Lake Allom, Lake Birrabeen, Lake Jennings, Lake Boomanjin, Ocean Lake and Basin Lake all warrant close attention to ensure that potential impacts from tourist activities are minimised. Interestingly, only one of these lakes (Ocean Lake) is in the northern half of the island and this result highlights the remoteness of sites to the north and the focus of tourist attention on the lakes closest to the settlements and barge landings in the middle of the island.

Physicochemical Parameters

As expected, the pH, conductivity and dissolved oxygen levels recorded in this series of 15 Fraser Island dune lakes fell within the range reported by Bayly *et al.* (1975) and Arthington *et al.* (1986).

Nutrients

Most of the dune lakes examined fell within the expected ranges for oligotrophic systems (Budy *et al.* 1998; Schallenberg & Burns 2001) and were consistent with recent monitoring findings (Hockings 1999). Only three lakes (Ocean, Wabby and White) had total phosphorus concentrations above the suggested threshold concentration (5 μg/L) for management of these lakes (Arthington *et al.* 1990). For the window lakes, Lake Wabby and Ocean Lake, phosphorus concentrations were expected to be higher than those in the perched dune lakes, owing to their connection to the comparatively nutrient-rich regional aquifer (Bowling 1988; Arthington *et al.* 1990). For the perched White Lake, the relatively high total phosphorus concentrations may arise as a consequence of the shallow depth and exposure of the system to the prevailing south-easterly winds, which together initiate sediment and therefore nutrient re-suspension (Luettich *et al.* 1990; Bailey & Hamilton 1997; Hockings 1999).

The comparatively high nitrogen oxide concentrations reported here for Lake McKenzie and Lake Birrabeen suggest that these clear lakes are showing signs of being somewhat chemically distinct from the stained perched lakes studied. Whilst it is unknown as to whether or not tourists are responsible for these unusual conditions, the high TPI scores of these systems and the known preference of tourists to swim in these clear lakes (Hadwen & Arthington in prep.) indicate that they are potentially at risk of receiving tourist nutrient additions.

In contrast to the clear lakes, the exceptionally high ammonium concentrations in Basin Lake cannot be solely attributed to the consequences of additions from tourist sources. Calculations of lake volume and total ammonium loads in this lake suggest that in excess of 32 million urination episodes from tourists would have been required to attain the levels measured in Basin Lake. Whilst such a number of additions is highly unlikely, the high TPI score for this system, coupled with a lack of facilities and the recent increase in visitation levels, suggests that some additions from tourist sources are likely to be ocurring (Butler *et al.* 1996).

Comparative Analyses

The results of comparisons of current and historical (Arthington et al. 1990) nutrient and chlorophyll *a* data in five lakes highlighted the difficulties associated with monitoring and the detection of changes in freshwater systems (Thomas et al. 1996; McCormick & Stevenson 1998; Vis et al. 1998). For example, on the basis of total phosphorus concentrations alone, only Ocean Lake has shown significant increases over time and can now be considered to be mesotrophic. Whilst smaller increases in Lake Wabby total phosphorus concentrations were not statistically significant, this lake now falls within the oligo-mesotrophic range (Arthington et al. 1990). Despite these increases in the window lakes, phosphorus concentrations in the three perched dune lakes (McKenzie, Birrabeen and Jennings) showed no signs of increasing with time. In fact, a significantly drop in total phosphorus concentration was recorded for Lake Jennings, highlighting the maintenance of an oligotrophic state in this system (Arthington *et al.* 1990).

The temporal increases in total phosphorus concentrations in Ocean Lake and to some extent in Lake Wabby, indicate that these systems are aging at faster rates than would be expected under normal circumstances (Havens *et al.* 1996b). Whilst the high TPI scores for these systems indicate that tourist visitation levels may represent significant potential for nutrient additions, there may be other factors responsible for this acceleration in aging. Since both systems do maintain a connection with the regional aquifer, higher nutrient loads may come from additions elsewhere into the aquifer. Furthermore, local conditions around these systems are likely to influence the rate at which increases in nutrient concentrations occur. At Ocean Lake, there is anecdotal evidence to suggest that cormorants and other waterbirds, which roost in the riparian vegetation that fringe the lake, may add substantial quantities of nutrients to the water column through their faeces (Pettigrew *et al.* 1998; Hockings 1999). For Lake Wabby, increases in nutrient concentrations may be attributable to the fact that the lake volume is reducing as a consequence of it being filled in by a large sand blow (Arthington et al. 1986).

Despite the variable nature of trends in total phosphorus concentrations over time, all five lakes exhibited substantial increases in chlorophyll *a* concentrations. Since chlorophyll *a* is a biological indicator of long-term changes in nutrient concentrations in aquatic systems (Whitton & Kelly 1995; Pan *et al.* 1996; Kelly 1998; Kelly & Whitton 1998), this result indicates that the rapid assimilation of nutrients by primary producers in these oligotrophic systems has prohibited their quantification in nutrient samples (Thomas *et al.* 1996).

The changes in total phosphorus and more importantly, chlorophyll *a* concentrations since 1990 (Arthington *et al.* 1990) suggest that the lakes on Fraser Island are moving from their pristine oligotrophic conditions towards a more productive, oligo-mesotrophic status (del

Giorgio & Peters 1994; Burns & Schallenberg 1996; Havens *et al.* 2001). These changes are highlighted in the total phosphorus versus chlorophyll *a* concentration scatterplots, which show a significantly greater slope for the 1999 data relative to that collected in 1990 by Arthington et al. (1990). Whilst changes in the relationship between total phosphorus and chlorophyll *a* concentrations cannot be solely attributed to the activities of tourists (Havens 1999), contemporary increases in total phosphorus concentrations in lakes Ocean and Wabby and chlorophyll *a* concentrations in all lakes indicate that they are becoming more productive. Monitoring should continue to focus on the rate at which changes are occurring in these systems, particularly in Ocean Lake, where increases appear to be occurring at a rate faster than would be expected under natural conditions.

Conclusions and Management Implications

On the basis of TPI scores, Lake McKenzie, Lake Allom and Lake Birrabeen are the lakes on Fraser Island most threatened by potential tourist impacts. Their current oligotrophic status ensures that they are potentially susceptible to nutrient additions from tourist activities and their facilities and relatively central location on the island suggest that they will continue to receive large numbers of visitors each year. Whilst it is currently unknown as to whether tourist activities have already begun to influence the ecology of these oligotrophic systems, the relatively high nitrate concentrations in Lake McKenzie and Lake Birrabeen should be further investigated to determine the likely origins of these nutrients. Management plans aiming to preserve the lakes on Fraser Island should focus on Lake McKenzie, Lake Allom and Lake Birrabeen, owing to their tourist appeal and their potential susceptibility to eutrophication.

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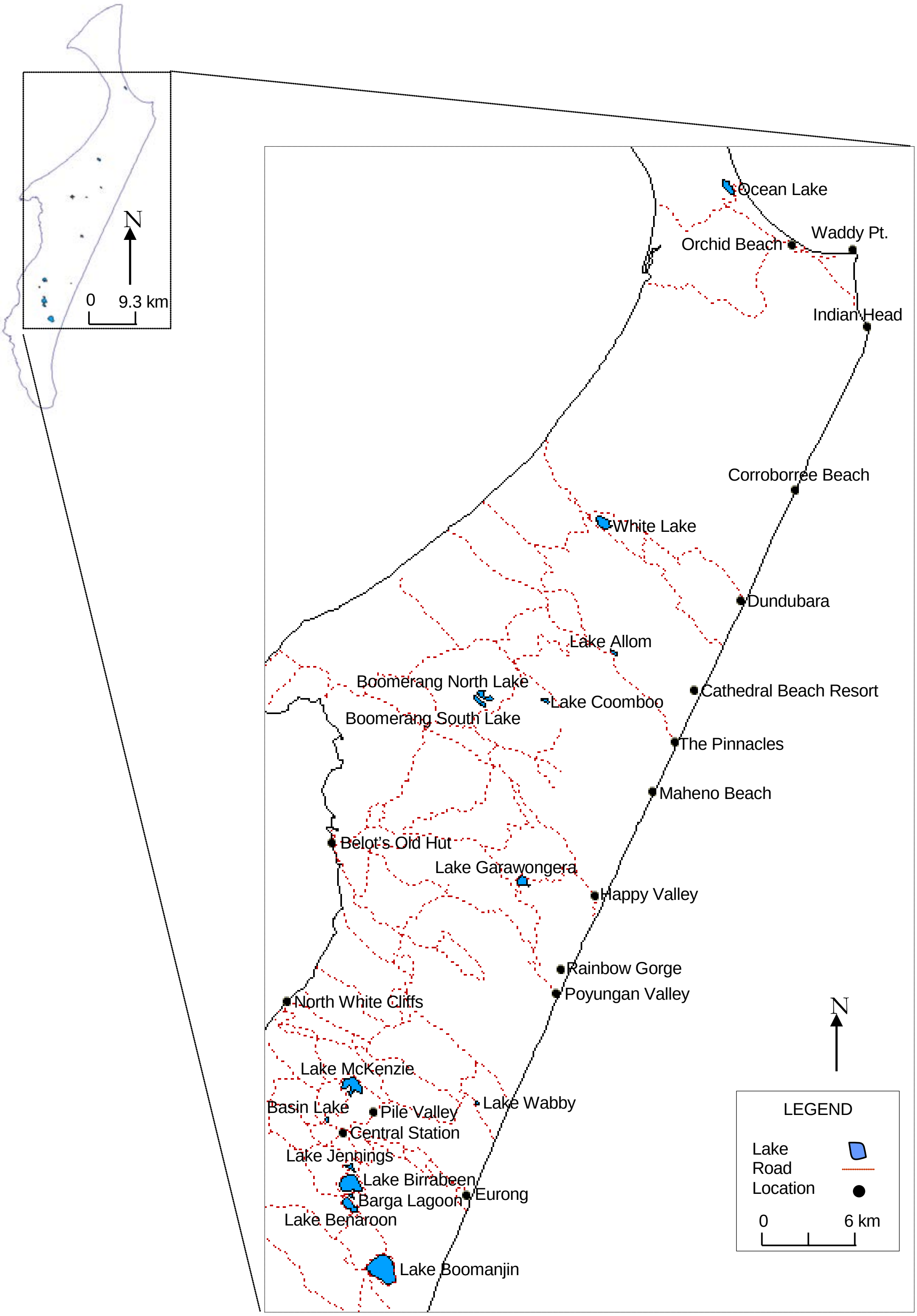
Figure 1. Map of Fraser Island. Insert shows all 15 study lakes, roads, streams and



major tourist locations on the island.

Figure 2.A. Mean (± s.e.) Total Phosphorus Concentrations in 15 Fraser Island Dune Lakes in February 1999. 2B. Mean (± s.e.) Concentrations of Total Nitrogen, Ammonium and Nitrogen Oxides in 15 Fraser Island Dune Lakes in February 1999. 2C. Mean (± s.e.) Chlorophyll *a* Concentrations in 15 Fraser Island Dune Lakes in February 1999.

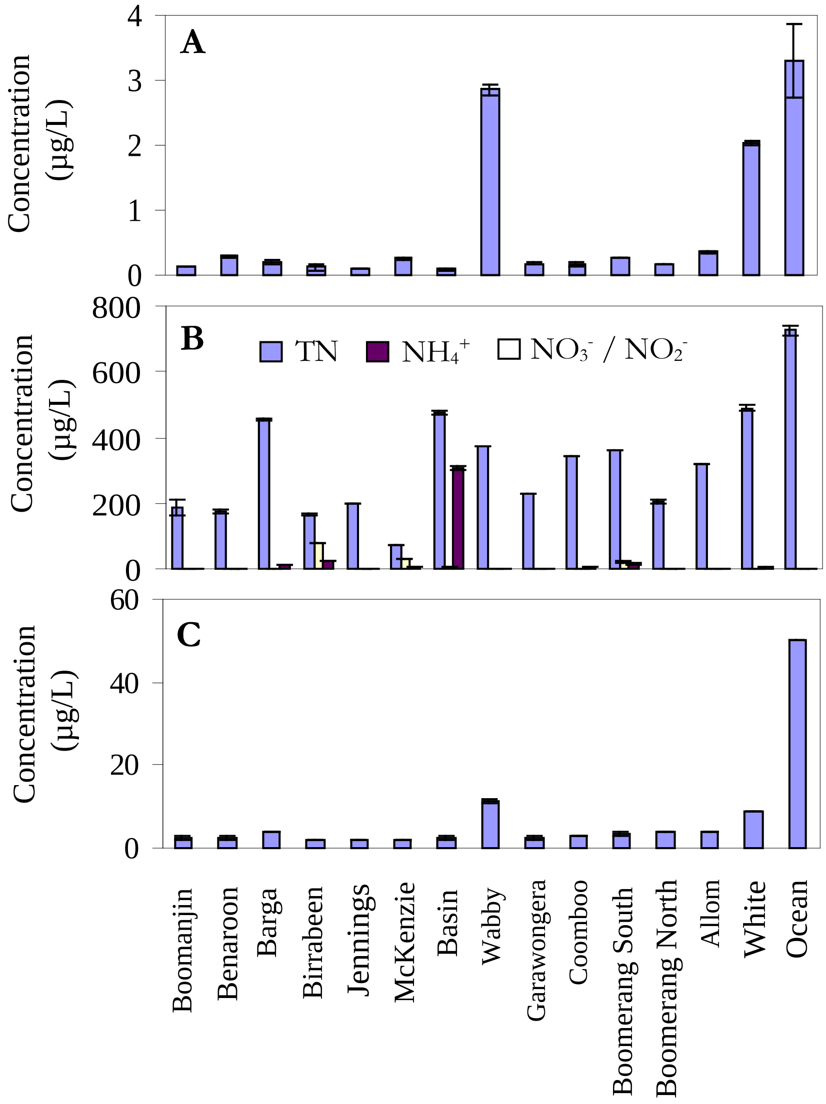


Figure 3a. Ordination Plot of 15 Fraser Island Dune Lakes based on Nutrient, Chlorophyll *a* and physicochemical variables. Lakes are ranked according to their TPI scores as follows: 1. Lake McKenzie, 2. Lake Allom, 3. Lake Birrabeen, 4. Lake Jennings, 5. Ocean Lake, 6. Lake Boomanjin, 7. Lake Garawongera, 8. Basin Lake, 9. Lake Wabby, 10. Barga Lagoon, 11. Lake Benaroon, 12. Boomerang Lake South, 13. Boomerang Lake North, 14. Lake Coomboo, 15. White Lake. Figure 3b. Vectors describing the pattern in Figure 3a. (Stress = 0.0141).

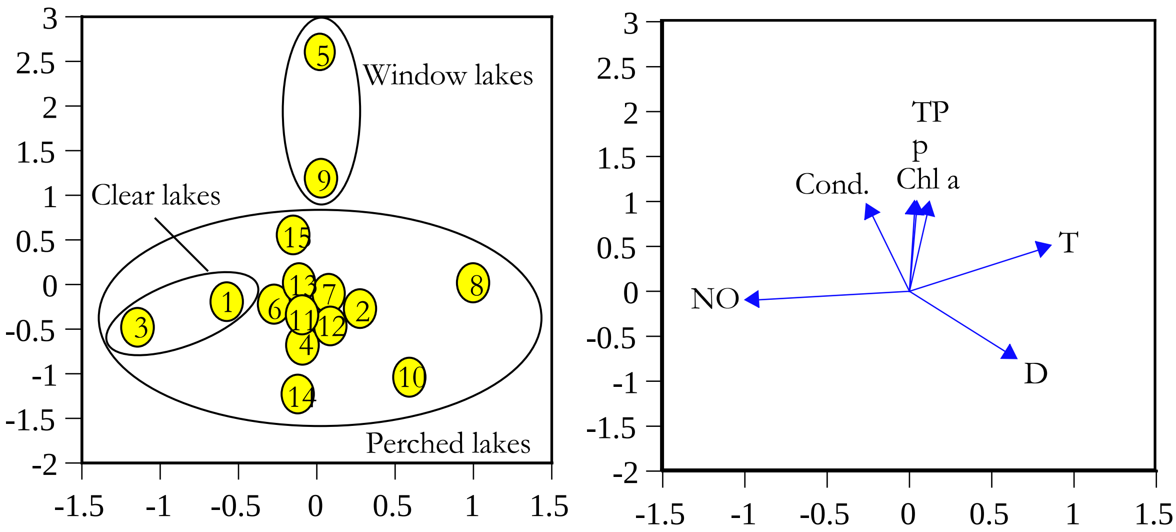


Figure 4A. Mean (± s.e.) Total Phosphorus Concentrations in five Fraser Island Dune Lakes in February 1990 (Arthington et al. 1990) and February 1999 (current study), 4B. Mean (± s.e.) Chlorophyll *a* Concentrations in five Fraser Island Dune Lakes in February 1990 (Arthington et al. 1990) and February 1999 (current study).

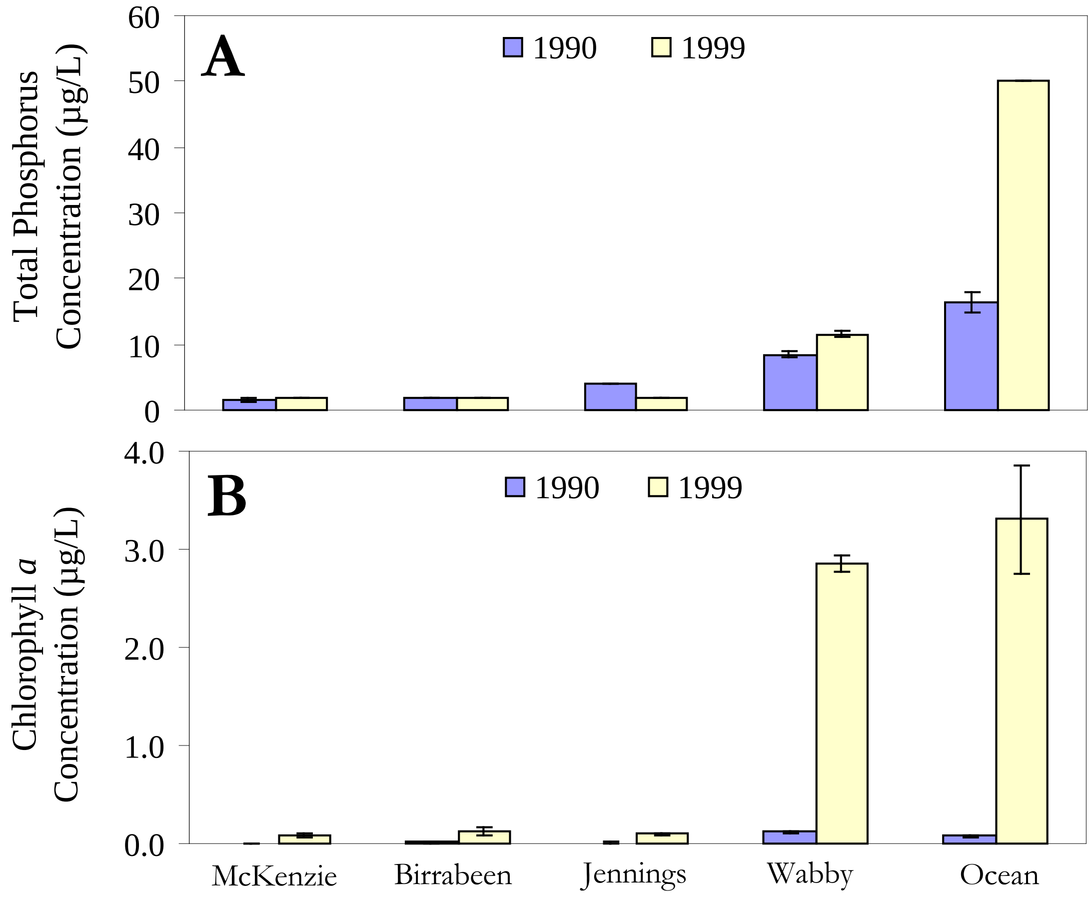
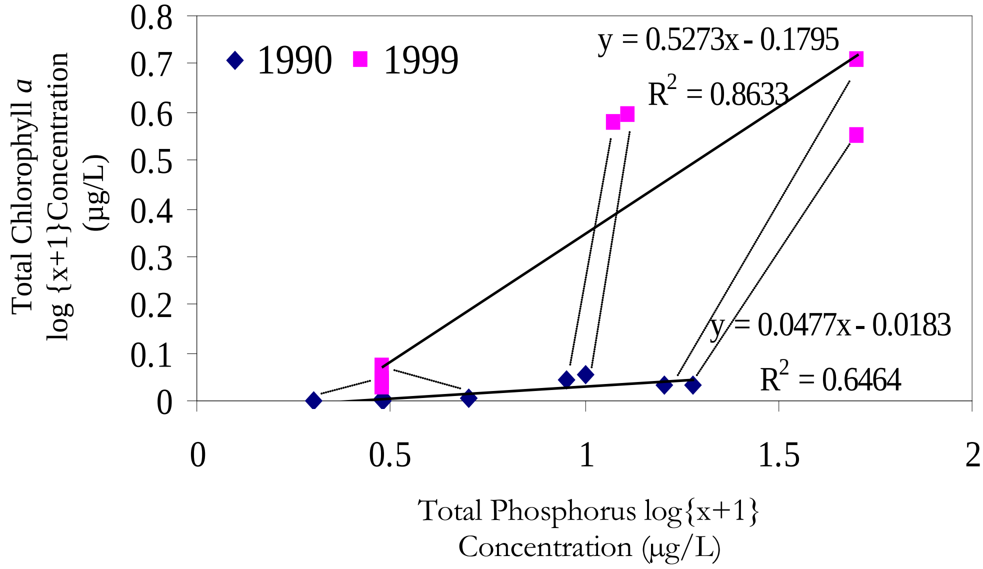


Figure 5. Total Phosphorus-Chlorophyll a Relationships in five Fraser Island Dune Lakes in February 1990 and February 1999.



Total Chlorophyll a
log {x+1}Concentration
(µg/L)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1990
1999
y = 0.5273x - 0.1795
R2 = 0.8633
y = 0.0477x - 0.0183
R2 = 0.6464
0
0.5
1
1.5
2
Total Phosphorus log{x+1}
Concentration (µg/L)

Table 1. Tourist Pressure Index (TPI) scores and ranks for 15 Fraser Island Dune Lakes (higher scores – lower ranks – indicate greater pressure and potential for adverse impacts from tourist activities).

Lake	TPI Score	Rank (Highest to Lowest)
Boomanjin	21.00	5
Benaroon	14.29	10.5
Barga	14.36	9
Birrabeen	34.29	3
Jennings	22.86	4
Basin	17.86	10.5
McKenzie	61.22	1
Wabby	15.68	8
Garawongera	19.05	7
Boomerang South	11.52	12
Boomerang North	6.91	13
Coomboo	6.05	14
Allom	35.71	2
White	2.65	15
Ocean	21.16	6

TPI = (P + R + A) / [(lowest of B or S) + C + T] .

Table 2. Mean (± s.e.) values for pH, dissolved oxygen, conductivity, tannin concentrations and secchi depths in 15 Fraser Island Dune Lakes, sampled February – March 1999.

Lake	pH	Conductivity (μS cm^{-1})	Temperature (°C)	Dissolved Oxygen (mg l^{-1})?	Tannins (μg l^{-1})	Secchi Depth (m)
Boomanjin	4.60 (0.05)	107.22 (1.84)	29.28 (0.01)	10.56 (0.00)	1650 (50)	1.48 (0.02)
Benaroon	4.56 (0.03)	84.27 (0.14)	29.08 (0.04)	10.50 (0.02)	500 (0)	2.92 (0.16)
Barga	4.15 (0.01)	54.86 (1.85)	30.41 (0.84)	11.15 (0.16)	4900 (200)	0.60 (0.05)
Birrabeen	4.64 (0.02)	91.80 (0.36)	29.11 (0.06)	10.51 (0.01)	100 (0)	5.83 (1.13)
Jennings	4.44 (0.01)	78.66 (0.14)	29.76 (0.04)	10.73 (0.01)	1450 (50)	2.23 (0.12)
Basin	5.00 (0.01)	63.71 (0.21)	28.80 (0.39)	10.60 (0.11)	200 (0)	4.73 (0.43)
McKenzie	4.82 (0.02)	91.25 (0.15)	27.96 (0.16)	10.09 (0.02)	100 (0)	8.60 (0.00)
Wabby	6.72 (0.19)	155.58 (0.03)	28.21 (0.05)	10.16 (0.02)	200 (0)	1.53 (0.08)
Garawongera	5.22 (0.03)	73.00 (0.25)	30.00 (0.71)	10.86 (0.30)	1000 (0)	3.16 (0.04)
Boomerang South	4.67 (0.01)	65.40 (0.60)	29.16 (0.04)	10.73 (0.13)	2300 (50)	0.80 (0.03)
Boomerang North	4.61 (0.00)	98.73 (0.25)	29.75 (0.34)	10.77 (0.01)	750 (0)	1.73 (0.05)
Coomboo	4.55 (0.00)	55.90 (0.21)	29.95 (0.02)	10.66 (0.15)	2700 (50)	1.41 (0.02)
Allom	5.34 (0.02)	64.90 (1.17)	31.10 (0.48)	11.37 (0.09)	1100 (100)	2.15 (0.20)
White	4.72 (0.00)	101.85 (0.62)	27.08 (0.03)	9.75 (0.01)	800 (0)	1.63 (0.03)
Ocean	6.81 (0.01)	343.73 (0.35)	26.64 (0.08)	9.60 (0.04)	1000 (0)	0.88 (0.02)

Table 3. ANOVA results comparing total phosphorus concentrations in five Fraser Island dune lakes in February 1990 (Arthington *et al.* 1990) and the current study, February 1999.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Birrabeen	1	0.0001	0.0001	†	†
Jennings	1	0.0906	0.0906	99999.99	0.0001*
McKenzie	1	0.0121	0.0121	0.60	0.4950
Wabby	1	0.0173	0.0173	17.13	0.0537
Ocean	1	0.2336	0.2336	149.01	0.0066*
LAKE	4	4.4790	1.1197	187.85	0.0001*
Error	11				
Corrected Total	20				

* indicates significant result at p=0.05. † no F value or p value was calculated, as samples were identical in both sample periods.

Table 4. ANOVA results comparing epilimnetic chlorophyll *a* concentrations in five Fraser Island dune lakes in February 1990 (Arthington *et al.* 1990) and the current study, February 1999.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Birrabeen	1	1.5203	1.5203	20.04	0.0065*
Jennings	1	1.3528	1.3528	388.96	0.0001*
McKenzie	1	3.7060	3.7060	20.06	0.0065*
Wabby	1	2.5262	2.5262	1567.75	0.0001*
Ocean	1	3.5568	3.5568	201.34	0.0001*
LAKE	4	14.0184	3.5046	55.31	0.0001*
Error	22	1.3939	0.0636		
Corrected Total	31	32.3715			

* indicates significance at p=0.05.