VISITOR IMPACTS AND CLIMATIC VARIABILITY WILL SHAPE THE FUTURE ECOLOGY OF FRASER ISLAND'S PERCHED DUNE LAKES

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Fraser Island's perched dune lakes are magnets for tourists. Our research has documented the ecological consequences of unregulated visitor use of these systems, with a focus on the likely visitor-mediated delivery of nutrients to these oligotrophic systems. In addition to threats from visitors, a significant sleeper issue for perched dune lakes is climate change. Perched dune lakes are not connected to the regional water table and water levels are known to fluctuate widely with local rainfall patterns. Given the projected changes in climate in the Fraser Island region - increased temperatures, reduced rainfall, increased evaporation and increased hydrologic variability – we anticipate that lake levels are likely to fluctuate even more in the future. These fluctuations are likely to have both ecological and infrastructure consequences.

In this paper, we present a conceptual model of the natural nutrient dynamics in perched dune lakes, with particular emphasis on the effects of water level fluctuations and grazing organisms. We then superimpose visitor activities and climate change and increased climatic variability on model functions, and suggest how they are likely to intensify interactions between nutrient processes and fluctuating hydrology. We predict that visitor-mediated nutrient inputs will stimulate algal growth, but that the consequences of this increase in algal biomass, especially for consumer organisms (but also for visitors themselves), will differ between wet (high water level) and dry (low water level) periods. Understanding the dynamic nature of algal production in perched dune lake ecosystems in the context of an increasingly variable climate, is essential to inform how these systems should be managed, particularly for the highly visited systems that inevitably experience the additional stress of nutrient inputs from visitors. Maintaining the natural oligotrophic status of perched dune lakes is an important management principle.

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Received: 23 March 2011; Revised: 26 June 2011; Accepted: 05 July 2011

INTRODUCTION

One of the striking features of the southern Queensland coastline is the abundance of relatively large sand islands. Occupying an area of 166 283 hectares between 24° 35' - 26° 20'S and 152° 45' - 153° 30'E off the Queensland coast (Figure 1), Fraser Island is the largest of the group and is considered to be the largest sand island in the world (UNESCO, 2001). One of the most unique and special features of Fraser Island is the number and diversity of perched dune lakes (Bayly, 1964; Timms, 1982). As their name suggests, perched dune lakes sit in depressions that lie above the regional aquifer (James, 1984). As such, perched systems only form when sand becomes cemented together with organic matter to form a semi-permeable B-horizon soil known as "coffee rock" (Bayly et al., 1975; James, 1984). As a consequence of this unique mode of origin, perched dune lakes are generally regarded as morphologically simple and hydrologically closed basins of rainwater (Bayly et al., 1975; Bowling, 1988; Arthington et al., 1990) and they typically do not have inflow or outflow creeks (Bayly, 1964).

The abundance of perched dune lake environments on Fraser Island, in particular, not only contributed to the island's successful nomination for World Heritage listing (UNESCO, 2001) but also to the boom in tourism on the island (Hadwen & Arthington, 2003; Hadwen et al., 2003). The most celebrated (and therefore visited) perched dune lake on Fraser Island is Lake McKenzie, which, at the height of the tourist season, receives in excess of 1000 visitors per day (Hadwen & Arthington, 2003). With more than 300 000 annual visitors to the island, coupled with the fact that perched dune lakes are naturally oligotrophic (low nutrient, low productivity), these systems are under increasing pressure from visitors (Hadwen et al., 2003; Buckley 2004).

The influence of visitors on the ecology of perched dune lakes has been the subject of considerable research

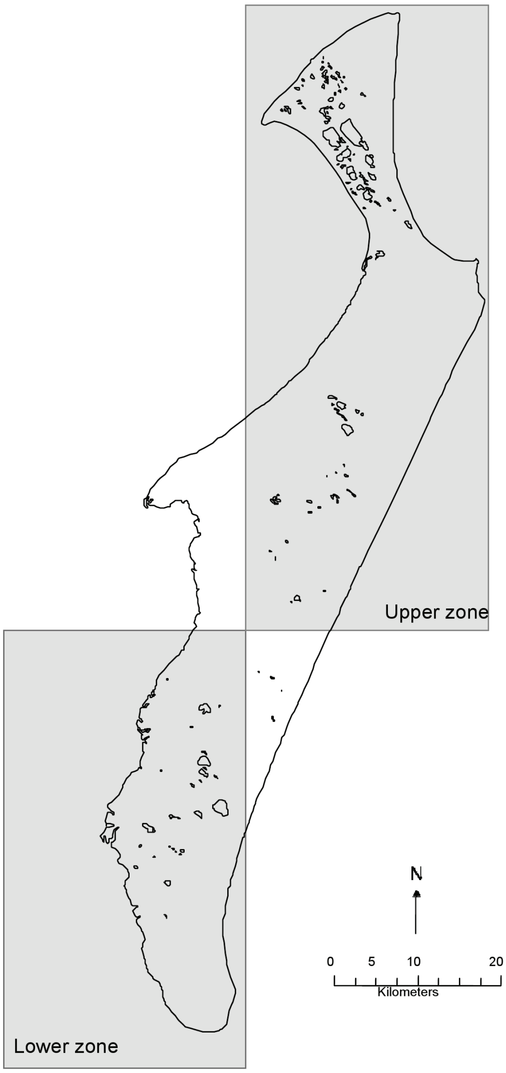

FIG. 1. Map of Fraser Island lakes with OzClim climate projection grids (upper zone and lower zone) shown.

(Hadwen et al., 2003; Hadwen & Bunn, 2004; Hadwen & Bunn, 2005; Hadwen et al., 2005) and as a result, we know how, where and why visitor activities can alter the algal productivity and ecological functioning of these systems. Briefly, these studies have shown that visitor activities in the littoral zones of perched dune lakes can increase periphyton (attached algal) productivity and alter the pathways of carbon flow through aquatic food webs (Hadwen et al., 2003; Hadwen & Bunn, 2004; Hadwen et al., 2005). Direct links between tourist-mediated nutrient inputs (from urine) and algal biomass accrual, supported by nutrient enrichment experiments, have identified visitors as a major potential threat to the condition of these oligotrophic lake ecosystems (Hadwen & Bunn, 2005).

The research described above largely focussed on the role of nutrients (especially those delivered by tourists) in shaping the ecology of perched dune lakes. Although the influence of lake water level fluctuations was not explicitly stated in those papers, Hadwen (2002) proposed a conceptual model that links tourist-mediated nutrient inputs and nutrient processing to the natural cycle of water level fluctuations expected in perched dune lakes (see Figure 2). The model identifies how nutrient inputs in lake littoral zones can stimulate terrestrial and aquatic environments, depending on whether the lake has low or high water levels.

At low water levels, nutrients can bypass the littoral zone (comprised of *Lepironia articulata* reeds and associated periphyton) and directly stimulate phytoplankton communities. Conversely, under high water levels where the *L. articulata* reedbeds are partially or fully immersed, nutrients are rapidly assimilated into periphyton biomass (as per the results from Hadwen et al., 2005 and Hadwen & Bunn, 2005). Excess nutrients may also stimulate phytoplankton communities under this scenario, as evidenced by increases in water column chlorophyll a in the littoral zone nutrient addition experiments of Hadwen and Bunn (2005). In addition to stimulating periphyton production and biomass accrual, nutrients may also stimulate the proliferation of unpalatable species of attached algae, either directly via competitive processes within the algal community and/or as a consequence of top-down pressure from grazers. Under stable lake conditions this is particularly likely to occur, as biomass and productivity will continue to increase with additional nutrient inputs into the system (Hadwen & Bunn, 2005). On the other hand, if water levels drop, much of the periphyton community attached to the *L. articulata* stems become exposed and begin to decay. Depending on the severity of the water level drawdown, dead and decaying periphyton can enter the open water (and act as a subsidy for phytoplankton communities) or the lake shoreline (and act as a subsidy to the terrestrial environment). Under the latter scenario, there is some chance the tourist-mediated nutrient inputs could be exported from the lake environment, but to what degree

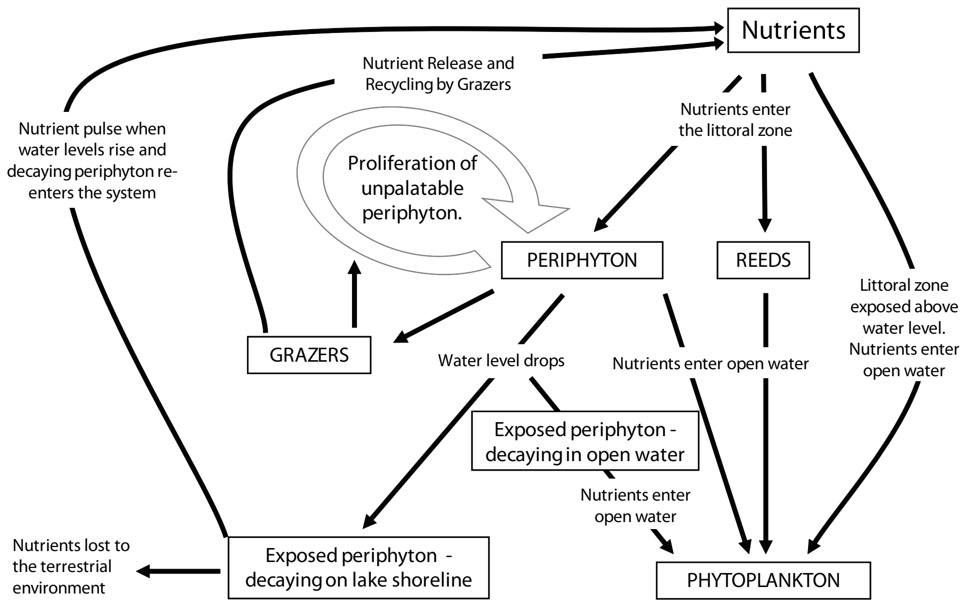

FIG. 2. Conceptual model of nutrient dynamics in perched dune lakes on Fraser Island, with particular emphasis on the effects of water level fluctuations and grazers (modified from Hadwen 2002).

this occurs is unknown, as very little is known of the interaction between terrestrial and aquatic ecosystems on Fraser Island. What we do know is that if terrestrial organisms do not utilise this aquatic subsidy (in the form of decaying periphyton), then subsequent rainfall and associated runoff is likely to transport this material back into the lake environment. This re-delivered periphyton material can then act as a pulse of nutrients into the system, which, coupled with visitor-mediated nutrient inputs, may greatly increase the response in primary producers and the consequences for higher trophic levels.

Almost a decade on from the development of this conceptual model (and the work that underpins it), it is now evident that climate change also represents a major threat to Fraser Island (IPCC, 2007; ANU, 2009). Although a recent Australian National University report (referred to as ANU, 2009), did not specifically investigate the impact that climate change will have on the perched dune lakes within the World Heritage Area, it did state that '*Prolonged drought and/or water extraction may affect the supply of water to spring-fed streams and lakes. Eutrophication caused by recreational activity is already a major concern, and is likely to be exacerbated by higher water temperatures'*. We agree with these individual statements, but propose that interactions between nutrient processes and variable hydrology will periodically intensify the effects of climate change. Our proposition is supported by similar statements by Bleckner (2008), who highlighted the synergistic effects of nutrient inputs and climate change for large lake ecosystems. We believe that not only will changes in temperature, rainfall and evapotranspiration influence water levels, but through links to nutrient and carbon cycles, it is possible that these fluctuations will shape lake response to visitor-generated nutrient inputs, through the links identified in Figure 2.

In the context of our understanding of visitor impacts and climate change drivers, the aim of this paper is to examine how the future ecology of perched dune lakes is likely to be driven by these two major forces.

TABLE 1. Projected seasonal and annual changes (from current climate conditions) in mean temperatures, rainfall and evapotranspiration for lower and upper Fraser Island in 2030, 2050 and 2070. Projections based on OzClim Climate Change Scenario Generator, using the CSIRO-Mk3.5 model and the emission scenario SRES marker scenario A1B with a moderate global warming rate.

	2030		2050		2070	
Mean temperatures (°C)	Lower	Upper	Lower	Upper	Lower	Upper
Summer	1.00	0.95	1.69	1.62	2.37	2.23
Autumn	1.01	0.93	1.72	1.59	2.36	2.17
Winter	0.99	0.94	1.69	1.62	2.36	2.23
Spring	0.94	0.87	1.6	1.51	2.23	2.08
Annual	0.99	0.92	1.70	1.59	2.33	2.18
Rainfall (mm)						
Summer	5.6	12.7	9.5	21.6	13.3	30.2
Autumn	-10.8	-5.3	-18.3	-9.0	-25.6	-12.6
Winter	-18.4	-15.1	-31.2	-27.7	-43.7	-35.9
Spring	-27.2	-26.7	-46.2	-45.3	-64.7	-63.4
Annual	-50.8	-34.4	-86.2	-60.4	-120.7	-81.7
Evapotranspiration (mm)						
Summer	22.3	21.5	37.8	36.6	52.9	51.2
Autumn	18.3	18.4	31.1	31.2	43.5	43.7
Winter	12.2	13.5	20.7	23.0	29.0	33.1
Spring	20.5	21.2	34.8	35.3	48.7	50.4
Annual	73.3	74.6	124.4	126.1	174.1	178.4

To do this, we bring together current understanding of tourist-mediated nutrient inputs and their effects on lake ecology and scenarios of the future climate of Fraser Island based on current climate change projections. This approach mirrors those recently suggested by Sipkay et al., (2009) and ter Heerdt et al., (2007) in their reviews of climate change effects on aquatic ecosystems. In both of these papers, the authors call for a process and model driven assessment of climate change consequences and emphasise the importance of understanding food webs and indirect effects of climate change on lake ecology (ter Heerdt et al., 2007; Sipkay et al., 2009). After evaluating the likely effects of climate and nutrient drivers on lake ecology, we then propose conditions under which visitor impacts might be exacerbated under a changed climate with increased climatic variability and discuss the implications for lake ecology, future visitation trends and management.

MATERIALS AND METHODS

STUDY AREA AND LAKES

Fraser Island has a subtropical climate that is strongly influenced by the Pacific Ocean to the east, with mean annual temperatures ranging from 14.1°C to 28.8°C (Anon, 1991). Rainfall on the island is high, with in excess of 1800 mm falling on the highest dunes each year (Anon, 1991). Fraser Island is believed to be one of the few regions in Australia where annual precipitation exceeds annual evaporation (UNESCO, 2001), although rainfall is quite seasonal, with the wettest period being January to March and extended dry periods typical in winter and spring (BOM, 2010).

The emphasis of this paper is on the perched dune lakes of Fraser Island, as these systems are likely to be vulnerable to both visitor impacts (Hadwen et al., 2003; Hadwen et al., 2005) and changes in climate, particularly those relating to rainfall and temperature

(ANU, 2009). Perched dune lakes are widespread throughout Fraser Island, with more than 40 named lakes and numerous smaller systems (see Figure 1). Because they are basically just basins of rainwater, with no connection to the regional aquifer and no inflow or outflow streams (Bayly, 1964; Timms, 1982), the water levels of most perched dune lakes are highly variable and they tend to respond directly to local rainfall (Bensink & Burton 1975, personal observations). Whilst lake heights have not been routinely measured on Fraser Island, major rainfall in early to mid 1999 resulted in significant water level changes in all of the perched dune lakes sampled by Hadwen et al. (2005). Given these observations and the ancedotal history of water level fluctuations, changes in climate that lead to drier and/or more variable rainfall patterns are likely to lead to even greater water level variability in these perched ecosystems. This prediction is consistent with the global view that increased climate variability, coupled with increased temperature and evaporation and a reduction in rainfall overall, will lead to more variable lake water levels (Bleckner, 2008; Sipkay et al., 2009).

To examine future climate and its implications for perched dune lakes on Fraser Island, we generated seasonal climate projections using the OzClim Climate Change Scenario Generator (http://www.csiro.au/ozclim/home.do). Specifically, we used the advanced climate projection tool and evaluated the changes, from 1990, of evapotranspiration (mm), mean air temperature (°C) and mean rainfall (mm), both on annual and seasonal scales. For all projections we used the CSIRO-Mk3.5 model and adopted the emission scenario SRES marker scenario A1B, which is a relatively moderate (and therefore conservative) climate change scenario. In keeping with the moderate theme we selected a moderate and conservative global warming rate (despite current evidence which suggests that we are tracking the most extreme IPCC scenario – IPCC 2007). This selection of moderate scenarios mirrors the approach used in recent tourism-climate change projects, like Turton et al. (2010). Furthermore, since the objective of this study was to highlight the need to incorporate climate change and climatic variability in perched dune lake management plans, it is not necessary to apply more extreme scenarios. All variables were interrogated for 2030, 2050 and 2070 and for two sections of Fraser Island (southern and northern) on the basis of the available OzClim modelling grids (Figure 1).

RESULTS

PROJECTED CHANGES IN MEAN AIR TEMPERATURES

Across both the upper and lower regions of the island (see Figure 1) and all time steps (2030, 2050 and 2070), mean annual air temperatures are set to increase on the basis of the OzClim projections (Table 1). Temperatures are anticipated to increase slightly more in the lower part of the island than in the upper part of the island. Some relatively small, yet consistent, seasonal differences are also anticipated, with temperature increases likely to be smallest in spring, at least relative to the increases anticipated for summer, autumn and winter (Table 1).

PROJECTED CHANGES IN MEAN RAINFALL

Mean annual rainfall is anticipated to decrease substantially across both the upper and lower regions of Fraser Island, and through all three future time steps (Table 1). Even for the smallest projected change (for the upper region and by 2030), rainfall is projected to be 34 mm lower than current levels. In addition to this annual trend, the projections indicate marked seasonality in changes in rainfall. These changes are consistent for both the lower and upper parts of the island, with increased summertime rainfall (positive values) and reduced rainfall in autumn, winter and spring (negative values in Table 1). These projections indicate that wet seasons will become wetter and that dry spells might be expected to be longer through autumn, winter and spring. Whilst these patterns mimic the current seasonality in rainfall for Fraser Island (BOM, 2010), they intensify the pattern and the changes will potentially influence the water balance of the island.

PROJECTED CHANGES IN EVAPOTRANSPIRATION

Evapotranspiration is anticipated to increase annually and across all four seasons in both the lower and upper parts of Fraser Island (Table 1). Coupled with decreases in rainfall through autumn, winter and spring, increased evapotranspiration rates are likely to result in faster and deeper drawdown of lake water levels between March and November.

PROJECTED CHANGES IN TOURISM AND VISITATION SEASONALITY TO FRASER ISLAND

Whilst we do not explicitly examine trends in visitation rates to Fraser Island in this paper, numerous studies have shown both increases and trends in visitors to the island over the past few decades. Significantly,

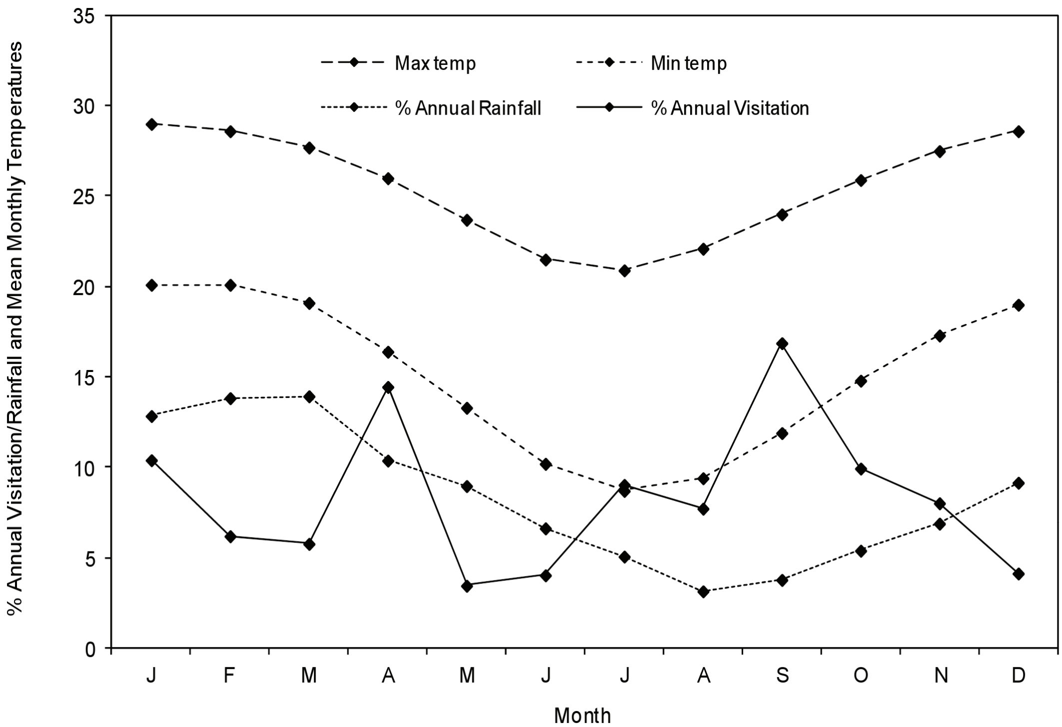

FIG. 3. Seasonality in visitation, rainfall, maximum temperatures and minimum temperatures in the Great Sandy National Park, Fraser Island, based on permit data collected between 1995 and 2000.

World Heritage listing stimulated an incredible boom in tourism on Fraser Island, with visitor numbers rising from around 5000 in 1970 to around 500 000 in 2009 (Alexander, 2009). Whilst evidence suggests that current growth is not likely to continue at such high rates, owing to global market trends and island infrastructure (Anon, 2002), it is likely that existing visitation will (at least) continue into the foreseeable future (Anon, 1998). Notwithstanding our expectation that visitation will remain at current levels for the next 5 -10 years, there are a large number of variables that need to be incorporated into projections of future tourism and visitation levels for areas like Fraser Island (Turton et al., 2010). These include changes in the tourism market – there is already a trend towards increased domestic visitation relative to international visitors – changes in global economies and, potentially, changes in visitation attributable to climate change itself (Turton et al., 2010; Hadwen et al., 2011). These latter changes can be manifested as changes in the push-pull markets of tourism, whereby visitors may find destinations more attractive if the climate at home is less tolerable, or, conversely, whether the climate at a destination has changed to the point that visitors think again about the timing of their visit, or indeed, whether they should visit the destination at all (Hadwen et al., 2011). It lies beyond the scope of this paper to examine all of the global variables that can influence tourism seasonality, but it is useful to consider how the projected changes in climate (summarised in Table 1), might influence future patterns of visitation to Fraser Island.

In order to avoid extreme weather conditions, the current recommendations for walking on Fraser Island (from the BOM, 2010), is that optimal conditions exist between April and September. However, the climate of Fraser Island is generally pleasant all year round and there is no evidence to suggest that climate currently plays a critical role in determining visitation seasonality on Fraser Island (Hadwen et al., 2011). Instead, peaks in visitation occur during domestic holiday periods, particularly in Dec-Jan, March-April, June-July and September (Figure 3). In their study of drivers of visitation seasonality to protected areas around Australia, Hadwen et al. (2011) concluded that the proximity of Fraser Island to large population centres in southeast Queensland ensures a steady supply of visitors. In fact, visitation to Fraser Island follows a quad-modal annual pattern, whereby peaks in visitor numbers coincide with the timing of school holidays. In contrast to the other climate zones assessed by Hadwen et al. (2011), the absence of a climate-driver explaining visitation seasonality suggests that visitation to Fraser Island might be buffered against climate change impacts – because visitors will come, principally during school holiday periods, regardless of the weather.

Whilst current visitation patterns to Fraser Island are not tightly related to climate variables at present, the projected changes in Fraser Island climate (Table 1) will make the island less pleasant in summer than it currently is. Not only will summertime temperatures be higher, but increases in summertime rainfall, may, over time, also influence the timing of visits. If this occurs, the visitation seasonality to Fraser Island may change, with reduced summertime visitation due to climate.

DISCUSSION

HOW WILL CLIMATE CHANGE AFFECT THE ECOLOGY OF PERCHED DUNE LAKES?

In broad terms, the OzClim projections of future climate for 2030, 2050 and 2070 suggest a drier and warmer future for Fraser Island (Table 1). These changes in mean annual rainfall and temperature will also lead to an increase in evapotranspiration (also modelled from OzClim – Table 1), potentially to the point at which rainfall no longer exceeds evapotranspiration. The implications of these changes, for perched lakes in particular, are considerably greater variability in water levels and more pronounced drawdown of water levels, particularly in the drier parts of the year through autumn, winter and spring. Significantly, some perched dune lakes that are currently permanently wet waterbodies may become seasonally or intermittently (interannually) dry.

HOW WILL TOURISM RESPOND TO CLIMATE CHANGE ON FRASER ISLAND?

Notwithstanding the effects of climate change that fall beyond the scope of this paper, like damage to roads and the loss of capacity for beach driving due to storm surge and sea level rises (IPCC, 2007; Buckley, 2008; ANU, 2009), it is conceivable that the major response by visitors to the anticipated changes in rainfall and temperature is a reduction in visitation to the island in January. As shown in Figure 3, more than 10% of the annual visitor load is currently attributable to January, but if temperatures and rainfall increase in this summer period, we would anticipate that this percentage will fall. The implications of a loss of January visitors are likely to be strongly felt by tour operators, resorts and other forms of accommodation, many of which are already marginal businesses (Turton et al., 2010). However, it is also conceivable that increased temperatures and reduced rainfall for the remainder of the year (between March and November in particular) might see an increase in visitation during these months. In effect, we may see a shift in tourism seasonality, whereby January visits gradually shift towards more visits during autumn, winter and spring.

HOW WILL CLIMATE CHANGE AND VISITOR IMPACTS INTERACT AND INFLUENCE THE ECOLOGY OF PERCHED DUNE LAKES?

In the context of the conceptual diagram of the interplay between nutrient inputs from visitors and changes in climate (Figure 2), there are a number of likely outcomes given the projected changes in climate presented in Table 1.

First, there may be a greater and more pronounced export of materials from perched dune lakes to the adjacent terrestrial ecosystems, owing to extended annual dry periods from autumn through to spring. These aquatic subsidies may fuel significant new terrestrial/ecotonal production and, as such may, in time, change the nature of the fringing vegetation communities. For example, many species, like the carnivorous plants such as sundews (*Drosera spatulata*), which currently inhabit the intermittently flooded but predominantly terrestrial fringe of perched dune lakes, prefer (and therefore dominate) areas where nutrients are scarce. If periphyton- and ultimately tourist-derived nutrients are exported into these fringing habitats, these species may be replaced and outcompeted by species that can make the most of the increased aquatic subsidies.

If the exposed and decaying periphyton (and its constituent nutrients and carbon) are not incorporated into new terrestrial production, then major rainfall events, especially those anticipated in the projected wetter summer months (see Table 1), will deliver significant pulses of materials back into the lake environment. Coupled with this delivery of nutrients, the warmer temperatures anticipated throughout all seasons will likely stimulate significant algal production (Hadwen et al., 2005; Bleckner, 2008; Sipkay et al., 2009). The consequences and magnitude of these pulses could have significant ecological effects on the food webs and overall condition of perched dune lakes. Not only would the contribution of periphyton carbon to consumers likely increase (a further demonstration of how human activities can shift the base of aquatic food webs – see Hadwen & Bunn, 2004), but periphyton biomass is also likely to accrue at a rate that outstrips the consumptive capacity of grazers, resulting in nuisance levels of algal material in lake littoral zones. As suggested by Hadwen et al. (2005) and Hadwen and Bunn (2005), excessive periphyton biomass may have significant implications not just for the food web, especially if non-palatable forms dominate, but also for visitors, who do not wish to visit degraded or nutrient enriched sites within World Heritage Areas (see Hadwen & Arthington, 2003).

HOW SHOULD WE ADAPT TO ACCOMMODATE THE ANTICIPATED CHANGES IN CLIMATE AND TOURISM?

The tourism sector is incredibly adaptable and will no doubt make the most of any climate-induced changes in the accessibility or appeal of the island at certain times of year (most likely to be summer) (Turton et al., 2010). Indeed, the increased temperatures and reduced rainfall anticipated through the bulk of the year may increase annual visitation and in effect be an opportunity for the tourism industry, especially during the winter months, which do not currently have high visitation.

Changes in tourism, especially potential changes in tourism seasonality, have potentially significant consequences for the ecology of Fraser Island's perched dune lakes. If visitation does increase through the extended dry season (March – November), then visitor-mediated nutrient inputs during this period may have significant flow-on consequences for the productivity and ecology of lake ecosystems. As identified in our conceptual model (Figure 2), the implications of nutrient inputs during periods where lake levels are low or stable may be increased periphyton production and biomass accrual. Ultimately, the ecological consequences of tourist-mediated nutrient inputs in these increasingly variable perched dune lakes will be driven by the interacting effects of nutrient-stimulated littoral zone productivity and rainfall-stimulated changes in lake level, especially those dramatic changes likely to occur during high rainfall events. From an environmental management perspective, these changes and interactions add considerable complexity to the challenge of sustainably managing oligotrophic perched dune lakes on Fraser Island, but if we are mindful of these anticipated changes and can implement monitoring and early warning indicators now, the anticipated impacts may be manageable.

ACKNOWLEDGEMENTS

This work builds heavily on the Sustainable Tourism Cooperative Research Centre (STCRC) funded PhD research of WLH, so special thanks must go to all of the people who helped with that work, especially supervisors Prof Stuart Bunn and Dr Thorsten Mosisch and the late Dr Christine Fellows, WLH's wonderful wife, Eli Hadwen's amazing mother and an incredibly talented and valued colleague.

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