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Kakadu National Park Landscape Symposia Series 2007–2009

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The symposium received significant contributions from the Department of Climate Change and from Energy Resources of Australia Ltd – without these funds the symposium would not have been possible.

Thank you also to the management and staff of the Gagudju Crocodile Holiday Inn where the symposium was held.

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1 Introduction

The Climate Change Symposium is the fourth in the series of symposia and workshops being held by Kakadu National Park focusing on agents of landscape change. Previous forums have included a landscape change overview and workshops on weed and fire management. The remaining forum in this series will deal with feral animal management.

The aim of the symposium was to have an effective two-way transfer of knowledge between KNP staff, researchers, the Kakadu Research Advisory Committee (KRAC) members, stakeholders and Traditional Owners on issues pertinent to:

- climate change
- management implications and recommendations
- visions of landscape health and resilience
- future research directions

and to ensure that the outcomes of research are integrated in a timely and sensitive way into Park management.

The objective was to place this knowledge in a management context and pose questions to Park Managers and Traditional Owners regarding future management frameworks and research directions.

The symposium was held at Gagudju Crocodile Holiday Inn in Jabiru on 6–7 August 2008. Over one hundred participants from a wide range of stakeholders including government agencies, academic institutions, landholders, Traditional Owners and indigenous associations attended.

The format for the symposium included a series of presentations followed by workshops on each day focussing on key issues relating to climate change. Presenters and workshop facilitators were given a series of focus questions to assist in guiding the information presented and the subsequent discussions.

The focus questions given to presenters were:

- Summarise the current knowledge in the area of expertise you are presenting (refer to relevant KNP management objectives as outlined in the Kakadu 5th Plan of Management).
- What are the main threats to landscape health in KNP as a result of climate change (ie what are the priority management issues)?
- How should the Park manage these threats to maintain and/or restore a resilient and healthy landscape in KNP?
- What information is still required to develop effective land management policy, ie what are the key knowledge gaps?

Workshop facilitators were asked to discuss the relevant presentations and any future management or research implications. Workshop facilitators were given the following focus questions.

With reference to KNP’s management objectives as listed in the Plan of Management, how should forum participants best:

- Consider and review the issues, questions and recommendations posed by presenters in the context of their focus questions?
- Review how threats are currently being managed and make any suggestions for improvement?
- Manage for the impacts of extreme events related to their workshop topic?

Forum participants were also asked to consider:

- What are the opportunities resulting from climate change?
- What needs and opportunities exist for collaboration across the region?
- What are the implications for vulnerable habitats and species including migratory species?
- Are refugia a viable option to preserve threatened species and habitats?
- What can be done to increase the resilience of the landscape?

The forum was very successful and certainly met its objectives with a considerable amount of very useful information generated that will inform the management of Kakadu National Park. Much of the information is currently informing the Park’s Climate Change Strategy which is nearing completion. Thank you once again to all those who participated.

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2 The views of Kakadu National Park's Traditional Owners on climate change

S Winderlich[1]

2.1 Introduction

The purpose of this paper was to focus symposium participants on what a selection of Kakadu National Park (KNP) Traditional Owners thought and felt about climate change. In so doing, it was hoped that participants would use this information through the subsequent presentations and workshops to consider how best to respond to the issues raised by the Traditional Owners.

Any management action in KNP needs to be consistent with the relevant legislation and the Plan of Management. Hence, this paper also summarises the sections of the Kakadu Plan of Management (2007–2014) that relate to climate change. Extensive consultation with Traditional Owners was undertaken in the development of this plan, so it reflects the views of a wide cross-section of the Park's Traditional Owners. Additional coverage of the views of local indigenous people can be found in the paper by Yibarbuk and Cook and in the workshop summaries for the symposium. The views of some Papua New Guinea nationals on climate change are also presented.

This paper does not attempt to analyse survey responses or to cross-reference it with other literature and surveys undertaken elsewhere. The survey results are also not truly representative of the broader indigenous population in the survey region given the selective nature of the sample and its small size. However, the results outline some key issues and concerns from the indigenous groups sampled that are highly relevant to any discussion on the issue of climate change.

2.2 Methods

Questionnaires were prepared that asked participants to respond to several key questions relating to climate change. One was designed to sample the views of key Traditional Owners of Kakadu, and a second was tailored to residents of the Morobe District in Papua New Guinea (in particular, the Siassi Islands area). The questionnaires were used as the basis for one-on-one interviews with Traditional Owners. Twenty interviews were carried out in Kakadu by Parks staff in July 2008, and 16 residents of Siassi Island were interviewed by Aaron Winderlich in October and November 2007 as part of a Jabiru Area School assignment entitled 'Indigenous survey on global warming'. The responses were later summarised in a presentation and in this paper. Traditional Owners' views expressed at the Landscape Change Symposium (the first in this symposia series) have also been incorporated.

2.3 The Views of Kakadu's Traditional Owners

The views expressed by Traditional Owners in the survey during the Climate Change and Landscape Change Symposia are presented in point form under the relevant subject areas.

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2.3.1 What do the words 'climate change' mean to you?

- Changes in weather
- Changes in timing of seasons
- Changes in environment, atmosphere, fire and water
- Rivers getting bigger, creeks shrinking
- Uncertainty as to what climate change actually is and what it means for local people

2.3.2 How do you think climate change might affect Kakadu?

- Salt water intrusion on freshwater floodplains due to sea level rise
- Food sources, the impact on bush tucker and the ability to hunt
- Weather concerns include: what if no rain comes to stir up billabongs; increase in cyclones/ super cyclones bringing bigger tides.
- It's a problem for all of us

2.3.3 Have you noticed any changes in the climate or seasons since you were a child?

Most people noticed changes such as:

- later seasons
- later fruiting/flowering
- more weather extremes
- change in fire frequency or intensity

These changes have been noticed from last year to 30 years ago.

2.3.4 Is there anything that worries you about climate change?

- Changes in hunting – especially seasonal distribution and abundance of hunting resources such as geese, turtle and file snake
- Killing of plants and animals
- Not knowing what is coming
- Disease and the future for kids
- Extreme weather events. 'What else is going to happen?'
- Weeds and feral animals might get worse

2.3.5 Is there anything you think we need to find out that might help look after the country from the effects of climate change?

Communication and awareness

- Need experts to come and visit us, share their knowledge and explain what is happening
- Need to tell Bininj (Aboriginal people) what's happening, how it might affect them and what they should do to get ready

- Communication with people living on land who have experienced changes. Look at old stories. Not many people left.
- Need to go to talk to the Traditional Owners and work together
- Look for appropriate and traditional ways of discussing and transferring information
- Communicate to neighbouring coastal communities – not getting any information to these people – all people across the region are lacking information – sharing information with the region
- ‘No medicine to cure’ – we need to prepare ourselves to give indigenous people some understanding about what is slowly happening

Research

- Look at plants, fire
- Looking at where we are now – what effect impacts are having
- When it is going to start happening?
- Indicators put up on coast to measure if sea level is rising. Big tides, big floods.
- Effects of climate change on Eleocharis, native Hymenachne and, hence, its effect on magpie geese
- Which animals will be most affected and when?

2.3.6 Is there anything you think we should do now about climate change ?

- Look after the country and keep it healthy.
- Control feral animals and weeds.
- Not so much talking. Need to get out and do something.

2.4 The views of Siassi Islands residents in Papua New Guinea

On a recent visit to the Siassi Island area in the Morobe District of Papua New Guinea, Winderlich (2007) conducted an ‘Indigenous survey on global warming’ as part of a school assignment. The results are summarised in the following section.

2.4.1 Have the seasons changed?

- All participants agreed that the seasons are changing, becoming less predictable and moving forward in the calendar
- A lot said that it was raining in the dry season and sunny in the wet and that the fruit and vegetables were coming at different times
- Some said that the seasons were less predictable so you couldn’t tell if it was going to be sunny or rainy

2.4.2 How long have you been noticing changes?

- All participants agreed that the changes had been happening slowly but there was considerable variation in their perceptions of the period of time over which changes had

2.4.3 Have plants changed their growth patterns?

- Nearly all of the participants (15 of 16) noticed significant changes in the growth patterns of plants.
- The majority of respondents stated that garden plants and food plants from the bush (fruits and nuts) had changed their growth patterns significantly, which was a concern to them because of their reliance on these plants for food. They were particularly concerned about changes to staple food species such as yams, taro and sweet potato. Some said that because of the changes, gardens were planted at the wrong time which meant the plants did not get water and died.
- People talked about the rains coming later but staying longer which affected growing time for vegetables which disadvantaged some key species like taro, corn and beans, but some species were now growing that wouldn't before.
- Inhabitants on one small island made mention of increasing periods of rough seas and strong winds blowing salt water spray onto gardens and killing food plants. Wind breaks are constructed around islands and gardens because of this problem.

2.4.4 Have animals changed their behaviour?

Responses to this question were mixed. Seven people said yes, six said no and three weren't sure. Of those that responded 'yes', the changes listed included:

- Animals being affected by trees flowering later
- Island birds nesting and mating later, and dogs are mating later
- Changes in the breeding season for marine turtles. They were breeding later but because there were fewer predators at that time more marine turtles were surviving.
- Less fish and more crown of thorns starfish on their reefs
- It is not clear if all those changes can be attributed to climate change

2.4.5 Have people been affected

- Because the rain is coming later babies are coming later – because when it's wet, people don't have much to do
- It is getting hotter and drying up the gardens increasing dust making it hard to breath
- Cold and flu outbreaks are getting shorter because there is less time when it is cold and wet, but because it's getting hotter, malaria is spreading
- The time for growing certain food is becoming more unpredictable
- This is both bad and good. Good because the time for sickness is now shorter and bad because malaria is easier to get and it's harder to get certain foods.
- Another significant impact on this group of people, who rely very much on the sea, was that changes in the windy season had led to changes in the fishing season as rough seas make it harder to travel in small vessels.

2.4.6 Have the tides changed?

Fourteen of the 16 respondents said that the tides have changed and two had not noticed anything. Responses included:

- The tides are getting higher and lower, going out further and staying out for up to three hours in some places
- There is increased shoreline and beach erosion and some are building sea walls to prevent this. Particularly low lying islands are experiencing gardens being flooded and dying and many have to have gardens on the mainland that they row to each day.
- Higher tides are drowning turtle eggs
- On one small island people build fences under their houses not to keep animals in or out but to stop their belongings floating away when the tides are particularly high

2.5 Kakadu National Park Plan of Management climate change prescriptions

Management actions in KNP need to be consistent with the EPBC Act and the Plan of Management (Director of Parks 2007). Discussion and actions relating to climate change are found in section 5.6 of the current plan. The contents of this section are summarised below.

Section 5.6 Landscapes, soils and water

Our aim

The landscapes, soils and water systems of the Park are protected and priority areas that are eroded or disturbed are rehabilitated.

Climate change

In recent years global warming and its implications for climate change have emerged as key issues for biodiversity and environmental management on a global scale. In the Arnhem/Kakadu region, the predicted effects of climate change as a result of global warming include a rise in temperature, variation in rainfall patterns and amount, rising sea levels and changes in climate variability.

Some of the potential management implications in the Arnhem Land/Kakadu region are:

Biodiversity: Loss of some critical habitats (including freshwater wetlands), changes in the abundance and distribution of some animal and plant species and an increased risk in the spread of exotic plant and animal species.

Water resources: Potential increase in drought and flood activity; reduction of inland and coastal water quality and saltwater intrusion into surface and groundwater resources.

Extreme weather: Increased frequency of extreme heat days and rainfall events and an increase in the intensity of tropical cyclones.

Fire: Changed fire regimes.

Bininj use of the Park: Possible changes in access to hunting areas and changes in abundance of foods.

Human health: Increase in heat-related illness; expansion of mosquito born viruses and an increase in injuries from extreme weather events.

Buildings and infrastructure: Increased infrastructure maintenance costs and the need to relocate infrastructure from high risk areas.

In the life of the Fourth Plan, a range of landscape and biodiversity monitoring/research programs were conducted including, fire plot monitoring and landscape change research. These and other similar programs provide valuable baseline data to detect landscape and biodiversity changes in the Park and may assist to monitor climate change impacts in the future.

In 2006, the Director of National Parks commissioned a study of the potential implications for climate change for management of Commonwealth reserves, including Kakadu. The results of this investigation will contribute to an improved understanding of and preparedness for changing conditions in Kakadu.

Issues

- A better understanding is needed of the different influences on landscape change in order to make decisions about levels and types of change that are within acceptable limits.
- Global climate change may have a range of impacts on the Park's natural and cultural resources, infrastructure and tourism value and opportunities. Bininj use of the Park may also be affected. Up-to-date expert information will continue to be needed to assess impacts and the risks of climate change, identify environmental monitoring indicators and to identify adaptive management measures to mitigate its impacts where possible.
- To more effectively undertake rehabilitation and protection measures, more needs to be known about how factors such as fire, weeds, feral animal impacts and floods interact in influencing the landscape during the different seasons and how their effects vary across different landscape types and vegetation communities.

What we are going to do

Policies

5.6.1 If parts of the landscape are changing in ways that are of concern, the Director and Bininj, in consultation with relevant stakeholders, will jointly decide on further monitoring requirements, and whether protective, rehabilitation or adaptation measures are feasible. If cost-effective, appropriate actions will be implemented.

5.6.10 An integrated approach will be taken in landscape management issues, such as fire, ferals and weeds in the various habitats in Kakadu (see also Section 7.2 Neighbours, stakeholders and partnerships).

Actions

5.6.11 Obtain expert engineering and environmental advice on measures needed to protect significant freshwater habitats from salt water intrusion. Work with Bininj and stakeholders to make decisions about the need for intervention and the choice of available options.

5.6.12 Identify priorities for further research or integrated monitoring programs to study the causes and effects of landscape change, how these processes interact and how effects vary across different landscape types and vegetation communities. Use this information to refine decisions about acceptable change.

5.6.13 Work with relevant experts and stakeholders to investigate climate change impacts and consider, and where possible implement, appropriate actions and responses.

2.6 Conclusions

The results of these questionnaires indicate that, as in much of the broader Australian community, the Traditional Owners of Kakadu and of the Siassi Islands of Papua New Guinea have concerns about the potential impacts of climate change on their country and their livelihoods. Because of their close association with the land and seasons, the Traditional Owners have already noticed changes that they attribute to climate change, more so than the wider community. In Papua New Guinea the residents were asked several questions about the changes they had noticed in seasons, plants, animals and people, and their responses indicate their close reliance on their gardens and the marine environment for subsistence. In Kakadu, fewer questions related to their perceptions of change and more probed their understanding of the potential impacts of climate change and what needs to be done to prepare them for those impacts. Traditional Owners of Kakadu reported changes in seasonality, the extremes of weather and the patterns of fire, and they are concerned about these changes intensifying.

It is apparent in the Kakadu surveys that one major area of concern for Traditional Owners is the uncertainty of the impacts of climate change. There is a clear call for greater information on the potential effects of climate change on the Kakadu climate, environment and biodiversity, and clear communication of that knowledge to the people. There is also an expectation or perception that current climate change science can provide accurate predictions of the timing and scale of impacts – an expectation that is, unfortunately, unrealistic. Providing clear information on the probabilities, possibilities, scale, and breadth of climate change impacts into the future to the Park's Traditional Owners and other stakeholders is a particular challenge facing scientists and Kakadu National Park managers.

The current management plan for Kakadu National Park (Director of National Parks 2007) recognises the potential for climate change to have major impacts on the environments and biodiversity of Kakadu, as well as on the lives and lifestyles of the Traditional Owners. It incorporates many of the concerns expressed by the Traditional Owners and sets out a framework to work closely with the Traditional Owners to ameliorate the worst impacts likely to affect the Park and its peoples over different time frames.

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3 Climate change, fire regimes and biodiversity conservation: A national perspective

RJ Williams[1], RA Bradstock[2], GJ Cary[3], NJ Enright[4], AM Gill[3], AC Liedloff[1] & C Lucas[5]

3.1 Introduction and background

The impact of climate change on Australia's fire regimes, and the management of fire regimes for biodiversity conservation will depend on the direct impacts of climate change on fire regimes, the interactive responses of species and ecological functional types to changes in climate, elevated atmospheric CO_2 and changed fire regimes, and the choices Australian society makes in mitigating and adapting to climate change.

This paper is a brief summary of work undertaken for the Federal Department of Climate Change on the impact of climate change on fire regimes, and their management for biodiversity conservation. The work complements two recent assessments of the impacts of climate change on biodiversity undertaken by the Department of Climate Change (DCC). These are 'A strategic assessment of the vulnerability of Australia's biodiversity to climate change' (Steffen et al 2009); 'Implications of climate change for the National Reserve System' (Dunlop & Brown 2008). The project was national in scope, was conducted by a multi-disciplinary research team, and involved State and Federal management agencies through the CLAN (Climate Adaptation and Natural Resources) network.

Our approach is to focus on potential impacts of climate change on fire weather and fuel, how this might affect fire regimes, and how this in turn might affect the local dynamics of species and ecosystems. In discussing these interactions, we explore the biogeography of fire regimes in Australia, and investigate specific interactions in four case studies in different parts of northern and southern Australia.

3.2 Research findings

3.2.1 Climate change and fire regimes

Examination of weather data from south-eastern Australia over the period 1973–2007 has indicated that fire-weather risk has increased, with more days of very high and extreme fire-weather. Fire danger (as measured by the annual sum of the Forest Fire Danger Index, (FFDI) rose by 10–40% at many sites from 2001–2007 relative to 1980–2000. Upward trends in (FFDI have also been detected elsewhere in Australia. Climate change projections are for continued warming and decreased humidity across Australia. Modelling suggests an increase

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of 5–65% (depending on location and emissions scenario) in the incidence of extreme fire danger days by 2020 in south-eastern Australia. Thus, further increases in the frequency of extreme fire-weather events in this region are likely.

There is a general positive relationship between mean annual rainfall and fuel production within fuel types. Reductions in rainfall are likely to result in reductions in vegetation productivity and therefore fuel accumulation rates and equilibrium loads, assuming no change in decomposition. An example of the potential impacts of 20% lower rainfall on fuel loads is provided for the karri and jarrah forests of SW Australia. Lower fuel accumulation rates and decreases in equilibrium fuel loads (reflecting decreases in forest productivity) of up to 50%, are indicated.

The impact of rising atmospheric CO_2 on fuels is uncertain, and will depend on changing patterns of moisture and temperature. Increased CO_2 may increase vegetation productivity, leading to more litter and grass fuels. Furthermore, the C:N ratio of litter (a measure of its propensity to decay or be consumed) may rise, resulting in slower litter decomposition or reduced palatability to herbivores. A major impact on fuel dynamics in coming decades will occur because of the spread of invasive species. Exotic grasses such as Gamba grass (*Andropogon gayanus*) can increase fine fuel loads by 5 times in tropical savannas. Other examples include Buffel grass (*Cenchrus ciliaris*) in arid hummock-grass systems.

Modelling climate change impacts on fire regimes is possible for some regions of Australia using current landscape fire models. We present an example for the Australian Capital Territory region using the spatially-explicit FIRESCAPE fire simulation model. This suggests that area burnt may increase, and intervals between fires may decrease significantly with a moderate warming scenario of 2^{o}C. Increases in simulated area burned with warmer climates accord well with other international studies on climate change and fire regimes, using similar landscape fire models.

Fire regimes across Australia currently vary because of variation in the rate of vegetation (and hence fuel) production, the rate at which fuels dry out, the occurrence of suitable fire weather for the spread of fire across the landscape, and ignitions. Regional fire regimes differ because of variation in one or more of these key drivers. As a consequence, fire regimes in some areas are constrained primarily by availability of fuel, in others by the occurrence of periods of suitable weather. Climate change can be expected to affect fire regimes under both circumstances, but by differing mechanisms. For example, in arid and semi-arid systems, where grassy fuels predominate, fire activity may decline if rainfall declines. In contrast, in temperate sclerophyll vegetation, where woody fuels predominate, more frequent days of high fire danger are likely to result in an increase in fire activity. Future fire regimes will also be affected by other agents of change, such as invasions of exotic species.

3.2.2 Climate change, fire regimes and biodiversity – four case studies

We explore the interactions between climate change, fire regimes and biodiversity in four case studies: (1) the alpine ash forests of south-eastern Australia, (2) the sclerophyllous forest and shrubland vegetation of south-western Western Australia, (3) the tropical savannas of northern Australia and (4) the sclerophyllous vegetation of the Sydney basin in south-eastern Australia.

Case Study 1: Alpine ash forests of the south-east highlands

The tall alpine ash (*Eucalyptus delegatensis*) forests of south-eastern Australia are relatively well known ecologically and so provide a benchmark for what we know and what we need to know if realistic predictions about the impacts of changed fire regimes on biodiversity are to be made. Being an obligate seeder, populations of the species are killed by fires of sufficient intensity to scorch the crown completely. Under enhanced atmospheric CO_2 concentration, the productivity of the forest may rise, resulting in higher fuel loads. With changes in weather towards drier and warmer conditions, the chance of fire occurrence would be expected to rise. All these changes point towards an increased risk of local extinction of alpine ash if fire return intervals fall below the period needed for juveniles to flower and seed. However, the species may be able to migrate (altitudinally) in response to warming. Alpine ash is an ideal target species for monitoring, and reacting to, any changes observed in the distribution as a consequence of changes to climate and fire regimes.

Case Study 2: Mediterranean forests and shrublands of south-west Western Australia

South-west Australia is one of 25 global biodiversity hotspots and its unique flora and fauna is potentially very vulnerable to the likely deleterious impacts of climate change. The vegetation ranges from tall forest to shrubland as a consequence of variation in moisture availability and soil nutrients. Under a climate change scenario of continued warming and drying, plants will show reduced growth rates and slower post-fire recovery rates, and communities will show lower fuel accumulation rates, if temperature and moisture act alone. CO_2 fertilisation may also affect fuels, but in an ecosystem specific way. In dry woodlands and shrublands drought effects might more than offset any potential CO_2 fertilisation effects. In contrast, in wetter forest areas, growth and fuel conditions might be maintained due to greater water-use efficiency brought on by CO_2 fertilisation. A greater frequency of high to extreme FFDI days under future climate change is likely to result in reduced intervals between fires.

A warmer, drier climate will make sensitive and restricted habitat types, including riparian zones and wetlands, more vulnerable to fire. These habitat patches support a high proportion of species with fire sensitive populations of plants (ie obligate seeders) and habitat dependent fauna (eg quokka and some ground nesting bird species) relative to the surrounding forest matrix. Projected climate shifts are also likely to increase the time to reproductive maturity for many perennial plant species (by slowing growth rates), so that estimated minimum safe fire interval may increase while actual interval is projected to decrease. Although such impacts are likely to be greatest on obligate seeder plant species, resprouter species may also show gradual population decline. Given the high biodiversity values of south-west WA, further research is warranted to investigate the interactive effects of climate change and fire regime change as threats to the biodiversity of this globally important region.

Case Study 3: Tropical savannas of northern Australia

The vast landscapes of northern Australia are dominated by savannas – a more or less continuous cover of C4 grasses and a variable cover of trees. The fire regimes in the savannas are driven primarily by the monsoonal, wet-dry tropical climate, which produces fine fuels annually during the wet season, which then dry off each dry season. Fire is very extensive. The mesic savannas of the Kimberley, the Top End of the Northern Territory and Cape York Peninsula have an annual abundance of tall tropical grasses, where neither fuel nor fire weather is limiting, and average fire frequency is about one year in two. In the semi-arid savannas, fire frequency is about one year in four, in Western Australia and NT, whereas in semi-arid Queensland, where properties are smaller, and land-use intensive, fire frequency is less than one year in ten. In arid savannas, dominated by hummock, spinifex grasses, fires are infrequent, and occur primarily in or following years of above average rainfall. Across the savannas, land use change (intensification of grazing; spread of exotic grasses) may exert a stronger influence on future fire regimes than climate change.

There is general resilience in the vegetation to variation in fire regimes, but there are also some plant species and vegetation types that are highly sensitive to variation in intensity and/or interval components of fire regime eg *Callitris*, some monsoon thickets, and heathlands of the Arnhem Land Plateau. Certain faunal groups, eg small mammals, are also sensitive to short fire intervals. Biodiversity monitoring programs have detected declines in a range of some faunal groups over the past decade; increased fire frequency and extent have been linked to this phenomenon, and climate change has the potential to exacerbate this problem. Targeted, active fire management strategies and programs for mitigation of fire, and associated biodiversity monitoring programs, both key components of current biodiversity conservation management, will become even more important under a regime of changing climate.

Case Study 4: Warm temperate sclerophyllous forests and woodlands of the Sydney Basin

The Sydney Basin has a high diversity of vegetation types and species, and includes high numbers of obligate-seeding plants. The distribution of plant functional types is partly affected by gradients of temperature and moisture. A warmer and drier climate may favour obligate seeders over resprouter functional types, predisposing vegetation to structural and compositional change under any regime of higher fire frequency.

Simulation modelling indicates that increases in FFDI could result in increased area burned. The consequences of such changes in fire regimes for biodiversity are, however, mixed. Shifts in inter fire interval (IFI) were predicted to be insufficient to significantly change landscape-scale extinction probability of IFI-sensitive plant species, assuming prescribed burning is held at current levels. In contrast, the probability of crown fires may increase by up to 20% under the high emissions scenario. Elevated risks to people and property, intensity sensitive populations of some taxa (eg arboreal mammals) and soil stability may ensue. The effects, of warming and drying on fire weather and hence area burned,, may outweigh any diminution of fuel loads caused by declining moisture.

Prescribed burning can have major effects (positive and negative) on biodiversity, catchments and human protection. Moderate increases over current levels of prescribed burning (eg 2–3 fold increase) are unlikely to increase risk to the integrity of plant diversity in the widespread, species-rich dry sclerophyll vegetation.

3.3 A response framework for fire-biodiversity management

The primary implication of our analyses for the management of fire in areas managed for biodiversity conservation is that fire management at landscape scales is likely to become more complex in the coming decades. However, because of the uncertainty and complexity of climate-change fire-regime biodiversity interactions, management prescriptions or guidelines require much further development. Hence, there are no prescriptive, generic ‘solutions’ to the problem of mitigating risk to multiple values and assets posed by climate change to fire regimes in areas managed for biodiversity conservation. Monitoring the spatial and temporal components of fire regimes at landscape scales and understanding thresholds and domains of concern for impacts of variation in disturbance regimes on biodiversity are two critical areas for further collaborative multi-agency research.

Prescribed burning will continue to be an important component of fire and biodiversity management. There have been calls, especially in south-east Australia, for more prescribed burning in the landscape, partly as a strategy to mitigate fire risk in the face of climate change. Modelling from the Sydney Basin suggests that feasible levels of increased prescribed burning (eg 2–3 times) would result in only modest risk reduction to urban and other ecological values sensitive to fire intensity. Larger increases in prescribed burning (ie > 5 fold) would be needed to counteract effects of warmer (high emissions) high climate change scenarios, but such an increase may not be feasible on the basis of cost and resources. Benefit-cost analysis of various prescribed burning options (treatment strategy; area burnt) as a function of risk to various landscape values (life, property, biodiversity, water) and developing and refining the means to evaluate the effectiveness of fire management actions against stated land management objectives are urgent research needs.

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4 River flow and climate in the 'Top End' of Australia for the last 1000 years, and the Asian-Australian monsoon[1]

RJ Wasson[2] & P Bayliss[3]

Abstract[4]

A 1000 year record of fluvial mineral sediment deposition on the Magela Plain and in a floodplain of the Daly River in the monsoon tropics of Australia reflects changes to rainfall. This record is believed to be representative of the 'Top End' of the Northern Territory of Australia because modern flow in the Magela Creek is highly correlated with flow in other rivers in the region, including the Daly River. The Magela record shows high flows at ~1000 years ago, falling to a low ~500 years ago, rising to present levels by ~250 years ago. This record is qualitatively similar to others from the Australia-Asia Monsoon region, and is consistent with a reconstruction of SST in the NIÑO-3 region of the Pacific. El Niño-like conditions appear to have dominated ~500 years ago. This analysis suggests that there is coherence in the long-term history of the Australia-Asia Monsoon, and that the impact on climate of solar irradiance is moderated by the Bjerknes feedback mechanism.

4.1 Introduction

Identifying human-induced climate change requires knowledge of natural climate variability and change (Jungclaus 2009). Considerable progress has been made in documenting and understanding the climate of the last 1000 years (eg Mann 2006, Mann et al 2000, the Millennium Project http://ralph.swan.ac.uk/millennium/). A key hypothesis that has emerged from this research is that El Niño mediates the solar influence on climate by means of the Bjerknes feedback mechanism both in the ENSO-dominated region and further afield (eg the N Atlantic) (Emile-Geay et al 2007, see also Asmerom et al 2009). If this hypothesis is correct, the irradiance-drive changes to ENSO should be synchronous in both Hemispheres. The 'water-hosing' hypothesis of Zhang and Delworth (2005) by contrast would be supported if changes to ENSO were not synchronous in the two hemispheres. A key gap in knowledge, and therefore a limit on tests of the two hypotheses, is the small number of palaeoclimatic records for the last millennium in the Southern Hemisphere.

In this paper, palaeoclimatic records for the last millennium, based on fluvial deposits, are provided from the monsoon tropics of Australia. The modern climatic and hydrologic setting of the area is examined to provide a basis for both interpretation and explanation of the sedimentary records. Also, comparisons are made with palaeoclimatic records from the Asia-Australia Monsoon region, obviously on both sides of the equator. The new data from the Southern Hemisphere support the hypothesis of Emile-Geay et al (2007).

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1 This paper is under review for journal publication – anyone wishing to use the material should contact Professor Bob Wasson or Dr Peter Bayliss first.

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4 Keywords: Northern Australia, Magela Plain, Daly River, history of streamflow, ENSO, PDO, monsoon.

Almost all rainfall and flood flow in streams in the far north of Australia occur during the austral summer (or northwest) monsoon (Taylor & Tullock 1985). This is driven by southward movement of the monsoon trough (or ITCZ) in which both low pressure systems and tropical cyclones form. The rainfall is modulated by ENSO, and the Madden-Julian Oscillation (MJO) with a 30–60 day period (Wheeler & McBride 2005, Suppiah & Hennessey 1996). Variability on longer time-scales is also suggested (Power et al 1999a, Power et al 1999b, Allan 2000).

Inundation of the large floodplains of the far north is determined by the summer monsoon onset, duration, and intensity, including the impact of individual low pressure systems within the monsoon. The biota responds to the highly seasonal rainfall in a variety of ways (Bayliss 1989, Bayliss & Yeomans 1990, Finlayson et al 1990, Whitehead 1999, Bowman 2002), and Indigenous people adapted their traditional lifestyle to the wet and dry seasons (Russell-Smith et al 1997).

In this paper a 1000 year record of sedimentation on the Magela Plain in Kakadu National Park in the 'Top End' of the Northern Territory (Fig 1) is used to infer climate change and is compared to global forcing factors to identify both long-period changes and their possible causes. In addition, a sedimentary record on the Daly River, ~320 km southwest of Magela Creek, is included.

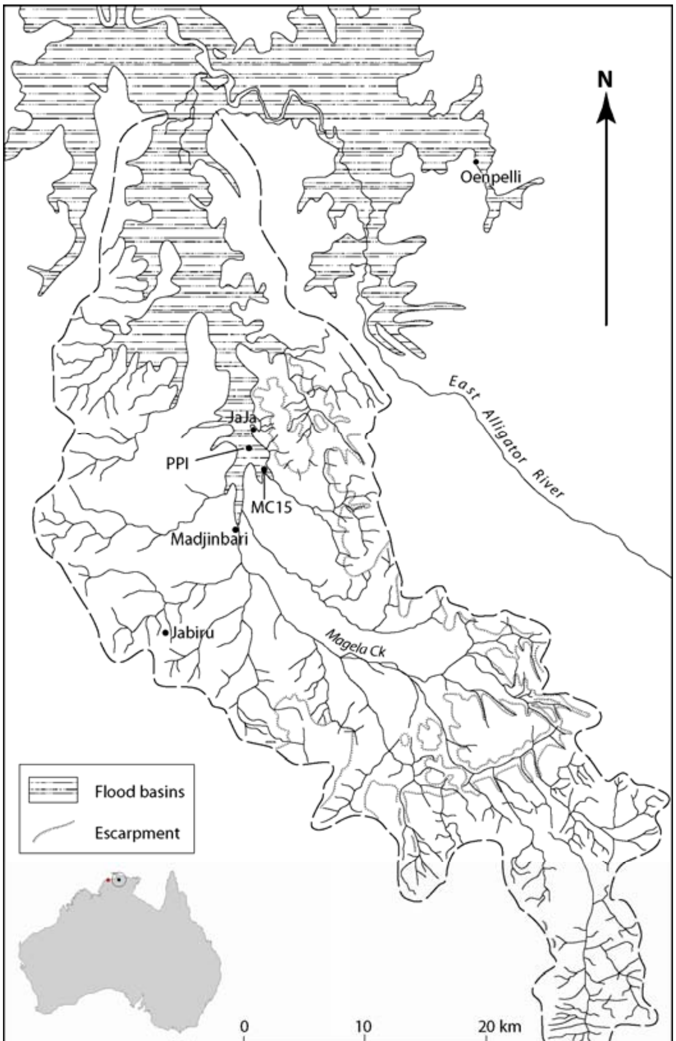

Figure 1 Location Map of Magela Creek catchment and floodplain, Kakadu National Park, Australia. Madjinbari and Leichhardt billabongs, Kawudjulah Creek and sample sites PP1 and MC15 are indicated also.

4.2 The Magela plain

The Magela Creek catchment has an area of 1570 km^2 at its junction with the East Alligator River (Fig 1). The creek rises on the Arnhem Land Plateau in rugged and resistant Kombolgie Sandstone. After passing over a spectacular escarpment, the creek flows for 30 km in sandy anastomosing channels into Madjinbari Billabong. Downstream there is no distinct channel, and flow occurs across the Magela Plain. This is a flood basin of ~200 km^2 in area that behaves as a seasonal swamp, which is between 2 and 5 m above sea level (Wasson 1992, Nanson et al 1989, Jansen & Nanson 2004).

More than 80% of the mean annual rainfall of 1503 mm at Jabiru (1971–2007), which is adjacent to Magela Creek, falls during the monsoonal months of December to March, with a more variable rainfall regime during the shoulder periods of the Wet Season, ie October to November and April. During the dry season (May to September) Magela Creek ceases to flow for several months and the Magela Plain dries, except for a few low lying areas and billabongs. Mean maximum temperature is 37.6ºC in October and 31.6ºC in June and July. Class A pan evaporation averages 2606 mm/yr at Jabiru. The mean annual flood ($Q_{2.3}$) at flow gauge GS-8210009 (~10 km upstream of Madjinbari, Fig 1) on Magela Creek is 525 m^3/sec, which is >13 times bankfull discharge (Jansen & Nanson 2004). On the annual series, the 10 year flood is 1180m^3/sec. The average wet season runoff coefficient was 37% between 1971 and 2006 (D Moliere, pers comm)

Changes in annual vegetation on the Plain are correlated to changes in rainfall pattern at the shoulders of the wet season, as well as the magnitude and duration of the monsoonal rains (Finlayson 1993). But downstream of Madjinbari Billabong and upstream of Leichhardt Billabong (Fig 1), the area of focus for this study, the dominants are *Melaleuca* open forest and woodland around the margins and a *Pseudoraphis* grassland with scattered *Melaleuca* trees across the plain (Finlayson et al 1989).

The history of the Plain for the purposes of this paper begins with the transition from the 'Big Swamp' mangrove phase that developed as sea level neared its current position following the last deglaciation. The transition zone consists of Grey Clay that formed on mudflats, part of which developed under freshwater conditions. Fully freshwater conditions formed on top of the transitional clays as sediments transported from upstream raised the surface level of the Plain. Organic-rich dark brown/black clay formed during the freshwater phase, and continues to accumulate. The freshwater conditions have so far lasted between 1000 and 2000 years (1 to 2 ka) (Wasson 1992).

4.3 The dark brown/black clay

This sedimentary unit forms almost the entire surface of the Plain, but only the upstream 15 km will be discussed here because it is closest to the inflow from the upstream catchment and therefore reflects changes of flow in Magela Creek and a major tributary. While most of the unit is moderately organic-rich (up to 10% org C) and dark in colour, there are thin beds of yellow and grey-yellow silty clay that usually have lower concentrations of organic C. These pale layers are rich in biogenic silica consisting of phytoliths, diatom valves, sponge spicules and gemmules, and scales and resting spores of chrysophytes (Wasson 1992).

Two sites were examined in detail (Fig 1). Site PP1 is located on the main Plain where most minerogenic sediment comes from Magela Creek. Site MC15 receives most of its minerogenic sediment from Kawudjulah Creek, a major tributary. The samples from each pit were treated to remove organic matter, and the biogenic fraction determined by density separation. The remaining fraction is minerogenic, that is, mineral sediment transported by runoff from the catchment.

The age of the sediments was determined by two methods: ^{14}C and ^{226}Ra (excess). Thirty ^{14}C dates for fine charcoal and leaf material from 18 sites show that the base of the dark brown/black clay has a weighted mean age of 1980 ± 120 cal BP, ~30BC (Wasson 1992). An excess of ^{226}Ra over its parent ^{230}Th is observed in surface sediment of the upper reaches of the Plain. This has been used as a dating tool by measuring the ^{226}Ra (excess) with depth. The approach and analysis is detailed in Wasson (1992). To use this technique it has to be assumed that both the ^{226}Ra and ^{230}Th concentrations at the time of deposition, and the sedimentation rate, were all constant. These assumptions were tested by using ^{14}C at the same sites used for ^{226}Ra (excess) determinations. The assumption of a constant sedimentation rate (within the uncertainties) was verified.

The minerogenic flux at the two sites is presented in Figure 2. At MC15 a 1cm sampling interval (equivalent to ~40 years) was adopted because there was almost no evidence of bioturbation. At PP1 a coarser sampling interval was based on intact sedimentary boundaries between which bioturbation appears to have occurred.

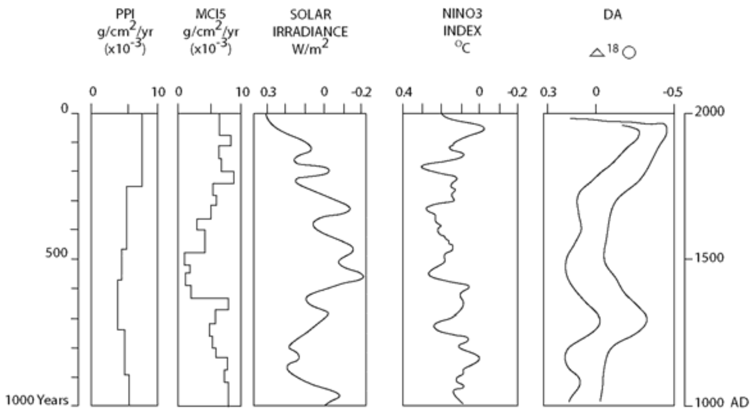

Figure 2 Minerogenic flux at PP1 and MC15 (based on Wasson 1992), solar irradiance anomalies smoothed with a 40 year low-pass filter. (from Crowley, 2000), NIÑO3 Index (from Mann et al 2005), and the envelope of 5 yearly resolution variations of proxy SW monsoon rainfall in a speleothem (DA) in Southern China (from Wang et al 2005). Note that samples at MC15 were taken in 1985 and at PP1 in 1986. The properties of the top sediments have been assumed to occur through to 2000, given the temporal resolution of the sampling.

4.4 The minerogenic flux and past discharge

The minerogenic fluxes at both sites show broadly the same pattern. Between 1000 and ~1360 AD at MC15 the flux was high then rapidly fell. It remained at about the same low value between ~1360 and 1500 AD and then steadily rose until ~1760 AD. Between ~1760 and 2000 AD the flux was nearly constant.

The present-day annual average specific suspended sediment load in Magela Creek a little way upstream from site PP1 (where the catchment area is 600 km^2) is 9 $t/km^2/yr$. At Kawudjulah Creek the yield is 19 $t/km^2/yr$ from a catchment of 63 km^2 (Wasson 1992). Assuming that the sedimentation rate on the Plain is proportional to the sediment yield of the input stream, the pattern of change over the last 1000 years shows that at PP1 the lowest sediment yield was ~60% of the current yield. At MC15 the yield was only ~30% of the current value; that is, ~6 $t/km^2/yr$ in both creeks, averaged over ~40 years.

Sufficient data are available only for Magela Creek to adequately define the sediment load/discharge relationship as follows:

$L=0.32Q^{1.33}$ $r^2=0.91$ $n=45$ SE=+123,-55%

where L is load (tonnes/day) and Q is discharge (m^3/sec).

The lowest minerogenic flux at PP1 is equivalent to 60% of the current discharge, assuming the same load-discharge relationship. This is probably a minimum reduction of discharge because the coarse sampling interval at PP1 has most likely smoothed variability and therefore the lowest minerogenic flux may not be properly represented.

4.5 Biological change at PP1

A surprising feature of PP1 (and MC15) is that the total (minerogenic, organic, and biogenic) sedimentation rate is constant within the uncertainties of ~6% (at 1σ) for the last 1000 years, as seen earlier. This implies that as the minerogenic flux declined there was a compensatory increase in biogenic deposition, given that this is the only other significant component of the sediment. Organic matter is generally <10% of the total material.

Figure 3 shows indicators of biological change at PP1, from Wasson (1992). Organic C is lowest between 1260 and 1440AD, being higher both before and after this period. Phytoliths of vascular plants are in greatest abundance during the period of lowest organic C, being lower both before and after. Diatom values show a small irregular increase through time, and sponge remains are lowest at the time of lowest organic C. Pollen is sparse during the period of low organic C, suggesting a period of both small pollen production and/or a dry period during which oxidation destroyed the pollen. This was the period of lowest minerogenic flux (Fig 2) and therefore river discharge. Before the period of sparse pollen, aquatic macrophyte and Poaceae pollen co-vary, while aquatic macrophyte pollen is not detectable between 1360 and 1760AD, and grass pollen is sparse. Between 1760 and 2000AD grass pollen is most abundant in the record and aquatic macrophyte pollen re-appears. During the entire 1000 years, Myrtaceae pollen (*Eucalyptus* and *Melaleuca*) dominate, blown or washed in largely from the upland areas around the Plain.

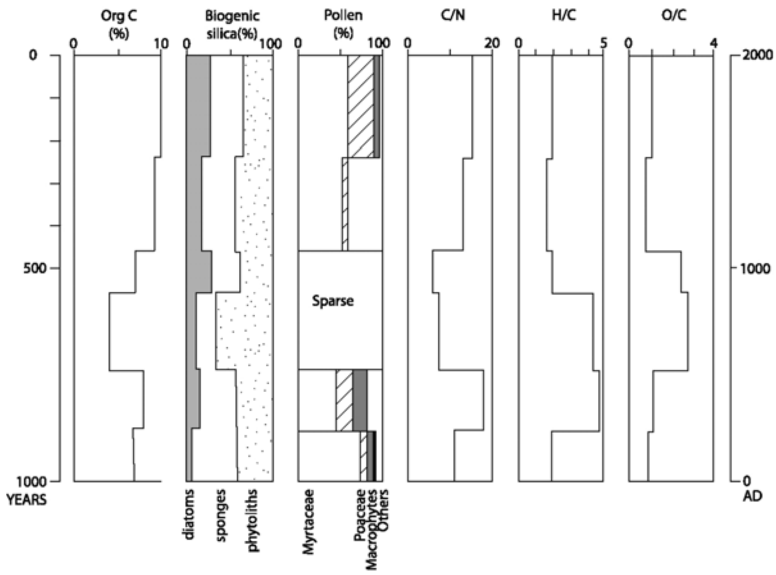

Figure 3 Indicators of biological change at PP1

There is a positive correlation between organic C and biogenic silica percentages (r=0.970, n=11, P<0.001), suggesting that the silica reflects vegetation biomass on the Plain. Most of the silica is from vascular plants in the form of phytoliths, and most of the diatoms and sponges are epiphytic to the vegetation of the Plain. Given this picture, the chemistry of the organic fraction may reflect the breakdown of vascular plants. The atomic ratios C/N, H/C and O/C in organic matter at PP1 were determined (Fig 3) to test this proposition. According to Steelink (1985) and J Head (pers comm), the following guidelines can be used:

1 Low H/C, low O/C and high C/N indicate vascular plant degradation products of the polyphenolic (aromatic) kind.

2 High H/C, high O/C and high C/N indicate the degradation products predominantly of algae, and are largely aliphatic.

From these guidelines, most of the organic matter at PP1 is from vascular plants. However, during the period 1260–1540 AD when organic C was low and phytoliths at their maximum, most of the organic matter was from algae. This is a contradictory result, because phytoliths are not produced by algae.

The alternative explanation of the atomic ratios is that the C/N ratio of 20 or more implies resistance to degradation, while a ratio of 10 indicates substantial destruction (Wasson 1992). The broad similarity between variation in C/N and minerogenic flux (and therefore discharge) suggests that during wet periods organic matter is preserved and during dry periods it is destroyed. The biogenic silica microfossils are generally well preserved, although often broken, but without signs of dissolution. Therefore they are likely to be the best indicator of the vegetation on the Plain, given that the pollen record is incomplete. Interestingly, the Plain appears to have been dominated by vascular plants during the driest period, many of which appear not to have supported epiphytic diatoms and sponges. Much of the Plain may have supported land plants rather than aquatic plants at a time when rainfall and discharge were low.

4.6 Causes of hydrologic change in the Magela Creek catchment

4.6.1 Short-term records

Annual rainfall is the major determinant of annual stream flow in tropical catchments. Analysis of annual rainfall-flow relationships in the Northern Territory tropics encompasses the period September-August to capture the entire wet season (Moliere et al 2004, Moliere 2007). For the period 1971 to 2006 the regression between Magela Creek (at Gauging Station, GS, 8210009) flow volume (Mℓ) and rainfall (mm) at the Oenpelli weather station, a longer record that that at Jabiru at a site ~50 km northeast of Magela Creek, is highly significant, explaining 56% of variation in flow (see Fig 4a & b; both variables transformed to $\log_{10}$). Similarly, for the period 1961 to 2006 the regression between flow volumes (Mℓ) in the Katherine River (GS8140001), a major tributary of the Daly River, and rainfall (mm, Katherine weather station) is highly significant, explaining 64% of flow variation (Fig 1d, both variables transformed to $\log_{10}$).

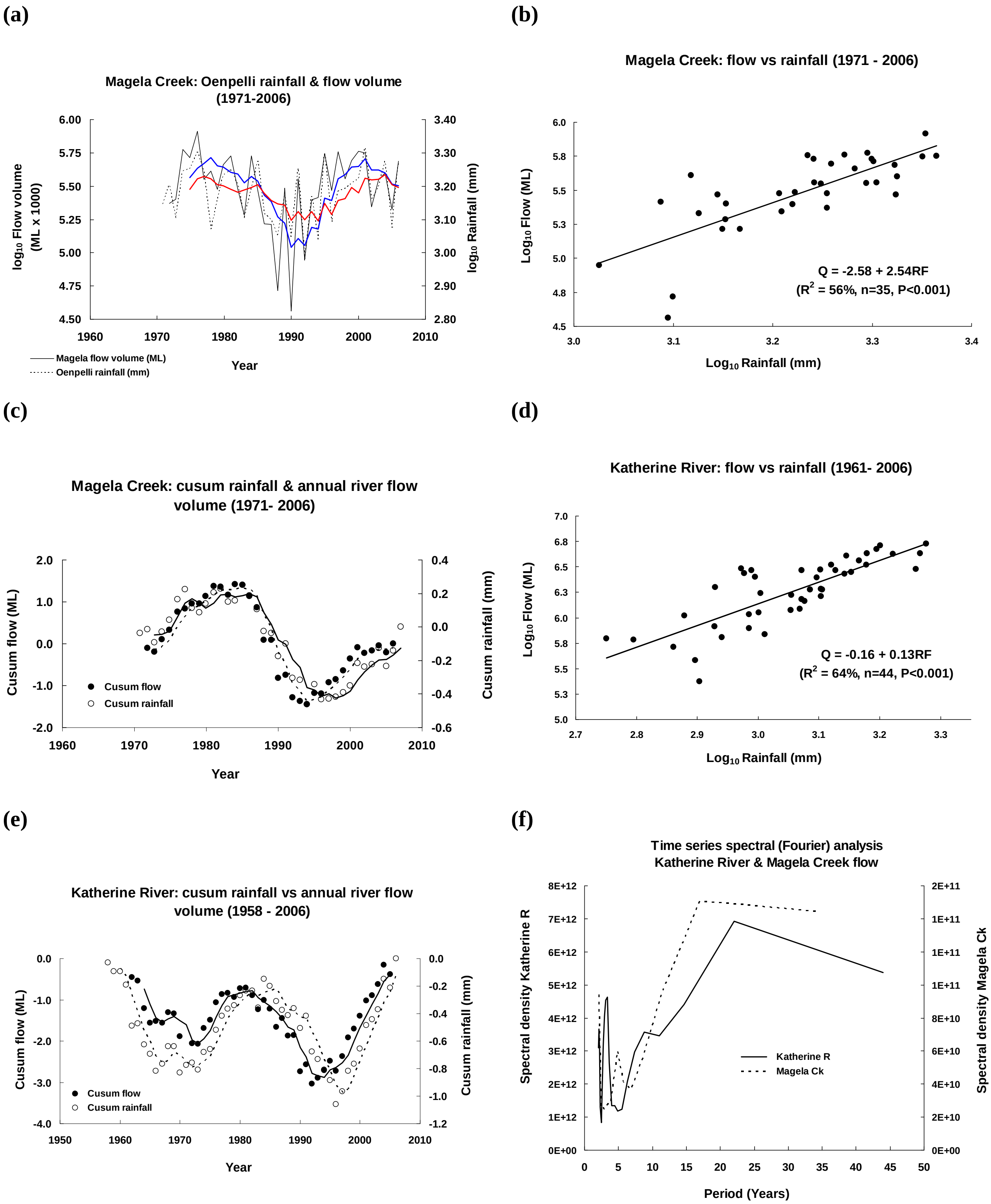

Figure 4a–f (a) Trends in annual September-August rainfall (RF, mm) and stream flow volume (Q, ML). Blue and red lines are 3y running averages for flow and rainfall, respectively. (b) Regression between Q and RF for Magela Creek (GS8210009) and Oenpelli weather stations, respectively, and (c) Cusum trends in RF and Q (1971-2006, lines are 3-year running averages) showing decadal trends. (d) Regression between Q and RF for Katherine River (GS8140001) and Katherine PO respectively, and (e) Cusum trends in RF and Q (1958–2006, lines are 3-year running averages) showing decadal trends. All data for a-e $\log_{10}$ transformed. (f) Time series spectral (Fourier) analysis for Magela Creek (n=35 y) and Katherine River (n=44 y) stream flow (untransformed) showing 18 y and 22 y periods, respectively.

The cusum (cumulative sum of the mean deviations of the time series; see Manly & MacKenzie 2003) trends of both rainfall and flow for the Magela Creek and Katherine River catchments all exhibit approximate 20-year decadal variations that are essentially in-phase (Fig 4c & e, respectively). Time series spectral (Fourier) analysis of annual flow volume indicates that the periodicities are 18 y and 22 y respectively (Fig 4f). A Kolmogorov-Smirnov 1-sample d statistic (Statsoft™ 2001) was significantly different from random white noise spectra for both Magela Creek and the Katherine River (P<0.01, for n=44 and, P<0.01 for n=34, respectively). However, Halley (1996) suggested that red noise, mid-way between white noise and the random walk, is the best null model of background environmental variation when attempting to separate signal from noise. The slopes of the power spectra (log_{10} power or spectral density vs. log_{10} frequency) of both time series were therefore compared with the slope of an equivalent red noise time series (= -1.5) being the null hypothesis, and were significantly different from red noise ($t_{(2)34} = 9.52$ & $t_{(2)44} = 9.23$, both P<0.001, respectively). However, the 'peaks' in the periodograms are not 'spikes' but rather broad bands in periods, especially for Magela Creek with 10 years less data than for the Katherine River. Such broad bands in periodicities of flow, in contrast to precise periods, most likely reflect natural variability that exists within and between streams in the 'Top End' of the Northern Territory due to catchment and local weather differences.

The analysis of interdecadal physical (and biological) variability is even the more challenging because of the relative shortness of available time series (Rudnick & Davies 2003), particularly for gauged stream flow data in northern Australia. Pusey et al (2009) analysed record lengths of continuously gauged stream flow data up to the year 2000 for records greater than 10 y, and found that the mean record length was 36 y with the longest record length being 123 y (NSW). The mean record length in the Northern Territory was 27 y with the longest record being 55 y. Time series analysis of decadal trends in flow volume of four other major streams across the 'Top End' of the Northern Territory with gauging records greater that 40 years all exhibit approximate 20–25-year periodicities as with Katherine River flow (Bayliss et al 2007a). This shows that, at least for the modern era, the record in the Magela Plain reflects change over a large area of the 'Top End' of the Northern Territory. Analysis of longer-term continuous rainfall (up to 122 y) and flow (up to 83 y) records in northern Australia outside of the 'Top End' of the Northern Territory also show approximate 20–25 y period trends, although the longer the time series additional lower (60 y) and even higher (10–11 y) frequency periods may become clear (Bayliss et al in prep.).

The El Niño-Southern Oscillation (ENSO) phenomenon affects climate over large areas of the globe, including Australia. El Niño tends to increase the chance of dry weather conditions and, in contrast, La Niña tends to increase the chance of wet conditions (Power et al 1998, Nicholls 1992). However, the observed relationship between ENSO and Australian climate variables such as rainfall is not consistent, being strong in some epochs but weak in others (Allan et al 1996, Allan 2000, Power et al 2006). ENSO and its teleconnections vary on decadal and longer time scales (Power et al 1999a,b, Allan 2000, Mann et al 2000), although the exact physical mechanisms are unknown. Some researchers suggest that interactions between ENSO and the Interdecadal Pacific Oscillation (IPO) may explain decadal variations of the effects of ENSO on climate, while others argue that the IPO is a decadal manifestation of ENSO. For example, Power et al (1999a) showed that interdecadal variability in the association between the Southern Oscillation Index (SOI – NIÑO3) and annual changes in Australia-wide rainfall, maximum surface temperature and wheat crop-yield, and annual flow volume in the Murray River in southeastern Australia, were coherent with changes in the IPO during the twentieth century. Additionally, they showed that the index for the IPO is highly correlated with the interdecadal component of an index for the Pacific Decadal Oscillation (PDO) (see also Mantua et al 1997 and Folland et al 1999). The nonlinear correlation between Australia-wide rainfall and the SOI described by Power et al (2006) exhibits much variability and, although significant, explains little overall variance in observed data. However, much of that variability most likely reflects regional variations in the response of rainfall to ENSO, particularly with respect to differences between tropical and temperate climates (Bayliss et al 2007b).

To tease out the influence of the ENSO-PDO interaction on Oenpelli rainfall and Magela Creek flow volume for the period 1971 to 2006, observations were grouped into the following four SOI-PDO classes and mean values obtained (after Power et al 2006): SOI<0 and >=0 in combination with PDO <0 and >=0 (n of combinations = 6, 16, 7 & 6 respectively). Results (Fig 5) show that, for the Magela catchment, mean annual rainfall (mm) in each SOI-PDO class increased with increasing values of the SOI (ie mean monthly SOI value in each SOI-PDO class). The linear regression is significant and explained a large amount of variability in observed data (r^2=88%, n=4, P=0.04). In contrast, the relationship between mean annual Magela Creek flow volume (ML) and SOI in each SOI-PDO class is nonlinear (r^2=99.6%, n=4, P=0.04), although with only 1 df. However, similar relationships were also found between rainfall, stream flow volume and SOI by SOI-PDO class for other catchments across the 'Top End' of the Northern Territory as that found for Magela Creek (Bayliss et al 2007b, Bayliss et al in prep.). Hence, the SOI is clearly an important explanatory variable of Magela flow and, most likely, for all streams in the northern part of the Northern Territory. The SOI is of course an indicator of the phase of the El Niño Southern Oscillation (ENSO), and significantly correlates with Top End rainfall (McBride & Nicholls 1998). But the MJO and tropical cyclones also affect rainfall and river flow in this region.

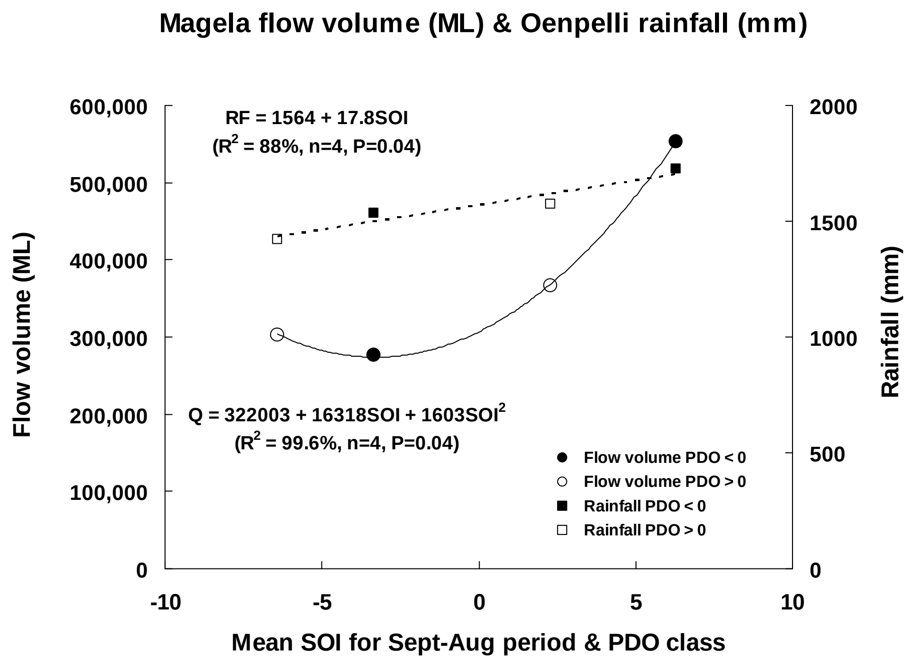

Figure 5 Nonlinear relationship between Magela Creek mean annual (September–August) flow volume (Q, ML) at GS8210009 and mean monthly SOI in four SOI-PDO classes (SOI<0 & >0 in combination with PDO<0 & >0) and, similarly, for the linear relationship between mean annual Oenpelli rainfall (RF, mm) and mean monthly SOI, 1971–2006

A rising trend has been observed in Top End rainfall, particularly since 1975 (Wardle & Smith 2004), and is consistent with some projected impacts of Greenhouse warming (Milly et al 2005, Allen & Ingram 2002; and the results of the Max Planck Institute for Meteorology MPI-ECHAM5 model which best simulates key features of the modern Australian climate according to Suppiah et al 2007). It appears to be the result of either pooling of warm waters off NW Western Australia, with a possible role for aerosols (Shi et al 2008), and/or an enhanced north-south pressure gradient caused by warming in southern Australia (Wardle & Smith 2004). This increased rainfall is not detected in either the gauged suspended sediment load estimates which end in 1983, or in the sedimentation record at PPI or MC15 that were sampled in the mid 1980s. Further sediment sampling is required to detect the change of rainfall and modelling of changes in fire regimes, ground cover and runoff.

4.6.2 Long-term records

Turning now to low frequency (decadal to centennial) variability, Mann et al (2005) used the Zebiak-Cane model of the tropical Pacific coupled ocean-atmosphere system to investigate the response of ENSO to radiative forcing, excluding anthropogenic greenhouse gases. In the analysis by Mann et al (2005), volcanic radiative forcing is restricted to explosive eruptions occurring between 30ºN and 30ºS. Solar radiative forcing is from Crowley (2000) (Fig 2) which is in the lower range of reconstructions of solar irradiance, but with an amplitude that is about twice as large as alternative reconstructions. The estimate is therefore considered by Mann et al (2005) to be mid-range.

Most volcanic eruptions included in the modelling by Mann et al (2005) are followed by an El Niño-like response, and weaker subsequent La Niña- El Niño cycling. The largest tropical eruptions are clearly evident however. The solar irradiance forcing, although much smaller than the volcanic, is of much lower frequency and produces a substantially larger (equilibrated) NIÑO3 response. The model SST anomaly response in NIÑO3 to both volcanic and solar radiative forcing is shown in Figure 2. On 40 year and longer time scales, the NIÑO3 response has been tested against reconstructions of sea surface temperatures from oxygen isotope analyses of corals from Palmyra in the tropical central Pacific (Cobb et al 2003). Mann et al (2005) argue that while the quantitative relationship between NIÑO3 and Palmyra might have changed through time, the sign of the relationship is unlikely to have changed. Therefore, the Palmyra data support the trend of NIÑO3 response to solar forcing in Figure 2.

A reconstruction of December-February SST in NIÑO3 based on subtropical tree-ring records for 1408–1978 AD by D'Arrigo et al (2005) show high ENSO variance during some intervals of decreased radiative forcing. This is in agreement with the results of Cobb et al (2003) and Mann et al (2005). The exception is for the solar minimum of the late 17th to early 18th century, known as the Maunder Minimum.

As seen earlier, ENSO phases are highly variable, with some researchers arguing that such variability can be explained by phases of the IPO or PDO. La Niña phases are suggested to be strengthened during negative phases of the IPO producing larger rainfalls and streamflows in the 'Top End'. The IPO is strongly correlated with the Pacific Decadal Oscillation (PDO), with indications that they are parts of the same phenomenon (Folland et al 2002). The PDO has been reconstructed by MacDonald and Case (2005) for the last 1000 years. The reconstruction is shown in Figure 2. Also, a ~300 year tree ring record from Vietnam shows that droughts are affected by ENSO-like anomalies with a possible link to the PDO (Sano et al 2008), providing some support for the idea that the linkages between ENSO and the IPO/PDO in the last few decades also occurred over centuries.

A comparison of the PDO, NIÑO3 Index, and the minerogenic flux at MC15 shows the following:

- Between 1000 and 1380 AD, the minerogenic flux was high, with a slight decreasing trend. This was a period when solar irradiance was decreasing, less El Niño-like in general, and the PDO was negative. The atmospheric and oceanic conditions were therefore conducive to high rainfall, streamflow and sediment flux.
- Between 1380 and 1540 AD, the sediment flux was at a minimum, solar irradiance was at a minimum, the NIÑO3 Index indicates El Niño-like conditions, and the PDO was mostly positive (although there is a period between ~1400 and 1450 AD when it was negative). Therefore, the influence of La Niña events is likely to have been small.
- Between 1540 and 1780 AD, the sediment flux increased as solar irradiance increased, the NIÑO3 Index trends weakened to a more La Niña-like state, and the PDO was either mostly near zero or was negative (except for a positive period from ~1500 to 1600 AD).
- Between 1780 and ~2000 AD the sediment flux was nearly constant while solar irradiance increased, the NIÑO3 Index shows (mostly) cooling to less El Niño-like conditions and then reversed in the last half of the last century, and the PDO was mostly positive (except for a few decades in the middle of the twentieth century when it was negative). The lessening of El Niño-like conditions during this period appears to have been offset by the PDO to produce nearly constant rainfall, streamflow and sediment flux, at least as averaged in 40 year intervals. Within the last 20 – 30 years, rainfall and streamflow have increased, but these changes are not captured in the sedimentary record because of the recency of the changes and/or change in the flow/sediment transport relationship.

These observations suggest that the sediment flux history can be qualitatively accounted for by variations in ENSO and the PDO (IPO), with external forcing of ENSO mainly by natural variations of solar irradiance.

Gergis and Fowler (2009) in a comprehensive analysis of multi-proxy climatic data from both the western and eastern Pacific Basin and the instrumental record have reconstructed both the phase and the strength of ENSO for each year from 1525 AD. The number of extreme and very strong ENSO phases for each of the 40 year time periods at MC15 have been identified from the reconstruction by Gergis and Fowler (2009) along with the average phase state of the PDO (Table 1). This is a very coarse analysis, made necessary by the temporal resolution of the Magela Creek sedimentary record. When the PDO is negative, the average sediment flux is 6.7×10^{-3} g / cm^2 / yr and when the PDO is positive the average flux is 5.8×10^{-3} g / cm^2 / yr. Although the difference is not statistically significant, the slightly higher sediment flux and inferred stream flow during La Niñas when the PDO is negative is consistent with modern observations of higher inferred streamflow during La Niñas when the PDO is negative. But the temporal resolution of the sedimentary record does not allow event-based analysis, and so all that can confidently be concluded is that the low frequency of ENSO, affected by the PDO (IPO), accounts for most of the variability in sediment flux in Magela Creek. Assuming a power-law relationship between sediment flux and streamflow, the phases of ENSO and the PDO (IPO) have largely controlled streamflow via rainfall.

A quantitative analysis using the 40year sedimentation rates at PP1 (SF) and 40 year averages of the NIÑO3 reconstruction (N3) and the PDO reconstruction showed that 64% of the variance in sedimentation rate is accounted for by the quadratic equation:

$$SF=25.0\ N3-152.0\ N3^2 + 64, \text{ where } PDO<0 \text{ and } p<0.001$$

A linear relationship between SF and N3 accounts for 22.7% of the variance with $p<0.01$. The averaging of the data produces few values of PDO=>0 (n=9 versus n=16 for PDO<0) and so the result may be biased. However, in broad terms the quantitative analysis supports the qualitative analysis.

Table 1 Extreme and very strong phases of ENSO (from Gergis & Fowler 2009), phase of the PDO (from MacDonald & Case 2005), and sediment flux in the Magela Creek (based on Wasson 1992)

Years AD	El Niño	La Niña	PDO	MC15 g / cm^2/y (x 10^{-3})
2000–1960	4	4	+	6.5
1960–1920	3	3	-	6.5
1920–1880	7	6	+	8.3
1880–1840	4	5	+	6.5
1840–1800	2	3	+	6.3
1800–1760	2	1	-	8.8
1760–1720	2	5	+	5.5
1720–1680	2	1	-	6.3
1680–1640	2	3	-	5.0
1640–1600	2	5	+	2.0
1600–1560	3	5	+	4.8

4.7 The Daly River record

A sand splay deposit at the Nancar Hideout on the lower Daly River (~320 km southwest of Magela Creek) has been dated using OSL (Optically Stimulated Luminescence) (Wasson et al in press). In addition, lower floodplain deposits (in benches set below a higher floodplain) have been dated by OSL to determine, inter alia, changes to flood frequency reflected in flood couplets of sand topped by mud.

At the Nancar Hideout, the Daly River has a catchment area of ~52 000 km^2. The sand splay deposit occurs downstream of a short bedrock gorge, and is part of a fan-shaped deposit that occurs on both sides of the river and is up to ~2 km across and at least 3 m thick. It is therefore a significant body of sediment and is likely to record major changes in sedimentation rate which is inferred to be caused by changes in river discharge. Six OSL dates from the sand splay at Nancar Hideout show that a high rate of deposition of 0.54 ± 0.07 cm/yr deposition occurred between ~820 ad 590a (~1160 to 1420 AD), a low rate of 0.12 ± 0.03 cm/yr between ~590 and 250a (~1420 to 760 AD), then a higher average rate of 0.41 ± 0.16 cm/yr to the present. This pattern of change broadly accords with that for Magela Creek.

4.8 Comparison with other proxy records

The Magela Creek and Daly River records are now compared with other records from Australia, India, and China. The only other long continuous proxy hydrologic record from tropical Australia is of discharge from the Burdekin, Herbert, Pioneer and Fitzroy rivers in north Queensland as recorded by fluorescent bands in corals of the Great Barrier Reef (Lough 2007). River flow in this region is modulated by both ENSO and the PDO and, like the ‘Top End’, is highly seasonal. From 1661 AD, however, only weak relationships with ENSO could be found.

More importantly, for current purposes, is the conclusion by Lough (2007) that since 1661 AD there is no evidence of a trend toward either wetter or drier conditions, but there is evidence of increased variability during the twentieth century. The absence of a trend over the last ~350 years is broadly consistent with the record from Magela Creek (Fig 2).

In apparent contrast, Wasson et al (in press) have shown that flood frequency, recorded by sedimentary couplets in benches on the Daly River (see brief description above), has been increasing over the last ~160 years, doubling in the last 60 years. If flood frequency has also increased in Magela Creek over the same time period, sediment transport during less extreme floods must have been either less significant or declined to explain the pattern of sedimentation rate in Figure 2. This inference implies greater intensity of runoff events within the last two centuries.

The monsoon regions of Asia, like northern Australia, are also sensitive to ENSO (Webster & Yang 1992, Allan et al 1996, Allan 2000, Goswami & Xavier 2005, Rajeevan & Pai 2007, D'Arrigo et al 2008). Low frequency variability in proxy monsoon records from South Asia and China is therefore examined to detect similarities or dissimilarities with the Magela Creek record. The most apposite comparison is with records of river floods from India (Table 2).

Table 2 Wet and dry period in India, China and the 'Top End'

Location	Dry Periods AD	Duration Years	Wet Periods AD	Duration Years	Source
Magela Creek	1380–1540	160	1000–1380	380	This paper
			1740–2000	260	
Daly River	1420–1760	340	1160–1420	≥ 260	Wasson et al in press
			1760–2008	588	
Indian Rivers	1240–1875	635	1875–2000	125	Kale & Baker 2006
Penner River	1400–1800	400	1000–1400	400	Thomas et al 2007
			1800–1960	160	
Indus River	1250–1600	350	1000–1250	250	von Rad et al 2006
			1600–2000	400	
Nilgiri Hills			1200–1400	200	Sukumar et al 1993
Yangtze River	1220–1640	420	1000–1220	220	Zhang et al 2008a,b
			1640–2000	360	
Dandak Cave	1260–1425	165	1000–1260	260	Sinha et al 2007
Dongge & Heshang Caves	1250–1750	500	1000–1250	250	Wang et al 2005
			1750–1850	100	Hu et al 2008

Kale and Baker (2006) have compiled data from five rivers from the south to the northwest of India, which provide the age of major floods derived from slackwater alluvial deposits. The records are up to 2000 years long, dated by both ^{14}C and OSL. There are century-scale variations in flood frequency, with floods evident from ~0 AD to an average for the five rivers of 1240 AD. There is then a complete absence of large floods until on average 1875 AD. This period of ~635 years was presumably a time of low flood-generating rainfall. Kale and Baker (2006) attribute most floods in the five rivers to decaying tropical cyclones, and so by inference the period from 1240 to 1875 AD was a time of weak or non-existent coast-crossing cyclones. The role of the Indian Ocean Dipole (a possible manifestation in SSTs of ENSO in the Indian

Ocean; R Allan, pers comm) as a modulator of cyclone frequency in India needs further investigation (Singh 2008) but this is beyond the current paper (also see Charles et al 2003).

Another fluvial record from South Asia comes from cores taken offshore from the Makran coast of Pakistan in the Arabian Sea (von Rad et al 2006). The laminated sediments appear to reflect both winter and summer discharge from the land, and one core is offshore from small rivers draining the Makran and another is offshore from the mouth of the Indus River. Therefore, the origin of the sedimentary signal is not clear. Nonetheless, there is a striking temporal pattern in the lamina thickness data for the last 1000 years (Figure 6). A period of thin laminae, interpreted as a time of low river discharge, occurred between ~1250 and ~1600 AD, with thicker laminae before and after. Staubwasser (2006) finds little evidence for this pattern of change using δ^{18} 0 records from the same area. That different proxies appear to be providing different signals, and some proxies cannot yet be reliably interpreted as indicators of either fluvial sediment or freshwater discharge into the coastal margin, suggests that these records should be treated with caution until a more definitive link with terrestrial processes is established.

Using Al % as a proxy for fluvial input, Agnihotri et al (2002) analysed a core from the continental shelf of the Arabian Sea offshore from Saurashtra in India. With an uncertainty of 50–80 years, they show a minimum of fluvial input at ~1550 AD and a high ~1000 AD. From ~1550 AD, fluvial input rises to ~1630 AD and then stays approximately constant until 1992 AD when the core was collected. This period of near constant input did not reach the highest values at ~1000 and ~1190 AD.

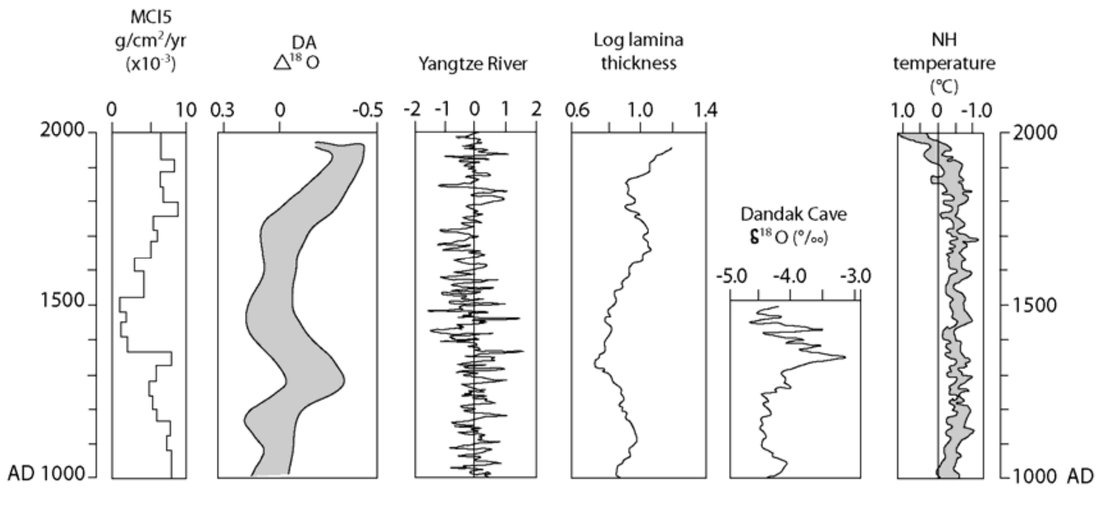

Figure 6 MC15 sediment flux (based on Wasson 1992), Dongge Cave (DA) $\triangle^{18}$ 0, (from Wang et al 2005) Yangtze River reconstruction (from Zhang et al 2008), lamina thickness offshore from the Makran coast (from von Rad et al 2006), Dandak Cave δ^{18}0 (from Sinha et al 2007), and NH temperature reconstruction (from D'Arrigo et al 2006)

In southern India, a record of fluvial and aeolian sedimentation from the Penner River catchment shows a record similar to that seen in the flood records from the five rivers discussed above. Thomas et al (2007) show that overbank fluvial sedimentation and high magnitude flood deposits occurred between ~1000 and 1400 AD. Aeolian deposits and an absence of floods date from ~1400 to 1800 AD, after which floodplain aggradation resumed between ~1800 and 1960 AD. During this period, one of the largest historically documented floods occurred, in 1851 AD. Floods have continued but none has exceeded this event. Thomas et al (2007) draw attention to the correlation of their record with extreme floods in the Narmada, Tapti and Luni Rivers. But they are careful to observe that large floods are anomalies and may not be representative of background climate. Nonetheless, the record of low flow/arid conditions for ~200 years between ~1400 and 1600 AD is strikingly similar to other records in ENSO-affected monsoonal systems discussed earlier.

Turning to other records, Sukumar et al (1993) used $\delta^{13}C$ measurements in peat from the Nilgiri Hills of southern India to show that at ~1200 AD there was a rapid shift to C3 vegetation that lasted until ~1400 AD. This is interpreted as a short wet phase, followed rapidly by a drier phase. The chronology for the last 1000 years is constrained by the age of collection of the core and by a ^{14}C age of ~2315 cal BP deeper in the peat, requiring interpolation to estimate the age of the wet period beginning ~1200 AD.

At Dandak cave in the state of Chhattisgarh on the east coast of India, Sinha et al (2007) used $\delta^{18}0$ from speleothems to reconstruct summer monsoon precipitation between 600 and 1500 AD. (Figure 6). A stronger (wetter) monsoon period occurred between ~1000 and 1260 AD followed by a weaker monsoon until ~1425AD with a stronger monsoon until 1500 AD. The weakest monsoon occurred at ~1360 AD, with a change of $\delta^{18}0$ of -1.2 ‰ in ~50 years from ~1310 AD.

A fluvial record from the Yangtze (Changjiang) River in China has been compiled for the last 1000 years by Zhang et al (2008a,b). Only the upper reaches of the catchment are affected by El Niño in the same way as in India (Dai & Wigley 2000). The reconstruction (Figure 6) is based upon documentary evidence of floods and droughts. The negative values indicate drought, and positive numbers indicate floods. The authors show a correlation between periods of drought and cold temperatures, and of note is the period between ~1220 and ~1640 AD, which was dominated by drought. Note that in Zhang (2008, b) the labels on Fig 2 for droughts and floods are reversed, and the labelling of Fig 3 in Zhang et al (2008,a) is correct (Q Zhang, pers comm).

In Dongge Cave in southern China where El Niño can produce either negative or positive rainfall anomalies, a $\delta^{18}0$ record from a speleothem has been used to infer monsoon strength since 9,000 years ago (Wang et al 2005) (Figure 6). A strong (wet) monsoon peak occurred around 1200 AD, with a weak monsoon between ~1500 and ~1800 AD, followed by a stronger monsoon. By comparing the Dongge record with that at Heshang Cave 600 km downwind, the $\triangle\delta^{18}0$ signal has been interpreted solely as the result of precipitation (Hu et al 2008). Between ~1000 and 1250 AD rainfall was more than the present and between ~1250 and 1750 AD it was below the present, rising to be once again above the present until ~1850 AD, then falling to the present.

Most of the records discussed above are terrestrial, mainly fluvial, or can be related to fluvial activity. The cave records are of a different kind, but are terrestrial. Various records of upwelling in the Arabian Sea have been produced (eg Gupta et al 2003, Anderson et al 2002) but the relationship between upwelling, monsoon wind strength, rainfall and runoff is not clear (cf Staubwasser 2006) and so have not been considered further.

4.9 Discussion

The age control and temporal resolution of the proxy records in Table 2 are of variable quality, and so exact correlations cannot be expected even if the hydrologic changes were synchronous. Also, the proxies have different sensitivities to climate, and spatial variability in climate changes can be expected. The data in Table 3 nonetheless show some distinct patterns. Is it clear that wet conditions prevailed between 1000 and 1200 AD, and dominated between 1200 and 1400 AD with subdominant transitional states and dry conditions. Dry conditions dominated between 1400 and 1600 AD and again between 1600 and 1800 AD along with transitional conditions and one proxy record indicating a wet state. Wet conditions dominated from 1800–2000 AD with a few transitional states and one proxy record showing dry conditions.

Table 3 Number of wet, transitional and dry climates based on the proxy records in Table 2

	Years AD				
	1000–1200	**1200–1400**	**1400–1600**	**1600–1800**	**1800–2000**
Wet	15	8	0	1	11
Transitional	0	5	1	3	3
Dry	0	5	15	7	1

Given that the locations of all of the proxy records are currently strongly affected by ENSO-induced precipitation, with the possible exception of the Chinese cave sites (Dai & Wigley 2000), the coincidence in time of the proxy records with the reconstructed SSTs in the NIÑO3 region is likely to be causal. If this is the case, then the role of natural radiative forcing in the history of the NIÑO3 SSTs is also causal (see also Tiwari et al 2005).

The dominantly dry period between 1400 and 1600 AD was a time when the NIÑO3 SST record shows warmer tropical waters in the central equatorial Pacific and thus that more El Niño-like conditions prevailed, but before the PDO (IPO) was dominantly positive. The early wet periods between 1000 and 1200 AD was a time of only slightly warmer SSTs in the NIÑO3 region but consistently negative PDO index, indicating that wet conditions in the monsoon region could be expected. The later wet period between 1800 and 2000 AD was a time of NIÑO3 SSTs only slightly higher than the earlier period, with periods of both negative and positive PDO.

In addition to the changes just described, there was a sharp decline in sedimentation on the Magela Plain in the fourteenth century. This change is also detected in central China (Zhang et al 2008a,b), Tibet, the Arabian Sea, Taiwan, and NE China (Morrill et al 2003). Zhang et al (2008b) observed that there is no correlative change in solar radiation that might explain the reduced rainfall, but Abreu et al (2008) and Knudsen et al (2009) show a major reduction in the solar modulation function at this time.

The climatic changes inferred from the proxies discussed above appear to have had dramatic effects on the people of the region. In northern Australia, Bourke et al (2007) document major changes to foraging and social behaviour from ~1200 to 1400 AD and again between ~1500 and 1600 AD, times when the climate was rapidly drying and then was dry respectively. In Timor Leste (Lape & Chin-Yung 2008) and the Pacific (Nunn 2007), fortification became common along with food stress and major societal change when the climate was driest. In southeast Asia, Angkor in Cambodia appears to have been abandoned at the time of the driest climate (Penny et al 2007, Stone 2009). And in India there appears to have been a time of active tank building for water storage when the climate was driest (Pandey et al 2003).

The two new palaeoclimatic proxy records from the Australian monsoon tropics are broadly in phase with similar records from the Asia-Australia Monsoon region in the Northern Hemisphere (Tables 2 & 3). The additional data from the Southern Hemisphere supports the hypothesis of Emile-Geay et al (2007), that El Niño mediates the solar influence on climate by means of the Bjerknes feedback mechanism.

4.10 Conclusions

A 1000 year record of fluvial sedimentation on the Magela Plain in Kakadu National Park, supplemented with a record from the Daly River, shows clear evidence of major change which is interpreted to be the result of variations in discharge and therefore (mostly) rainfall. Modern discharge in Magela Creek is highly correlated with that in four other streams in the Top End of the Northern Territory, including the Daly River, and is strongly influenced by ENSO. Therefore, the history of discharge and rainfall as represented by the sedimentation record on the Magela Plain is likely to apply to an area much larger than the Magela Creek catchment, including the Daly River catchment.

The millennial history is consistent with the reconstructed variation of SST in the NIÑO3 region of the Pacific Ocean, which is thought to be driven by changes in solar irradiance, explosive volcanic dust, and redistribution of heat in the ocean. A reconstruction of the PDO, which is strongly correlated with the IPO, has been used with the reconstruction of NIÑO3 to qualitatively explain the variation of discharge in northern Australia.

A marked feature of the Magela record is a period of 160 years of low flows between 1380 and 1540 AD when terrestrial plants appear to have dominated the vegetation of the Plain. This period coincides with El Niño-like conditions in the NIÑO3 reconstruction. It also coincides with periods of low flows in Indian rivers and in the Yangtze (Changjiang) River of China, and low rainfall in India and southern China.

The new results from the Australian monsoon tropics are consistent with the hypothesis of Emile-Geay et al (2007), and are inconsistent with the hypothesis of Zhang and Delworth (2005). That small changes in the solar irradiance can be amplified by the Bjerknes feedback mechanism to produce substantial changes in ENSO underlines the sensitivity of the global climate to small changes in the radiation budget.

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5 Climate change and biodiversity conservation: some implications for Kakadu National Park

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5.1 Summary

Global climate change is the environmental problem of the 21st century. While the specific impacts of global warming are difficult to predict the Intergovernmental Panel on Climate Change (IPCC) most recent report has identified with *very high confidence* that as soon at 2020 there will be a significant loss of biodiversity across a range of ecologically-rich Australian environments. On the list of threatened environments are the wetlands of Kakadu National Park that currently supports high density of wildlife that at risk because of saltwater intrusion associated with sea-level rise. Arguably Kakadu qualifies as a World Heritage Area at risk because of climate change, so it is with bitter irony that these famous World Heritage wetlands have now become an media icon of the looming threat of global climate change to Australia's biodiversity.

The effects of climate change on nature reserves such as Kakadu presents profound issues that are currently being grappled with by conservation biologists worldwide. At the root of the problem is that protected areas were never designed as an insurance against climate change. Thus climate change demands managers of protected areas such as Kakadu tackle novel, deeply unsettling and unresolved scientific, administrative and philosophical issues. While the challenges of climate change are formidable, I believe solutions can be found in looking at biodiversity conservation in new ways. This requires a commitment to research, monitoring and adaptive management, managing ecosystem services such as carbon storage and water security whilst explicitly incorporating cultural perspectives in conservation planning. Despite degradation associated with climate change, protected areas like Kakadu will remain important foci for nature conservation.

5.2 Climate change

The world is currently warming rapidly as a direct consequence of the increased concentration of greenhouse gases in the atmosphere, notably carbon dioxide, largely due to forest clearance and the combustion of fossil fuels. Over the last century global mean surface temperatures have risen by about 0.7°C and the rate of warming over the last 50 years is almost double that over the last century (0.13°C vs. 0.07°C per decade) (IPCC 2007a).

While there is uncertainty about the ecological consequences of global warming, the prognosis for Australian environments is not good. For example, the Intergovernmental Panel on Climate change report entitled 'Impacts, adaptation and vulnerability – summary for policy makers' (IPCC 2007b) states that there is 'very high confidence' that there will be significant

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loss of biodiversity by 2020 in some ecologically-rich Australian regions. IPCC specifically identifies Kakadu National Park's freshwater wetlands because of their vulnerability to accelerating sea level rise. Over the last century the mean rate of sea level rise has been 1.2 mm per year and the IPCC predicts sea level rise is between 20 and 60 cm by the year 2100. In northern Australia, the effects of sea level rise are likely to be exacerbated by the predicted increase in severe tropical cyclones and associated storm surges.

It is true that there is also evidence of other changes in Kakadu including the expansion of rainforests (Banfai & Bowman 2006), increased density of savannas (Lehmann et al 2008), increased density of woody plants on the freshwater flood plains (Bowman et al 2008). These drivers of these changes also appear to be associated with increased rainfall, and possibly elevated CO_2 which increases the growth of woody plants. Significantly, the control of feral buffalo in the 1980s appears to have been of little consequence for these landscape changes. Nonetheless, these effects are insignificant in comparison with the immediate threat of sea-level rise to the freshwater floodplains. This is not to belittle management issues such as fire management, feral animal impact or weeds that will also be synergistically affected by climate change, but rather sea-level rise has the capacity to *totally transform* an entire ecosystem that is iconic of Kakadu National Park.

5.3 Biodiversity, ecosystem services and climate change

Conservation biologists are increasingly concerned about the potential effects of climate change on nature reserves, ecosystem services and the conservation of biodiversity. In this context the Australian Government has published, or is currently commissioning, a number of important reports on climate change that explore these issues. The reports 'Climate change and the national reserve system' (Dunlop & Brown 2008) and 'Managing Australian landscapes in a changing climate – a climate change primer for regional natural resource management bodies' (Campbell 2008) provide essential background readings concerning the climate change and biodiversity conservation and natural resource management.

Fundamentally climate change is going to transform our world into 'another green world' where life goes on but the 'look, sound and smell of the bush' (Dunlop & Brown 2008) will be different from what we consider currently to be 'normal'. Indeed, the ubiquity of global climate change means that everyday 'biology' is morphing into a new science of 'global climate change biology'. For example, climate change is set to cause the substantial reorganisation of landscapes associated with species tracking the changing geographic extent of habitats. Some species population will be driven to extinction and others may become successful in environments where they are currently rare. This scale of change raises a fundamental problem for the current network of protected areas: they were never designed as an insurance policy against such comprehensive change.

Because of magnitude of the problem and limited budgets, not all species can receive the same priority and differing human values are placed on them. While science must provide evidence to inform such management debates, it is unrealistic to expect scientists to resolve philosophical dilemmas such as settling conservation priorities in the face of climate change. Political and cultural values must be accepted in this conservation planning mix, and this is especially important in a jointly managed National Park such as Kakadu where management necessarily needs to incorporate the values of the traditional Aboriginal owners. Magpie geese are a good example of this for Kakadu. Their populations in Kakadu are likely to collapse due to the loss of extensive areas of freshwater floodplains. This will have significant consequences for the traditional Aboriginal owners of Kakadu given the cultural significance of magpie geese.

Because it is certain that the composition of nature reserves is going to change with some species in future lying outside the boundaries of the current reserves, solutions to nature conservation demand a successful blending of formal protected areas and off-reserve conservation. A focus on ecosystem services, such as the provision of clean air, carbon capture or water security is also an essential ingredient in nature conservation strategies. In northern Australia the West Arnhem Land Fire Abatement (WALFA) project is a concrete example of the ability to combine management of an ecosystem service with broader biodiversity outcome outside the formal reserve system. Such approaches also show how such 'ecosystem service' thinking can be a more effective approach to conservation than a strict adherence to the 'biodiversity imperative' that explicitly claims to be managing for the conservation of all species. Such blending of outcomes demands evidence-based decision making which, in turn, requires drawing together a diversity of research approaches and findings. Research investment is required to address immediate and longer range issues, and both applied and pure problems. For example, fixation of a single issue such as a single animal species can blind managers to the more complete, albeit complicated, perspective provided by studies that span a range of spatial and temporal scales. For example, understanding the current decline of small mammals or the impacts of cane toads can't be isolated to the effects of landscape change associated with changed management practices, particularly fire use, invasive organisms such as flammable African grass or the impact of feral buffalo.

5.3.1 Managing another green world – the case of Kakadu's wetlands

One perplexing aspect of climate change is while the science community is confident of the reality, there remains great uncertainty about how the global changes will impact local and regional climates and ecologies such as Kakadu. This is because although the physics of global change are well understood, the climate and biological feedbacks are so complicated that forecasting with any precision is probably impossible (Bony et al 2006). Therefore, managers must straddle the uncomfortable reality that on the one hand enormous change is certain, but on the other hand the future is uncertain and surprises most likely. For example, there is great uncertainty how the recurrence of tropical cyclones will change with global warming or how their strength will change. In Australia, and especially northern Australia the lack of historical records makes contextualising the projection of climate change models extremely difficult. We remain ignorant of the background incidence of dry wet seasons, massive flood, destructive storms and so on. Given these knowledge gaps, managers must draw on all available historical reconstructions to help contextual the current and possible future climate trajectories. There are many lines of evidence that can be used to reconstruct environmental history ranging from soil stable isotopes to historical aerial photographs – see special issue of *Australian Journal of Botany* for an overview of these results (Bowman & Farrer 2002). Kakadu should continue to invest in such historical research. Such knowledge has already placed the threat of salt water intrusion into a historical perspective: research into the history of the South Alligator floodplain conducted by Australian National University in the 1980s demonstrated that as recently as 7000 years ago this landscape supported a vast mangrove forest (Woodroffe et al 1985).

Managers need to set clear priorities and practise clear thinking. Panicked responses are counter-productive, and investment in hopeless cases is socially and politically self defeating. For example, there appears to be only a limited number of adaptive options to protect the freshwater floodplains from sea level rise beyond abruptly reducing global greenhouse gas pollution in order to halt sea level rise (known as 'mitigation'). An immediately available adaptive response is the construction of levees to protect floodplains from saltwater intrusion. While some success has been had with this approach on the Mary River floodplain to the west of Kakadu, this approach is expensive and not without side-effects such as limiting fish migrations. A formal cost-benefit analysis has been undertaken for the Mary River floodplain (see NTDIPE 2003). However, this analysis is based on limited biological data and is therefore little more than a demonstration of the use of such economic analyses in making such major natural resource management investments.

A pilot program to protect the Kakadu wetlands is required to analyse the efficacy of levees in terms of biological outcomes and economics costs. Such a study should be a high priority given that the wetlands are now at risk. It is possible that such a study will show that artificial protection of the freshwater floodplains by geo-engineering is not practical, economically possible or biologically desirable, and not acceptable to the traditional owners of Kakadu. If this is the case, then all stakeholders will have to accept that Kakadu's floodplains are going to be transformed by climate change. Understanding Kakadu in a regional context is a crucial step in planning for climate change. For instance, such a perspective might show that the South Alligator floodplain could become an important refuge for mangroves given that in most tropical coastal regions this vegetation is already threatened by rapidly growing human populations and sea level rise will compound this problem. Whatever management prevails on the floodplains there is no question that the 'story' that underpins these iconic wetlands and ebullient wildlife will have to change. It is counter-productive to focus on the negative aspects of climate change in Kakadu – rather, a new story must be told explaining why Kakadu remains an important place despite inevitable ecological degradation.

The threat to the floodplains is not restricted to Kakadu. It is important to undertake a regional assessment of likely less vulnerable wetlands, and also sites that could become new wetlands via natural processes or following geo-engineering. Such intervention requires using land outside the current protected area network. However, expanding conservation actions outside nature reserves demands building new constituencies that include a diversity of stakeholders, working out who has the responsibility for management, and identifying who has the capacity to implement change. The simultaneous provision of ecosystem services such as carbon storage and water supplies has the potential to reinvigorate management practices. For example, with skilful planning dams could create wetland habitats well away from areas afflicted by sea level rise.

5.4 Conclusion

Maximising the biodiversity values of protected areas raises profound and deeply unsettling unresolved scientific, administrative and philosophical issues. For example, because of the different human values placed on them, there needs to be acceptance that not all species have the same conservation priority. While science must provide evidence to inform management debates, especially by providing a historical context and prognoses of the emerging threats, it is unrealistic to expect scientists to resolve such painful philosophical dilemmas. There is no doubt some management actions may not be scientifically rational. Landscape-scale conservation is going to be crucial to allow species and habitats to geographically reassemble themselves. Therefore off-reserve conservation is an essential element in this broader perspective. In sum, the widely held assumptions that underpin nature reserves such as Kakadu require major readjustment in the face of global climate change.

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6 Climate change and indigenous communities of the Kakadu region

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Abstract

The remoteness, lack of quality infrastructure, low income and chronic health problems of indigenous communities of the Kakadu region mean that they will be more susceptible to climate change impacts than the general Australian population. The dependence of many communities on bush tucker, while helping ensure their health and links to country, puts them at risk from rapid environmental change that could result from the loss of wetlands. Freshwater wetlands provide a high proportion of bush tucker but are acutely at risk from sea level rise and storm surge. Changes to the hydrology of wetlands could impact on arboviruses that are already prevalent in the area, but more work is required to understand these impacts. Climate change does provide some opportunities for engagement of communities in greenhouse abatement projects. Environmental changes elsewhere are likely to create pressure for change and considerably impact indigenous communities. Anticipation of and engagement in changes brought about by such external pressures will be essential to optimising outcomes for indigenous communities.

6.1 Overview of projected changes

The report into Northern Territory climate change projections by Hennessy et al (2004) indicates that the Northern Territory is expected to warm 0.2 to 2.2°C by 2030, and 0.8 to 7.2°C by 2070, relative to 1990, but less warming is expected over the Top End compared with central Australia. Currently Darwin averages about 11 days over 35°C, and this is projected to increase by 1 to 51 days by 2030, and by 13 to 300 days by 2070. The number of hot spells of three to five consecutive days over 35°C at coastal sites is also projected to increase by 2 to 97 by 2070. It would be expected that the duration and frequency of hot spells would increase inland from the coast.

Little change in the timing and magnitude of monsoon rainfall is likely in future in the Darwin/Kakadu region. The intensity of tropical cyclones is likely to continue to increase due to greenhouse warming, but changes in cyclone frequency are uncertain. The combination of sea level rise, stronger wind speeds and more intense rainfall may lead to more significant coastal impacts due to tropical cyclones.

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6.2 Potential impacts

6.2.1 Human health

Compared with the general Australian community, many north Australian indigenous communities are disproportionately vulnerable to the impacts of climate change due to a number of factors including (Greene 2006):

- A close connection between the health of their county and their physical and mental well-being;
- Often inadequate infrastructure;
- Lower social and economic status;
- Existing chronic health problems.

Rising temperatures, and in particular extended hot spells, are likely to interact with existing chronic illnesses such as cardiovascular disease to exacerbate the wide gap between indigenous health and that of Australian society generally. Increased effectiveness of health care, preventative actions, and education and employment should reduce the susceptibility of indigenous communities to increases in temperatures. Increased use of airconditioning could decrease the exposure to high temperatures, but will come at the cost of increased energy use, and significant changes to lifestyle.

Of the infectious diseases, those transmitted by insects and especially mosquitoes are the most likely to be affected by climate change (McKenzie et al 1998). Any increased prevalence of heavy rainfall and flooding may result in outbreaks of Murray Valley encephalitis, and greater tidal penetration of coastlines associated with rising sea levels or storm surge may lead to an increased incidence of Ross River virus. Nevertheless, the environmental factors affecting the transmission of arboviruses are complex and relatively poorly understood in Australia, so further research is required to understand fully the implications of climate change. With regards to malaria, the vectors already exist in northern Australia, but the disease was eradicated by 1981. While the potential for the spread of this disease remains, and could increase if increased flooding and coastal inundation occurs, maintenance of current vigilance should prevent its reestablishment (Bryan, Foley & Sutherst 1996).

Although likely changes in many environmental factors, such as rises in sea level and temperatures, are slow compared to human lifespans, the impacts of climate change on health could occur quickly. For example, an arbovirus could expand its range or prevalence in a short period, or an extended heat wave could have a major impact on vulnerable people.

6.2.2 Infrastructure

Due to their isolation from the Darwin, remote indigenous communities currently experience more difficulty than other Australians in accessing basic housing, infrastructure and community services. Many communities are inaccessible by road for many months every year due to low-level river crossings. Even where engineered bridges provide access, the flood return intervals on which roads and bridges are designed are typically based on inadequate data. Thus they may not cope with the current climate, and could be under greater strain with the projected increase in the intensity of cyclones. Climate change events might also change landscape hydrology for extended periods. For example, Cyclone Monica snapped or uprooted trees across thousands of square kilometres. Such damage will for some decades increase the amount of water in the landscape due to reduced transpiration. Thus the period during which streams and rivers block road access to many communities is likely to increase.

Under the current wind loading standard (AS/NZS 1170.2: 2002) and building codes (Australian Building Codes Board 2005), category 5 cyclones are deemed to have no practical significance for buildings in the Northern Territory. However, three category 5 cyclones have affected the NT in the past decade, and some engineers are designing structures for much greater wind speeds than currently required. Such a practice provides additional security for communities with little supporting infrastructure and no road access during the wet season.

Many communities are also very susceptible to flooding and storm surge, with no road access during the wet season. The risks to human populations are great, as worldwide most deaths due to cyclones result from storm surge rather than directly from wind impacts on buildings (Emanuel 2005). Evacuation plans for indigenous communities threatened by extreme cyclones, or provision of flood proof cyclone shelters should be considered to mitigate this risk. Currently, the Building Code of Australia has no design provision for cyclone shelters (Australian Building Codes Board 2005).

Granger (1990) pointed out the potential difficulties resulting from the high degree of dependence of communities in the Top End of the Northern Territory on supplies from Darwin, which was supported by only one road to the south. Clearly supply chains to indigenous communities could be affected when Darwin is again impacted by a major cyclone.

The greater demand for energy and water for cooling systems under rising temperatures will increases peak energy demand. Thus growth in the need for peak generating capacity is likely to exceed that of underlying economic growth. Thus the risk of blackouts is likely to increase (IPCC 2007).

6.2.3 Bush tucker and bush medicine

The freshwater wetlands of the Kakadu region are a major source of sustenance for indigenous people of the region, providing water birds, fish, turtles, crocodiles and eggs, as well as freshwater food plants such as waterlilies. Altman (2006) showed that over 80% of adults living in discrete indigenous communities fished or hunted for livelihood. Managing aquatic environments in accordance with traditional law and custom also provides the means to pass on social and cultural knowledge to younger generations (Davies et al 1999). Aquatic habitats are the most vulnerable to climate change with sea level rise and storm surge inundation potentially causing rapid loss of extensive freshwater systems.

6.2.4 Economic opportunities

Attempts to mitigate climate change have lead to the creation of markets for carbon sequestration and emissions abatement. Savanna burning produces about 3% of Australia’s accountable greenhouse gas emissions. Indigenous people in the Kakadu region retain extensive knowledge and experience in fire management (Yibarbuk et al 2001). A fire abatement project is already underway for emissions abatement in Western Arnhem Land (Russell-Smith et al 2009). Such project create employment opportunities in remote areas using traditional skills, and supporting traditional responsibilities for land management (Gorman et al 2007, Cook & Meyer 2009).

6.2.5 Other indirect impacts

Despite past agricultural failures (Cook & Dias 2006), there is renewed interest in irrigated agriculture in the north due to severe drought in southern Australia coupled with greater controls on land clearing and over-use of water resources (Jackson et al 2008, Agriculture & Food Policy Reference Group 2006). Future economic development in the northern Australia will almost certainly involve the exploitation of its water resources (Hart 2004). As well as the economic pressures for agricultural enterprises seeking to expand or relocate from southern Australia there are also social pressures to provide regional development opportunities (Hamilton & Gehrke 2005). While the extent to which such pressures will affect indigenous communities in the Kakadu region, the issues are indicative of the pressures that will increase under climate change. In the case of the North Australia Land and Water Taskforce, established under the National Plan for Water Security, two of its fifteen members represent the indigenous communities of northern Australia. This is a marked departure from previous Commonwealth initiated inquiries into the prospects for agricultural developments which have not previously included indigenous representation (for instance, the 1959 Forster Committee (Forster 1961, Forster, Kelly & Williams 1959).

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7 The impact of climate change on Australian tourism destinations – developing adaptation and response strategies for the Kakadu/Top End region

P Tremblay[1]

7.1 Introduction

This paper discusses the background, methodology and preliminary findings of a national research project funded by the Sustainable Tourism Cooperative Research Centre (STCRC). The discussion in this paper emphasises the tourism-specific adaptation aspects, to distinguish it from the prominent topics treated in most other presentations at the symposium that were related to climate sciences, bio-physical implications as well as broad repercussions of climate change for major stakeholder groups. The discussion is organised under the following headings: background, methodology, economic assessment of potential climate change impacts on tourism, conclusion: preliminary findings emanating from tourism stakeholders interviews.

7.2 Background

The STCRC project itself was initiated early in 2008. It is a scoping study aimed at increasing our understanding of climate change impacts on regional tourism (economic and non-economic) and to inform and prioritise adaptation strategies which can be undertaken within destinations, and by tourism businesses. This research aims at supporting decision-makers (linked with tourism) in government, business and the community to incorporate climate impacts into policy and operational and strategic decisions. For the sake of both using efficiently existing climate data and providing tourism businesses with relevant time frames, stakeholder discussions and data gathering focus on years 2020, 2050 and 2070.

The STCRC project is itself a response to a prior decision by the Tourism Ministers' Council to establish a Tourism and Climate Change Taskforce (3 August 2007) to guide the development of the Tourism Action Plan on Climate Change. This STCRC project should support the development of the Action Plan while other projects already undertaken considered directly the issues of travel and mitigation.

The national scoping project did not seek to examine only the most exposed tourism regions, but to scope a number of differentiated cases, with a unified methodology. Kakadu was identified early among a number of possible cases (with the Great Barrier Reef) as highly exposed from a media perspective as well as critical from a tourism viewpoint. It was also hypothesised (on the basis of existing scientific and media resources) to constitute an environment potentially highly vulnerable to tourism climate change trends. Kakadu is therefore one of five case studies designed to provide a national overview of climate change adaptations and potential costs across key Australian destination areas. It remains a scoping

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endeavour by providing an indirect testing ground for building up a tourism-specific methodology to support the development of climate change responses involving a variety of stakeholders.

The National Project eventually decided to focus on the following five destination cases (of varying size and significance) categorised along perceived vulnerability to climate change impacts:

Significant vulnerability

1 Cairns region, including the Great Barrier Reef (GBR) and Queensland's Wet Tropics rainforests

2 Kakadu National Park and adjacent communities

3 The Victorian Alps and ski-fields

Some vulnerability

4 The Barossa region

Little vulnerability:

5 The Blue Mountains

The tourism region of Margaret River (WA) constitutes a sixth case study to be researched in 2009. Each region had developed similar teams, roles and methodologies, so as to ensure comparability of methods and consistency in outlook. The project team for the Kakadu case includes Dr Pascal Tremblay (from Charles Darwin University [CDU] as case study leader, also undertaking 'economics' and 'tourism' roles), Prof Eric Valentine (from CDU, fulfilling the 'biophysical-sciences' role), Dr David Mearns (in social sciences and Aboriginal studies role) and Ms Anna Boustead (STCRC Project research assistant) also undertaking a separate Master's degree project looking at the impact of climate change on competing values and future uses of wetlands within Kakadu National Park.

The definition of the region boundaries constitutes a delicate matter, as the focus of the biophysical climate change impacts has generally been on the wetland regions (mainly on the Kakadu and Mary River systems) while the tourism industry implications well extend beyond these immediate physical regions and beyond the Park limits (as examined in Tremblay 2007, 2008). The project needs to consider the potential for substantial climate change impacts on the Kakadu region itself (the statistical tourism sub-region referred to as 'Kakadu' by Tourism NT or 'Alligator' by ABS divisions) as well as the potential for significant impacts on the broader 'Top End' tourism region, in particular the Darwin gateway and destination. This is critical for the assessment of potential economic impacts and can be defended on a number of grounds:

- There is a fair amount of political and institutional integration between stakeholders from the Kakadu tourism region and Top End tourism interests and industry (institutional integration);
- From a human geography viewpoint, Darwin itself constitutes the critical gateway to Top End tourism while Kakadu is more significant as a key attractor. Together, they constitute essential and complementary parts of a tourism region integrated through landscape and attractions (marketing integration);
- The analysis of potential economic impacts needs to consider the role that Kakadu plays in driving regional tourism outside its own boundaries (see Tremblay 2007, economic integration).

7.3 Methodology

As stated above, the same general methodology is applied to all cases, so as to support consistent aims relating to the scoping of tourism adaptation issues and perceptions around tourism. The general process itself is somewhat intuitive, involving the following general steps:

1 choice of stakeholders: the VICE grid

2 first-round interviews

3 scenarios

4 workshops

5 economic assessment

These are discussed in turn below.

7.3.1 Choice of stakeholders: The VICE grid

The STCRC methodology tested imposes a uniform set of stakeholder types or categories applying to the 5 cases. The 'VICE' matrix includes the following types:

- **V**isitors (destination based)
- **I**ndustry (tourism based)
- **C**ommunity
- **E**nvironment

Given the amount of diversity in regional scope and size across the cases, the approach expects a first series of choice to be based on expert knowledge, complemented by a snowballing process in which interviewed organisations are asked to recommend further participants. The original, basic participants list follows in Figure 1.

Role	Policy/Practice	Organisation
Visitors		
	Policy	Tourism Northern Territory
	Practice	Kakadu Tourism Consultative Committee
	Practice	Kakadu National Park (Tourism services)
Industry		
	Policy	Tourism Top End
	Practice	Gagadju Holdings (Crocodile Holiday Inn Hotel / Gagadju Lodge Cooinda / Yellow Water cruises)
	Practice	Kakadu Culture Camp / alternatives
Community		
	Policy	NT Govt – planning
	Practice	NLC
	Practice	New mega-shire representative
Environment		
	Policy	NT parks
	Practice	NAILSMA
	Practice	Kakadu National Park

Figure 1 The VICE matrix of tourism stakeholders applied to the Kakadu region

Some additional considerations applied specifically to the Kakadu region. The first pertains to the representation of *Traditional Owners* interests. This was treated as critical, but it was deemed desirable to avoid presupposing a particular set of homogeneous values for that group. Instead, Aboriginal representation (direct or indirect) was sought across the 4 VICE roles. Kakadu being strongly associated with 'the Park' and governed as a protected area, entities of the *Kakadu National Park* (KNP) need also to be integrated, when fitting the roles found in the matrix. Lastly, the *scientific community* was not incorporated as a separate tourism stakeholders group, although its accumulated contribution clearly influences both the survey participants (in particular environment stakeholders) and the researchers involved in the process who collected the empirical evidence and analysed it.

7.3.2 First-round interviews

The second phase of the methodology involves scoping interviews with the participants identified above. The primary function of the interviews is to inform the project teams of existing knowledge, understanding and considered adaptations to climate change in the tourism context. The supplementary purposes include snow-balling role (whereby stakeholders beyond those named in the VICE grid can be identified and invited to the social learning workshops) and to inform (jointly with the climate projection data from CSIRO) the structure and approach to drive the stakeholder social learning workshops. In the main, the interviews gathered information about the following aspects of climate change and tourism:

- Extent of *awareness* that climate change is happening, and its relevance for tourism planning decisions;
- The *types of positive and negative effects* climate change could have on tourism in the Kakadu/Top End region?
- The consequences of effects on natural environment, infrastructure, activities, operational costs, community life etc;
- The ways in which the Kakadu/Top End tourism region may *respond or adapt* if the climate changes, to negative impacts and/or to take advantage of positive impacts;
- The extent to which *actions* or responses are happening now or need to happen now;
- The *ability* of the Kakadu/Top End region to adapt to the likely effects of climate change, the desirable scale and drivers for response;
- The *time frames* required to properly respond and adapt to climate change in the Kakadu/Top End region;
- *Knowledge needs* in order for the tourism sector in the region to adapt to climate change, to understand tourism's reliance on human resources, infrastructure, the natural environment, communities etc;
- The existence of other individuals or organisations that should be included in the interviewing process? (snowballing);
- Interest in participating in the *workshop*.

7.3.3 Scenarios

The third phase of the generic methodology consists of building scenarios relating climate forecasts and tourism impacts based on CSIRO predictions for the Kakadu region, scientific reports collected on the topic as well as the expected consequences on tourists and tourism businesses articulated during the interviews. The overall purpose is to:

- Present ‘what if’ statements (of a more tangible nature) to workshop participants;
- Integrate scientific knowledge components into credible stories about what the future for tourism in the region might look like;
- Formulate ‘tourism-specific’ visions of regional impacts, taking into account local particularities and dynamics;

The construction of the scenarios themselves involves the integration of highly diverse types and sources of knowledge relating to:

- *Climate* raw data (recently purchased by STCRC from CSIRO – scenarios for rainfall, temperature ranges & seasonality, cyclonic, sea level, etc);
- *Scientific bio-physical* data/projections integrated by bio-physical experts;
- *Tourism* trends based on current expectations of long-term drivers for local, national and global tourism in the future;
- Relevant aspects of the *cultural/social/economic* environment, for instance possible tensions between KNP values and stakeholders*;*
- Main *stakeholder* perceptions (main elements from the first-round interviews).

7.3.4 Stakeholders workshop

Each region has held a workshop with the following aims:

- To assess how all components (VICE segment groups) of the tourism sector might adapt to the presented scenarios;
- To undertake ‘social learning’, whereby all stakeholders from each VICE component will together discuss the implications of the climate change scenarios on the tourism sector;
- To identify how the sector, or particular components within it, might be able to implement adaptation strategies in response to the anticipated changes.

The workshop involves preliminary presentations about climate to tourism stakeholders, and focuses on small group discussions of adaptation strategies, with respect to a number of physical and institutional aspects of the region:

- range
- ranking or priorities overall
- priority through time
- area of application/relevance (natural environment, local infrastructure, operational costs, community life and social activities, etc)
- drivers, sources of implementation
- potential barriers to implementing
- resources needs
- likelihood of implementation

7.3.5 Economic assessment

The STCRC methodology also develops a preliminary estimate of the potential costs and benefits of climate change, combining scenarios of potential tourism transformations with gain or loss of tourism economic activity for each region. The methodology involves making ambitious conjectures about the future, and combining intricate suppositions that have not yet been tested. A complete prognosis would require to extend speculations in a number of hazardous fields, that require further research. While some of these areas are addressed in this scoping study, some will require further development in an appropriate time frame:

- The implications of climate change on tourism through various levels of modifications on the *supply-side* of tourism (climate change impacts on tourism destinations, their marketing, business responses and practices, reactions from key tourism communities (as tourism inputs – infrastructure, key industry decisions, environmental management, etc);
- The implications of climate change on tourism through *demand-side* impacts (variations in tourist-consumer preferences, consumer tastes, lifestyles changes, future travel patterns, and related individual/social mitigation choices, etc);
- The implications of climate change on *institutions* (public and private) designed to address it, and on *planning frameworks* that will shape how these questions should ultimately be addressed (including the nature of mitigation strategies adopted at the macro-economic level).

While the first two dimensions are acknowledged as relevant for any tourism impacts work or methodology, they remain difficult to address separately in a futuristic context because tourism stakeholders strategic responses will naturally aim at identifying threats and controlling media messages, maintaining their competitiveness and influencing future choices to minimise local social and economic loss. The third type of conjecture is even more challenging as it must consider the interface between local-regional and global issues caused by climate change.

For instance, it is usual for most tourism regions to perceive in the first instance threats to their existing competitive positions due to change (except for some more remote cold-climate destinations). The future strategic position of a region such as Kakadu (and the Top End) depends largely on broader geo-political influences, including perceptions that will be held about:

- the main region or broader destination (Asia, Australia) for international markets;
- the nature of substitutes and how they will be affected by (and respond to) climate change themselves – that is the extent to which alternative ecosystems and environments will be affected, qualitatively and quantitatively;

For instance, there is currently a high level of perceived threat on long-haul destinations such as Australia (and potentially such as the Top End within Australia) for European markets, but it is unclear how distant notional competing destinations (such as the Mediterranean region, other South East Asia resorts, etc) will fare, and whether the intensity and pressure from warmer climates will be felt in those places.

An other aspect equally difficult to conjecture is related to the shape and nature of regional-global conflicts over resources and values connected with regions such as Kakadu. As climate changes reignites debates about water, energy, wetlands, conservation and development, various groups of stakeholders will react differently to these tensions. The indirect impacts of climate change on debates about landscapes and values might impact indirectly of various uses of the regions, and the place of tourism within it, in a way that this scoping methodology can not address appropriately.

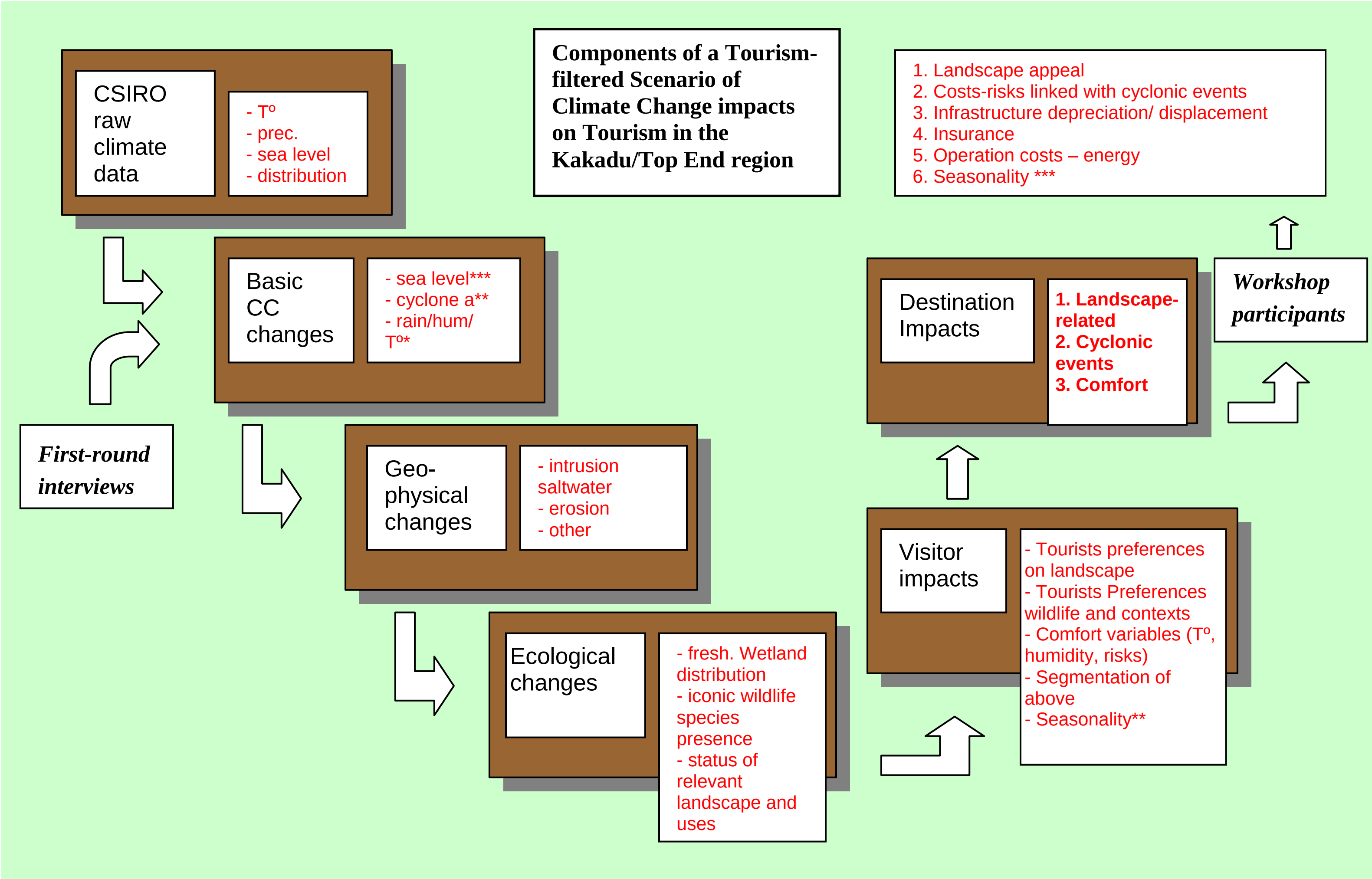

Figure 2 The VICE matrix of tourism stakeholders applied to the Kakadu region

Recognising the limitations discussed above, a tourism-specific methodology to analyse climate change impacts involves attempting to connect climate change forecasts (holding a high degree of uncertainty) to landscape-science transformations, to eventually assess social/economic impacts (both highly uncertain and complex). To maintain such a tourism focus, it is possible to try to establish these connections (from climate to landscape to human environment and tourism impacts) by linking the critical building blocks and imposing tourisms-specific filters, as done in Figure 2. While incomplete in terms of addressing the full range of possible institutional responses, the process has the advantage of attempting a crude integration of geo-physical, ecological, cultural, socio-economic knowledge aspects with those involving tourism scenarios. In Figure 2, the attributes (in red) represent Kakadu-specific dimensions that translate climate into tourism effects, using the pre-conceived filters. The resulting framework is, hopefully, broadly comprehensible by all tourism stakeholders participants, and can be used (for instance in the workshop) to provide a cohesive causal path linking climate to tourism sector evolution.

7.4 Conclusion – preliminary findings

At the time of the presentation at the KNP Climate Change symposium, stakeholder interviews had taken place, but the main workshop that would attempt to integrate the CSIRO data with original findings from the interviews had yet to come. From the long and repetitive list of perceived positive and negative impacts of climate change, the following 3–4 key elements or categories were largely identified by the VICE stakeholders as potential threats (of an uncertain nature and magnitude):

- *Sea-level rise* → salt water intrusion → freshwater wetlands (main attraction in Kakadu) decline;
- *Higher intensity of extreme weather* → cyclone intensity + greater risks of floods → tourist risks and costs (infrastructure, insurance, facilities, industry);
- *Higher temperatures and humidity* → significant increase in tourist discomfort and alleviation costs to industry;
- *Compression of tourist season* → possibly post-peak tourist season arising earlier because of higher day temperatures, peak season delayed because of increased average flooding events or water levels + safety issues.

The three first dimensions of these climatic categories were largely confirmed as significant (but uncertain in their manifestation) by the KNP symposium itself, where various aspects were separately examined, although not related to tourism. The fourth dimension is of relevance for human development and of specific interest for tourism. It is included in this list because of its importance for tourism management in the Top End, but is even less clearly ascertained by climatic data and research. Given its significance for the regional tourism destination (and its recognition as a target objective by Tourism NT), it is included as worthy of consideration.

As part of the scenario-building process, adaptation or response strategies were also considered and derived from the initial interviews. A preliminary list of statements made by stakeholder-interviewees is presented in the table below, which was presented to workshop attendees. Some of these overlap slightly but, in context, reflected sufficiently different intentions to be mentioned separately. The first column of the table indicates those responses which were formulated many times.

Table 1 Adaptation strategies or responses

	Adaptation or responses (in no particular order)
	Ensure we manage public perceptions and avoid hysteria about the nature and/or extent of the damage anticipated
**	Ensure that the region increases its environmental/green credentials (operating standard, accreditation schemes, efficient and appropriate energy sources, waste management, pollution control, recycling, etc)
***	Capitalise on green credentials and promote the travel to the region as environmentally sound and worth visiting
	Rethink the relationship of tourism to the landscape, and its cultural appropriateness – for planning purposes
*	Modify transportation and accommodation technology mix – diversify operations
**	Change the way tourism (to Kakadu/Top End) is marketed, and the nature of the product emphasised – as well as the landscapes that feature in tourism promotion
	Develop/invest in technological solutions to deal with business operational concerns
*	Modify tourist segments and targets to fit new environment
***	Review (modify, replace, displace, redesign) tourism infrastructure and basic tourism facilities in Park (accommodation, visitor services, cruises, campgrounds, boat ramps)
**	Confront the new seasonality challenges triggered by CC
*	Consider new/different transportation modes/mixes and tour scheduling
	Become carbon-neutral
	Place greater emphasis on the role interpretation (tour guide or otherwise) can play in managing change in the environment
	Shift the marketing/attraction away from the freshwater wetlands
	Engineer strategies to connect market segments with seasonal offerings and control access
*	Shift away from natural assets towards cultural assets
	Adopt and implement regional disaster management plans and policies for extreme events
	Promote to tourist markets (and the general public) our ability at managing sea rising impacts
	Address fire management (which is both mitigation and adaptation)
	Stop caring about CC and deliver value for money to tourists – they will come anyway
	Address other more immediate threats first (invasive species, fire management, etc)
	Develop new-alternative-appropriate accommodation projects (locations, types, designs)
	Consider engineering solutions to limit saltwater intrusion
	Develop energy efficient ways of increasing tourist comfort
	Plan for more comprehensive safety, health and heat stress services and strategies/training to support tourism
	Monitor and obtain data about impacts
	Undertake broad tourism plan to monitor and deal with CC
	Place standard restrictions on tourism industry to reduce impact on landscape/ carbon impact
	Act now to manage risk and reduce impact rather than wait for detailed scientific info
	Audit operations of businesses to identify areas where changes can be made.
	Develop a cohesive network of agencies/businesses to share knowledge and strategies
	Promote small tourism operations involving indigenous land management activities in remote areas and support them with proper training, infrastructure and resources.
	Lobby government to provide structures and resources to adapt to climate change.

*, **, denote increasing level of recurrence of the response

A fair amount of convergence in these initial statements could be observed, as well as sentiments that reflect individual or organistional opinions about the seriousness of the threat. As concluding comments, it is useful to comment further on the those preliminary findings, extracted from the transcription and collation of stakeholder perceptions that:

- There is a degree of confusion between climate change 'adaptation' and 'mitigation' in general. This is partially due to the fact that both destination and industry stakeholders view as a priority the need to address through 'green marketing' the potential emergence of a 'mitigation backlash' unfavourable to the tourism sector. Hence, from a tourism viewpoint, adaptation and mitigation are subtly connected.
- When assessing the importance of adapting or responding to climate change threats and opportunities, stakeholders differed, but two broad types of reactions were typical:
  - The view that adapting is not a choice but a must – but with a reactive undertone, in the sense that 'life' must go on and governments and businesses would have to do with change…
  - The view that focus should be on those elements that the tourism sector usually focuses on (and thinks it can control) – those dimensions that shape tourism futures, mainly 'market development and marketing', technological change and infrastructure growth or redirection.

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8 Bininj (Aboriginal) perspective on climate change

D Yibarbuk[1] & P Cooke[2]

8.1 What do our Bininj (Aboriginal) people know about climate change?

Well Bininj people have experienced very dramatic climate changes that have been happening since long before balanda (white people) settled in our country. In our belief our ancestors have been here from the beginning, when the earth was still soft and when some animals were like people before they became the animals we know today.

Our old people used to tell us dreamtime stories that happen long time ago, stories about animals – birds – and reptiles of how they've gone through those processes of change.

When our ancestors saw changes happening, they started to adapt to the changes by looking out for solutions of how to live and survive.

They were hunters and gathers looking for food to hunt and good places to live and enjoy a new kind of life in changed circumstance. When walking about, they would cover the whole area as part of their role as land managers – looking after country according to our traditional land management practices.

Our people have lived through period of great changes. Knowledge has been passed down from one generation to another of what they've experienced through those changes.

One of the stories that are still talked about by our old people concerns a great drought. Balanda (white people) have their bible story about a great flood but we have a story about a great drought.

When springs and rivers dried up the first people, or Nayiyunki, were desperately walking around looking for water, they came across a paper bark tree it had a hump like camel with drinkable water in it.

So they used their stone axes to crack the humped side of the paper bark tree and out came the water to save their lives. So they found a way of getting water from the paper bark tree. We call the hump and the water that comes from it Djidjindok. Nayiyunki lived on that drinking water from the tree for long period until water came back in springs and creeks.

We don't know just when this happened but we do know that balanda (white scientists) are able to tell us that this part of Australia went through a very dry period between about 35 thousand years ago and 18 thousand years ago.

Another story our people talk about is how Northern Australia was attached to Papua New Guinea. It was one big land and the Nayiyunki first people walked around managing the whole landscape looking for better hunting places or lake stocked full of fish.

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There are stories from Maningrida. Just off from Maningrida township is Entrance Island. It lies about three kilometres from the nearest land, at Ndjudda Point. Our people remember when the island was connected to the mainland. In the middle, was a big billabong, a big wetland area full of fish and geese and water chestnuts and water lilies and other game for hunting. It was a very well known wetland place for our past generation till today people still talk about this lost wetland. When the sea level rose all that wetland went under the seawater.

At Goulburn Island the people there still have more stories about these times – stories about islands where people used to live that are there no longer.

Also people tell stories about ‘volcano time’ – not so much volcanic eruptions but violent seismic activity. Our Nayiyunki first people have experienced this volcanic period and lived through it. When the time of modern bininj came, all the seismic activity started to cease down, because the climate started to change and our people continued living and sharing knowledge also passing on stories to able to tell next generation about the changes they’ve experience before. The Bininj word for earthquake or tremor caused by volcano is Bulla. Borlk Wurloo-Wurlmenga country was still burning caused by volcanic eruption.

So we have been experiencing Climate changes for long-long periods up until today’s generations. But the climate changes they experienced were climate changes brought on by nature – not climate changes brought on by people like the situation we face today.

Our Nayiyunki first people watched the way nature worked. They looked at how things change at the yearly scale and named six calendar seasonal movements – Bangerreng – Yekke – Wurrkeng – Gurrung – Gunumeleng and Gujewek.

These are the six (6) calendar cycles of movement for our hunting and gathering purposes. People knew when the seasons changed by seeing the signs and signals in nature that mark the changes. We see changes in winds and clouds and rain, we read the changing seasons through the flowering of plants and grasses, we read the movement of birds and other animals.

These seasonal calendars have been built up over thousands of years but now our old people and even middle aged people like me are seeing the seasons start to look wrong. We see things not really happening when they should.

Our old people are confused. They don’t know what’s happening. These are the signals that tell us when we should be burning grass or when we can find the food we want. Scientists tell us the monsoon stopped for more than 10 000 years a long time ago. What would our world be like if we didn’t have the monsoon to give a regular annual cycle of grasses growing, drying and burning. What would tropical Australia be like if it had years of drought like down south? It’s a scary thought.

People move around for observation looking for signs of what things are there and what things aren’t there, if things aren’t there people knew that something going wrong some where.

During the changes been happening Nayiyunki first people knew the country very well through they observation they would talk to spiritual being and ask for its help to show them in their dream so that they could be ready for unexpected event .

Nayiyunki were able to deal very well with the changes in their times because these were changes made by mother nature. These were natural climatic changes been happening from the first and past generation. But the changes we are looking at today not natural changes – they are caused by human behaviour. People, not nature, are responsible.

Our present generation, We have been hearing media news and TV about global warming. Changes are happening and everybody around the world is running around madly trying to figure out a way to support each other and tackle the problems.

But for our Bininj (Aboriginal) people its not new topic for us about climate changes, we have known it along, we being told stories from our old people before about the changes that happen many-many years ago before our generation. We are very worried about what is effecting us today, sometime we see wet season comes at the wrong time. In recent years we have experienced strong cyclones – Monica set a new mark for violent cyclones. We had unexpected floods hitting our communities. Sometime we hear our old people saying these things are happening because our sacred objects are not happy with us because of disturbances to the sacred land. Dynamite and mining, big machines and roads, these are all things that worry our people.

Within Northern Australia our country has changed in a big way ever since I was born. These are the most affecting symptoms that I see:

- The human population has tripled ever since I was child
- We are losing our language and culture
- Feral weeds and animals have entered our community
- Establishment of towns and settlements
- Mining happening in our country and weather changing and many more.

Feral animals and weeds are changing our natural environment, large animals like buffalos damaging our landscape, weeds are already in placed within our communities and homelands.

Traditional fire management have change in big way no more traditional practices is happening no more walk about like it use to be, people have changed in many ways because of the contemporary changes has put upon to us.

We each, balanda and bininj, have to look at what we can do to fix the damage that is being done to the climate by greenhouse gases and so on.

Out there at Kabulwarnamyo, an outstation in Western Arnhem Land, we are tackling climate change by bringing back and strengthening our traditional burning, the tools that we have used for thousands of years for managing our landscape.

By bringing back our way of land management and making it strong for the future we are doing our bit to help the world deal with climate change.

9 The potential impacts of climate change on fire and vegetation

J Russell-Smith[1, 2] & A Edwards[1]

9.1 Introduction

While there remain considerable uncertainties as to the nature and magnitude of regional climatically-induced changes over the remainder of this century, it is generally accepted that: (1) sea levels will rise by over a metre; (2) annual precipitation will remain somewhat the same, possibly with a slight increase; (3) mean annual temperatures may increase by as much as 2 to 3ºC; and (4) the annual number of days where temperatures exceed 35 ºC is likely to increase by an order of magnitude (CSIRO & Bureau of Meteorology 2007, Garnaut 2008).

Higher sea levels will have obvious impacts on lowland estuarine and fresh-water wetland systems (see Whiting 2010, Douglas & Traill 2010), including higher base-level water tables, hence increased productivity in adjacent monsoon forest and woodland savanna systems.

Changes in temperature, especially the suggested substantial increase in numbers of very high temperature days, likewise will have profound effects on the severity of regional fire regimes – especially for fires occurring in the late dry season (*Gurrung*) period, typically from August to mid-October or November.

9.2 Management responses

There are three major points to make with respect to impending management challenges posed by climate change.

9.2.1 Strategic fire management for biodiversity outcomes

The first concerns further developing the strategic approach to fire management laudably commenced with the first habitat-based fire management plan for fire-sensitive sandstone habitats in the Park. This plan sets 'ecological management thresholds', particularly with respect to ecologically sustainable intervals – between fires, and fire frequency generally, for fire-sensitive habitats (Petty et al 2007). For successful implementation the plan requires: (1) detailed annual planning and ongoing revision; (2) adequate human and logistical resourcing to deliver a strategic and fine-scaled patchy operational fire management program; and (3) ongoing monitoring including provision of fire mapping throughout respective fire seasons, and periodic assessment of the status of fire-sensitive flora and fauna to gauge the effectiveness or otherwise of program delivery and to make necessary adjustments and refinements.

Development of and commitment to this sandstone program build on substantial salutary assessments undertaken in recent years concerning the status of fire-sensitive sandstone assemblages (eg Russell-Smith et al 2001, WWF 2005, Petty et al 2007, Brennan 2008). Similar evidence-based approaches are required for addressing fire management more generally

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throughout lowland areas of the Park. Thus, despite considerable progress with the delivery of aspects of the lowland fire management program since the Park's inception in 1979 (eg diminishing fire sizes, reduced extent of late dry season fires, increased fire patchiness/heterogeneity – Russell-Smith et al 1997, Price et al 2005), recent assessments point to ongoing problems with small mammals (see Garnett & Woinarski 2010) and some lowland fire-sensitive vegetation types such as Cypress Pine, *Callitris intratropica* (Russell-Smith et al 2009). Strategic fire management approaches need to be applied more consistently throughout the Park and, just as importantly, in collaboration with neighbouring tenures.

9.2.2 Management of flammable grassy weeds

The spread of flammable grassy weeds is likely to compound further the effects of climate change, especially the effects of substantially increased temperatures and thereby fire severity impacts, on natural vegetation systems. In particular, terrestrial species such as Gamba grass (*Andropogon gayanus*), perennial Mission grass (*Pennisetum polystachion*), and annual Mission grass (*P. pedicellatum*), provide for development of fuel loads well in excess of grassy fuel loads in typical natural savanna systems.

A salient example is provided by a recent assessment of the impact of Gamba grass invasion on fire danger indices in the Coomalie Shire, south of Darwin (Setterfield & Rossitor-Rachor 2008). On the basis of an assessment of grassy fuel loads on 259 properties in the Shire, these researchers estimated that average fuel loads were 11 $t.ha^{-1}$. Such fuel loads compare with average maximum fuel loads of 6 $t.ha^{-1}$ in uninvaded savanna woodlands. Applying these data to the calculation of the Grassland Fire Danger Index, they found that, whereas native grassy fuels would have resulted in the declaration of 3 fire ban days under climatic conditions prevalent between May 2007 – April 2008, current average fuel loads in the Coomalie Shire would have resulted in 30 fire ban days over the same period. Further, with likely increases of average fuel loads to around 15 $t.ha^{-1}$ in future years given ongoing invasion of Gamba grass, 89 fire ban days would have been declared for the same period. Controlling the spread of flammable grassy weeds is a key management priority.

9.2.3 Fire management and carbon stocks

Development of more conservative fire regimes through strategic fire management also has the dual benefits of reducing greenhouse gas emissions from savanna burning, and associated sequestration (incorporation) of carbon into living above- and below-ground biomass. The implementation of the Western Arnhem Land Fire Abatement (WALFA) project over 28 000 km^2 adjoining Kakadu aims to reduce accountable emissions of the greenhouse gases methane and nitrous oxide by at least 25% compared with a pre-project ten-year baseline total of 370 000 t CO_2-e p.a. By implementing a strategic early dry season fire management program where the pre-project proportion of late dry season, high greenhouse gas emitting fires are reduced by half (from 32% to <17%), Murphy et al (2009) calculate that resultant carbon sequestration in living biomass would amount to an average of 0.22 t CO_2-e ha^{-1} yr^{-1} over 100 years, compared with just 0.04 t CO_2-e ha^{-1} yr^{-1} associated with greenhouse gas emissions abatement.

While these quanta of greenhouse gas emissions abatement and associated carbon sequestration in living biomass would not be achievable in Kakadu given that fire regimes in the Park have already been substantially transformed since 1979 (see above), it is eminently feasible that significant abatement and sequestration benefits could still be achieved, especially through reduction in the extent of burning in lowland savanna woodland systems.

Thus, in a recent assessment of the extent of burning in Kakadu over the period 1995-2004 associated with the first ten years of the long-term fire and vegetation response monitoring program, just under 50% of lowland savanna woodlands were burnt each year; such systems constitute 65% of the entire Park area (Russell-Smith et al 2009). Reducing the annual extent and thereby frequency of burning in Kakadu's savannas is also a key management recommendation for the conservation of small mammals (Garnett & Woinarski 2010).

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10 Potential impacts of climate change on terrestrial biodiversity

S Garnett[1] & JCZ Woinarski[2]

10.1 Introduction

That the climate is going to change is as inevitable as the change that has happened in the past. This has led to great fears for the biodiversity across the globe, with Kakadu having been identified as a hotspot for biodiversity loss in the near future (Garnaut 2008). However, Kakadu is both large and diverse and the changing climate will affect different species, ecosystems and landscapes in quite different ways depending on their location and adaptive capacity. In this short paper we review the current state of knowledge about the impacts of climate change on Kakadu's biodiversity, describe what we consider to be the main threats and why, outline potential ways of maintaining the resilience of the Park as the climate changes and identify areas where more knowledge is needed.

10.2 What do we know?

While the most recent report on climate change in Australia (CSIRO & Australian Bureau of Meteorology 2007) is equivocal about rainfall in the Kakadu region over the next half century, three trends are almost inevitable – temperatures will rise, particularly the number of exceptionally hot days, cyclones will get stronger (Elsner et al 2008) and sea level will rise (IPCC 2007).

However we are also acquiring increasing knowledge of past climates which almost all species currently present in Kakadu have successfully survived. For instance 20,000 years ago the sea level was much lower than today and Kakadu was well inland (Nix & Kalma 1972). While the global ice age climate would have been cooler than today, the more continental location of Kakadu is likely to have resulted in far greater fluctuation in temperature, with extremes both higher and lower than currently occur. Rainfall was almost certainly lower at that time. Later sea level rise brought mangroves almost to the base of the sandstone cliffs (Woodroffe et al 1985). Even as recently as 500 years ago Magela floodplain, today a prolific wetland, was a savanna woodland (Wasson et al 2010). At this time we do not know where the wetland birds survived, probably in swamps now inundated with seawater, but few would have lived within the current borders of what we know as Kakadu National Park.

Such extremes of climate will have winnowed out some species through natural selection. And we have documentary evidence in the form of cave paintings that species like the Thylacine and the Tasmanian Devil succumbed to previous rapid environmental change and/or the influence of humans and dingoes. However, this previous winnowing means that those species which have survived are likely to be reasonably adaptable, with the genetic variability or ecological flexibility to withstand substantial climatic stress. This is likely to be particularly true of the sandstone endemics. While many savanna woodland and wetland

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species probably followed changing rainfall and temperature gradients north and south, sandstone species must have evolved in situ and have withstood everything thrown at them since. Of course, the deeply dissected and rugged stone country offers a particularly wide range of environmental settings (and consequently microclimates), from very sheltered ever-moist canyons to baking rock faces, over very short distances, allowing the option of responding to regional-scale climatic changes by spatial re-arrangement of their populations within distances as short as metres or a few kilometres.

10.3 What are the main threats?

Although Kakadu's terrestrial biodiversity has survived much variation in the past, the current bout of climate change is different and its consequences difficult to predict. This is because:

- we are not really sure how climate will change: how much, where, and when
- some species will be affected more by extrinsic climate change (eg loss of habitats elsewhere) than by climate change in the area we are specifically considering
- as we enter uncharted climatic conditions, we can't be sure how species and environments will respond – ie we're extrapolating beyond the bounds for which we have data
- many climate change impacts may be complex, and there are likely to be unexpected synergies between fire, exotic species and other processes. Thus species survival may be dictated not so much by individual species responses but by the responses of a myriad other species (eg species A may actually like warmer temperatures, but if its competitor, species B, likes warmer temperatures even more, species A will be disadvantaged).

Certainly three changes are new within the evolutionary history of many Kakadu species, high temperatures, increased levels of atmospheric carbon dioxide and stronger cyclones. And sea level may reach more extreme levels than at any time in the last million years.

Change in temperature may directly affect those reptile species that have temperature-related sexual determination of eggs, including crocodiles and some turtles, so may unbalance their sex ratios. The changing temporal patterning of temperature may change fruiting and flowering patterns in plants; emergence times in diapausal insects; triggers for migration in highly dispersive species; availability of water (permanence of pools and streams) and the life that depends upon it; thermoregulation, behaviours and foraging efficiency of animals; respiration, growth rates and competitive ability of plants; fire characteristics; breeding success for many species; and habitat suitability. Many existing interspecific relationships may be decoupled (eg emergence times for butterflies and availability of host plants), and specialised species may be particularly susceptible. Stresses during late dry season are likely to be increased. Fires are likely to be more intense and increased temperatures may favour some exotic plants, animals and diseases.

An example of limits to temperature adaptation is well demonstrated well by the spread of the cane toad *Chaunus marinus*. Over the past two decades toads have been able to adapt to average summer maximums of about 37.7^{o}C (Urban et al 2007). While this greatly expands their possible range, the capacity of toads to occupy climatic regimes beyond that temperature limit has evidently reached a physiological ceiling which they do not have the genetic potential to exceed. Such physiological thresholds can sometimes be at far lower temperatures, as is the case with some upland possums from Queensland (Williams et al 2003). The limits for most native Kakadu species are unknown.

Carbon dioxide can act like a fertiliser for plants, allowing them to use water more efficiently and grow faster. Higher levels of CO_2 favours some species groups, such as shrubs and trees, over others, such as many tropical grasses. How this plays out in terms of vegetation structure remains to be seen but woody thickening and the expansion of rainforest patches (eg Banfai & Bowman 2006) can be interpreted as a manifestation of this already happening.

Cyclones probably keep the forests in coastal regions of northern Australia at subclimax levels (Bowman & Panton 1994). Stronger cyclones will cause even more damage to standing trees and occasionally cause great loss of life among both plants and animals. Hollow-bearing trees, and their dependant fauna, will almost certainly become less common. The other main threat from cyclones is that there are now new exotic species in the Park which occupy disturbed ground more rapidly than native species. The propagules of weeds such as mission grass *Setaria* spp and gamba grass *Andropogon gayanus* are likely to be spread further by cyclones into areas the cyclones have disturbed. The short-term loss of forest canopy post-cyclone in these areas may trigger ideal conditions for these exotic grasses to establish and flourish. These new foci of infection will be hard to find and eradicate because the disturbance could be anywhere, allowing weed recruitment not just along roads as is currently the case with most anywhere. The damage from stronger cyclones will also change fuel loads and fire intensities in the times after the cyclone has passed, which have knock-on effects on the structure and function of the affected savanna landscapes.

The familiar landscapes of Kakadu will also be the main casualty of sea level rise as mangroves push back over the freshwater swamps. Just where and when such changes will occur will be difficult to predict. As the more seaward of the mangroves die, the most coastal sediments will be released and coastal architecture will be altered in ways that are difficult to predict. The more extreme predictions of sea levels rise, however, will eventually overwhelm all the most productive coastal wetlands leaving the less fertile laterite plains to abut the sea. Substantial reductions of lowland freshwater biodiversity can be expected at this time. Even the area of mangrove ecosystems, which are likely to expand, will become smaller again as the sea above the coastal plains becomes too deep. As in previous changes in sea level, however, it is unlikely that all the freshwater species will disappear, they will simply become more restricted and less common.

10.4 How do we maintain resilience?

Management responses to climate change impacts upon terrestrial biodiversity may be worth considering relative to:

- likelihood
- ability (and cost) for us to mitigate
- severity of impact
- flow-on consequence
- rapidity

For example, floodplain sedgelands will almost certainly be affected, the impact will be severe, and there will be substantial consequential effects on other biota, but it is unlikely to occur for 20 years so we may be able to come up with some remedial measures. Under such circumstances developing such measures is probably a high priority.

That said there are some principles that should underpin management of a site like Kakadu. For instance there is a temptation for the rarest species in any landscape to be considered insignificant and therefore not worth saving. However very rare species can play significant roles in ecosystem functioning (Zavaleta & Hulvey 2004) and, under changing climatic conditions, selection pressures alter and uncommon species can prosper. Thus today's losers can be tomorrow's winners, and provide ecological functions that would not have been possible had they become extinct. A resilient system needs untapped redundancy (Walker et al 2002), whether that be a surfeit of individuals or of species. Only with such redundancy do ecosystems have the capacity to re-establish the functions they had before they were disturbed. Thus there are sound ecological reasons, as well as legal obligations, for every species currently in Kakadu to be conserved if at all possible. Any temptation to institute a process of triage, whereby species at some arbitrary level of rarity are neglected and their millions of years of evolutionary history allowed to peter out, should be resisted. Such an approach, of course, should apply under existing threats as well as under the additional threats that will be generated by climate change. Just how such conservation will occur is a separate debate, determined on a species by species basis.

Resilience is far more difficult to maintain in the face of rising sea levels. In fact landscapes and ecological communities as a whole are more difficult to conserve than their component species because they often consist of multiple species on different ecological trajectories that occur together at a particular time and place, then disperse as conditions change. Thus, with landscapes, a triage is entirely appropriate, in fact the only strategy that can sensibly be adopted. The landscapes that will change most dramatically are the freshwater wetlands, just as they have always done through evolutionary history. Even so sea level rise will be gradual and some freshwater wetlands will persist longer than others. These are probably the most valuable in the medium term, and it is on them that management should be concentrated, particularly to attempt to diminish the detrimental impacts of their load of exotic organisms. It may even be appropriate to adopt more heroic conservation responses, such as through translocation of wetland elements to systems further inland and/or through the use of physical barriers to seawater intrusion where environmental engineering is conceivable. In the meantime the mangrove systems most likely to replace the freshwater swamps are also richly biodiverse, and warrant celebration even as their predecessors are being salinised.

Any increase in resilience under a regime of stronger cyclones will need to be built round responses to changes in vegetation. More vigilant fire management and a rapid response to weeds will be critical. For timely weed control after a cyclone, contingency plans need to be in place identifying potential sources of propagules and likely patterns of spread. Surveys and eradication in the year immediately following a cyclone may save years of control expenses if the weeds are allowed to linger longer.

10.5 What are the information gaps?

For each threat and resilience strategy there are gaps in knowledge that, if filled, are likely to improve response efficacy. Management of climate change in Kakadu will be greatly enhanced with better information on:

- likely climate change at a regional scale derived from finer scale climate change models;
- climatic associations, tolerance and drivers of at least representative species;
- trends in species and landscapes derived from monitoring programs that allow detection of climate change impacts, and early indication of unanticipated trajectories;

- probabilities of change derived from risk analysis frameworks which can then be used to prioritise management responses.

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11 The potential effects of climate change on marine and coastal biodiversity

S Whiting[1] & N Smit[1]

11.1 Introduction

There is a growing body of literature that provides collective evidence of a warming world and significant changes to the climate system (Houghton et al 2001, Gitay et al 2002, Hennessey et al 2004). The earth has warmed 0.6–0.8° C since 1880 and is expected to warm 2–6° C by 2100 (Houghton et al 2001). In addition there is increasing evidence that this warming is related to human activities including greenhouse gas emissions and aerosols (Hennessey et al 2004).

The broad types of proposed impacts of climate change on the marine environment include:

- increase in temperature (sea water, coastal sands, and air)
- increased coastal changes including shoreline position (increased erosion and deposition)
- changes in river flow regimes (changes in sediments, nutrients)
- sea level rise – elimination and formation of habitats, changes in distribution of habitats and habitat processes
- changes in ocean current flows
- changes in sea water chemistry (acidification, salinity)
- increase in stochastic events (destructive cyclones)
- changes in light levels
- changes in precipitation

11.1.1 Recorded and predicted climate changes in the Northern Territory

Recorded and predicted changes are different in different locations in Australia. Even within the Northern Territory the temperature changes will be buffered in the Top End compared with the southern NT.

Recorded changes in climate include:

- an increase Australia's in average temperature of 0.76° C from 1910 to 2000
- an increase of 0.12° C in maximum temperature in the NT since 1950
- an increase of 0.17° C in minimum temperature in the NT since 1950
- an increase average rainfall of 14.2 mm during the wet season in the NT since 1950

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- intensity of heavy rainfall events has risen by 10% in the NT since 1950 (Hennessey et al 2004)
- an increase of 1.2 mm/y in sea level rise at Darwin Port (Church et al 2004)

Predicted changes in the NT include:

- warming of 0.2–2.2°C by 2030 and 0.8 to 7.2°C by 2070 (relative to 1990) – with the least warming over the Top End
- decrease in rainfall over most of the NT
- little change in the timing and magnitude of the monsoon
- atmospheric moisture balance is expected to decline 30–130 mm by 2030 and 90–400 mm south of Daly River with smaller changes north of Daly River, 10–80 mm by 2030 and 70–320 mm by 2070
- increase in the number of days over 35°C
- increase in intensity of cyclones with increased wind speed, wave height, rainfall and storm surges
- unknown changes in frequency of cyclones (Hennessey et al 2004)

11.1.2 Kakadu National Park

Kakadu National Park (KNP) lies within the SE corner of Van Diemen Gulf. Van Diemen Gulf is a large, almost fully enclosed, body of water located approximately 100 km west of Darwin. It has narrow openings to the north (Dundas Strait) and southwest (Clarence Strait). Circulation in the Gulf is forced primarily by the semi-diurnal macro-tides with freshwater discharges in the wet season having additional influences (Green 1998).

The coastal marine environment with KNP is dominated by extensive low, flat, estuarine, coastal plains fringed at the coast by mud flats/banks often associated with a narrow band of mangroves. Within the Park boundaries two large rivers (the South and East Alligator Rivers) and two smaller rivers (West Alligator and Wildman Rivers) create large floodplains during the wet season. The rivers are typical tide-dominated estuaries with a naturally high turbidity, fringed by intertidal flats, mangroves and saline flats/salt marshes. During the wet season, it is believed that the freshwater flow into Van Diemen Gulf is an important driver in ecosystem processes (Green 1998).

Field Island, located in the mouth of the South Alligator River, is characterised by intermittent fringing reefs with extensive sand flats and an occasional beach along the eastern and northern side, whereas mangroves and mudflats dominate the western side.

Baron Island is characteristics by mud banks/flats lined with mangroves. On extreme low tides, the channel between Baron Island and the mainland dries out and seems to be characterised by bare rocky reef.

Marine fauna surveys for KNP have been limited to estuarine fishes and crustaceans (eg Larson 2004); soft-bottom fauna (Russell & Smit 2007), intertidal seagrass (Roelofs et al 2005) and marine/coastal vertebrates (eg sea turtles, crocodiles, dugong and birds). In general terms the marine and coastal environment for KNP hosts a wide range of species groups such a seagrass and macroalgae, marine invertebrates, fishes, marine turtles, marine snakes, crocodiles, seabirds and marine mammals. Nevertheless, the invertebrate fauna for KNP is still poorly known. Similarly, there is a lack of knowledge of marine community structure, extent and diversity; and the physical environmental parameters that drive the Alligators Rivers/Van Diemen Gulf ecosystem.

11.2 Potential impacts on species, species groups and communities

In the most part, impacts on species groups and habitats will be negative with the range of impacts are summarised by category in this section. However, some groups which have high resilience and are well placed geographically and ecologically may experience neutral or positive impacts. The most likely of these groups to benefit is the mangrove communities which are not constrained to move landward as sea levels rise. Secondarily, groups such as soft bottom communities and seagrasses (especially colonising species) may benefit by increased area as sea levels rises and inundates flat low-lying coastal plains. However, these positive impacts may occur in the longer term and may be neutralised by negative impacts in the short term caused by rapid environmental changes.

11.2.1 Coral communities

At a global scale, coral reefs are susceptible to climate change and increasing CO_2 levels. Major impacts will include changes in: water temperature, air temperature, water chemistry, cyclone frequency, turbidity and freshwater flows (Hoegh-Guldberg 2006, Kleypas et al 2006, Hoegh-Guldberg et al 2007). Major coral bleaching events were recorded in Australia in 1983, 1987, 1991, 1998, 2002 and 2006 (Hoegh-Guldberg et al 2007). In general, the two impacts of greatest concern are increased mortality from bleaching events from increase sea temperatures and the reduction in coral growth and reef degradation by acidification of the oceans through increased carbon dioxide (Hoegh-Guldberg 2006).

In the Northern Territory, some coral species are relatively tolerant to extreme environmental stressors compared with corals in cooler and clearer waters. In the intertidal areas of the macro-tidal regimes such as the waters around Kakadu, corals exist in the waters of extreme temperatures (up to 38°C), long periods exposed to air and freshwater (especially during the wet season) and extremely turbid water. However, species may be at edge of threshold and be impacted by relatively fast changes due to climate change outside these ranges. Subtidal corals within Garig Gunak Barlu National Park, 100 km to the north, have already experienced catastrophic coral bleaching from increased water temperature (Gomelyuk 2007).

Table 1 Summary of impacts of climate change of coral communities (Hoegh-Guldberg 2006, Hoegh-Guldberg 2007)

Susceptibility	Climate change Issue	Impacts
temperature	↑ temperature	↑ coral bleaching
light	↑ sedimentation	↓ productivity
	changes in irradiance	↑ coral bleaching
disturbance	↑ cyclone/storm activity	↑ physical damage
ocean chemistry	↑ acidification	↓ calcification rates
		↑ coral bleaching
freshwater runoff	↑ precipitation	↑ coral bleaching
inundation	↑ sea level rise	↓ in distribution of corals
dispersal	changes in ocean circulation	changes in dispersal and distribution

KNP lacks true coral reefs that comprise a thin veneer of living corals atop a base of calcium carbonate built up by their predecessors. However, the waters of KNP support important complex coral communities comprising corals, sponges and algae, living atop a rock substrate. These communities, especially those found sub-tidally, are relatively unstudied with no complete taxonomic lists prepared. Similar, but more extensive, intertidal reef systems are found at the Vernon Islands near Gunn Point and along Lee Point and Nightcliff foreshores near Darwin.

11.2.2 Seagrasses

Seagrasses are flowering plants found in the sea and have leaves, roots and underground stems (Poloczanska 2006a). They can occur in clear to turbid waters and range from the intertidal areas to depths of more than 30 m. they play an important role in nutrient cycling, sediment stabilisation, serve as a nursery area for many species groups such as crustaceans and fish and support green turtles and dugongs (Poloczanska 2006a, Waycott et al 2007).

The distribution and abundance of seagrasses in the KNP are described in Roelofs et al (2005).

The majority of seagrasses in the coastal waters off Kakadu National Park are found on intertidal habitats around Field Island (2050 ha, Roelofs et al 2005). No seagrass are found on the extensive mainland mudflats, except for those north of Mud Island (near the entrance of the South Alligator River) and just west of Gularri (Point Farewell, near the mouth of the East Alligator River). Seagrass meadows are all intertidal except for two locations: northwest and east of Field Island. The NW subtidal seagrass meadow appears to have a high biomass, as in places it could be easily seen from the surface and the beam trawl seemed to sample greater quantities of seagrass than anywhere else known in the SE Van Diemen Gulf region. The intertidal meadows showed evidence of turtle and dugong feeding.

Table 2 Summary of impacts of climate change on seagrasses (Poloczanska 2006a, Waycott et al 2007)

Susceptibility	Climate change issue	Impact
light	↑ sedimentation, sea level rise	changes in species composition, ↓ in productivity
temperature	↑ in temperature leads	↓ productivity/ growth rates (above 30°C)
nutrients	↑ nutrients -	may lead to competition by algae
disturbance	↑ in cyclone frequency and intensity	↑ disturbance
salinity, CO_2 and pH	↑ rainfall and outflow, changes in CO_2	↓ growth rates, impacts unknown
available habitat	changes in shoreline position and increased erosion	changes in availability
seed dispersal	changes in ocean currents	changes in community structure

11.2.3 Rocky reefs and macroalgae

Rocky reefs and shores occur within the KNP (also see coral communities). Tidal regime and wave action are two prominent influences for any rocky area. Sea level rise will influence tidal regime and depth of water above the substrate and climate change will influence storm and cyclone intensity (Poloszanska & Babcock 2006). In addition water temperature and air temperature during exposure periods will influence distribution and abundance of most organisms. Macroalgae are the most obvious life on most rocky shores and are likely to impacted by climate change. Other sessile organisms such as barnacles and oysters will also be impacted.

Table 3 Summary of impacts of climate change on rocky reefs and macroalgae

Susceptibility	Climate change Issue	Impacts
water clarity/turbidity	↑ sediment	smothering of organisms, ↓ algal growth
changes in optimal water chemistry ranges	↓ salinity, ↑ nutrients, ↑ pH	changes in composition of organisms, ↓ in coralline algal growth
disturbance	↑ storm intensity	↓ species composition eg premature detachment of macroalgae

11.2.4 Soft sediments

Soft sediment habitats is a broad categories and many fauna overlap with other habitats such as seagrasses and mangroves. Soft sediments play an important role in supporting the detrital food web which recycles much of the overall energy budget (Okey 2006). Soft sediment habitats include muddy estuaries to the high water mark down to the abyssal plains of the deep sea. For KNP, the scope covers the muddy and sandy substrates of the nearshore (Okey 2006).

These habitats are shapes by a combination of temperature, food input and disturbance regimes (Okey 2006).

Table 4 Summary of impacts of climate change on soft sediments

Susceptibility	Climate change issue	Impacts
changes in nutrient/ food input	changes in water currents	↓ productivity
changes in optimal water chemistry ranges	↓ salinity, ↑ nutrients, ↑ ph	changes in composition of organisms,
disturbance	↑ storm intensity	↓ changes in sediment composition and species composition
narrow optimal ranges for most soft sediment organisms	↑ sea temperature	changes in species composition, lower productivity

11.2.5 Mangroves/coastal wetlands

Mangroves will be impacted by climate change in several ways including degradation from increased storm and cyclone intensities, changes in growth patterns through changes in salinity, temperature and atmospheric CO_2 concentration, decreased protection from storms from the degradation of coral reefs (Mcleod & Salm 2006). On a global scale, the mangrove communities of the NT will be the least vulnerable to climate change impacts and potentially gain in area because they are:

- relatively pristine
- have room to move landward
- have large areas of riverine mangroves
- they occur in remote areas
- they occur in macro-tidal areas
- they occur in dense forests which allows a supply of propagules and seeds

Table 5 Summary of impacts of climate change of mangrove communities (Mcleod & Salm 2006, Poloczanska 2006b)

Susceptibility	Climate change issue	Impacts
habitat availability	rising sea level – landward migration	change dependent on sedimentation rates
air and sea temperature	↑ temperature	↓ productivity at low latitudes
dispersal	altered circulation patterns	altered community composition
atmospheric conditions	↑ CO_2	↑ productivity – dependent on salinity, humidity and nutrients)
	↑ UVB radiation	Unknown
growth, sediment retention, subsidence	↑ cyclone/storm activity	↓ forest cover
salinity	sea level rise	tidal inundation of freshwater wetlands (↑ habitat estuarine extent, ↓ in freshwater wetland extent)

11.2.6 Freshwater coastal wetlands, coastal beaches and islands

One of the most serious and obvious impacts of climate change will be the changes in distribution, structure and function of coastal wetlands. The shoreline with coastal dunes and mangroves protect the wetlands from saltwater intrusion and act buffer as a natural buffer against cyclones, storm events, storm surge and sea level rise (Gitay et al 2002). Loss of freshwater wetlands will be one of the most serious impacts for KNP. In addition sandy beaches of the mainland coast and islands provide habitat for nesting sea turtles and seabirds.

Table 6 Summary of impacts of climate change on freshwater coastal wetlands, coastal beaches and islands

Susceptibility	Climate change issue	Impacts
shoreline position	rising sea level – landward migration	saltwater intrusion of freshwater wetlands ↓ extent of freshwater wetlands
shoreline position – shifting beaches	sea level rise and increase storm intensity	↓ in nesting habitat for sea turtles and seabirds

11.2.7 Fishes

This section will deal with all fishes including the benthic and demersal fishes, the elasmobranchs and the pelagic fishes. Increased sea temperatures will have the most marked impact on the abundance and distribution of fishes (Okey & Hobday 2006) as temperature is the principle factor in determining distribution and abundance (Rossig et al 2004) and biomass (Ware 1995).

Table 7 Summary of impacts of climate change on fishes (Okey & Hobday 2006, Munday et al 2007)

Susceptibility	Climate change issue	Impacts
optimal environmental ranges for distribution and abundance	↑ temperature, changes in ocean chemistry (salinity) and ocean circulation	changes in distribution and ↓ abundance
optimal physiological ranges that act as cue	↑ temperature	changes in the phenology of fish life cycles
dispersal	changes in winds and currents	changes in distribution
survival on planktonic larvae	↑ UV radiation	↓ survival
degradation of habitat	disturbance of key habitats (seagrass beds, coral reefs)	↓ abundance
nursery habitats	sea level rise	changes in function of seagrass beds and mangrove communities as nursery habitats
optimal environmental ranges for water chemistry	increased fresh water inflow	changes food availability and species reproductive cycles

11.2.8 Seabirds/shore birds

Seabirds usually feed at sea in coastal or pelagic water and nest in colonies of varying sizes on the mainland or on islands (Richardson et al 2006). Shorebirds or waders usually feed on invertebrates on coastal mudflats and undertake reproductive migrations with the most spectacular covering distances of many thousands of kilometres to the northern hemisphere

Table 8 Summary of impacts of climate change on seabirds/shorebirds (Richardon et al 2006, Congdon et al 2007)

Susceptibility	Climate change issue	Impacts
nesting habitat availability	rising sea level, ↑ cyclone storm activity	↓ availability of nesting habitat eg sand islands
air and sea temperature	↑ temperature	changes in food distribution changes in seasonality, timing changes in nesting ranges and growth ↓ hatching success
food availability	changes in ocean currents	changes in breeding success
food availability	sea level rise	↓ foraging habitat

11.2.9 Marine reptiles

The marine reptiles include the marine turtles, marine snakes and the saltwater crocodile. They cover the full scope of marine habitats including open ocean, continental shelf, coastal waters, estuaries, sand beaches, seagrass beds, coral and rocky reefs and sand beaches.

Major impacts will include increases in air and sea turtles temperature and destruction of foraging and nesting habitats. Increased temperatures will impact on marine turtles and crocodiles as they exhibit temperature dependent sex determination, which for marine turtles is exacerbated by strong site fidelity to nesting beaches. Changes in habitats such as coral reefs and seagrass beds will impact on food availability for marine snakes and marine turtles while changes in shorelines and islands will impact on nesting success of sea turtles and may shift them to less optimal incubation beaches.

Table 9 Summary of impacts of climate change on marine reptiles (Poloszanska & Milton 2006, Hamann et al 2007)

Susceptibility	Climate change issue	Impacts
air and sand temperature	↑ temperature	more females hatchlings, ↓ hatching success changes in spatial and temporal distribution
food availability	↑ temperature, changes in ocean currents	↓ food, changes in breeding success
habitat availability	↑ cyclone/storm activity, ↑ sea levels	↓ in nesting habitat in short term
dispersal of turtle hatchlings	changes in ocean circulation	changes in foraging distribution
food availability for green turtle	↑ changes in UV	unknown changes in food abundance

11.2.10 Marine mammals (dugongs and cetaceans)

In the tropics, marine mammals include the cetaceans and the dugong. For cetaceans in the NT, major impacts are unknown because of the lack of data regarding abundance, distribution and linkages within the ecosystem. For both dugongs and cetaceans it is expected that most impact will be related to food availability due to habitat changes and prey abundance.

Table 10 Summary of impacts of climate change on marine mammals (Lawler et al 2007)

Susceptibility	Climate change issue	Impacts
temperature	↑ temperature	↑ habitat dugongs changes in habitat for cetaceans
food (dugongs	↑ storms and cyclones	↓ seagrass
physical damage/injury	↑ storms and cyclones	increased mortality
food (cetaceans)	changes in ocean currents ↑ storms and cyclones	changes in distribution and abundance
strandings	↑ storms and cyclones	↑ strandings

11.3 Prediction/mitigation

There still remains a great level of uncertainty regarding the occurrence and severity of impacts on many species groups, habitats and ecosystems, especially in northern Australia where a limited baseline exists and many of the processes remain unknown.

11.3.1 Baseline information, understanding processes and prediction of impacts

For most of northern Australia, and in particular the Northern Territory, much of the baseline information required for prediction and consequently mitigation in the marine environment is lacking. Basic information such as the occurrence and relative abundance of species and the habitat maps and species distributions (what occurs where)are not available in the NT, which means many of the processes are not well understood.

Currently, most of the NT climate change impact prediction in the marine environment will rely on basic information and extrapolation from studies from outside the NT.

To improve climate change impact prediction and mitigation in KNP and to improve marine management in general the following steps could be used:

1 use existing information and extrapolations from studies from outside the NT to best estimate climate change impacts

2 identify data gaps and complete basic habitat mapping of coastal marine areas including species occurrences, distributions and relative abundances

3 set-up monitoring of key environmental indicators, species and habitats to ensure that data is available to interpret trends.

4 obtain a better understanding of the marine processes involved by identifying and monitoring unique features of NT marine systems that cannot be extrapolated from other studies.

5 use latest mathematical modelling and simulations to predict impact based on local or extrapolated data.

11.4 Mitigation

Mitigation measures can be divided into three broad categories.

1 greenhouse gas emission reduction (important and effective, but long lag times)

2 resilience – maximise the capacity of the system to resist, adapt or recover

3 direct intervention

The first category will not be discussed as it will occur largely outside KNP and is beyond the scope of this document.

11.4.1 Resilience

Ecological resilience refers to the capacity of an ecosystem, habitat, population or taxon to withstand, recover from or adapt to impacts and stressors (such as climate change) and retain the same structure processors and functions (McCook et al 2007).

The main aim of mitigation using resilience is to enhance the natural resiliences of species groups, habitats and ecosystems. The main steps in achieving this include:

- assessment of resilience
- identifying and protecting critical areas that are naturally positioned to survive climate change (REFUGIA)
- understanding, protecting and restoring connectivity between areas (CONNECTIVITY)

- assessing and managing human stresses that reduce resilience – healthy populations/habitats are more resilient
- establishment of baseline data (able to recognise stress and changes in extent of habitat)
- monitoring key species and habitats (eg sex ratios in reptiles, incubation success of birds and reptiles, coral bleaching)
- implementation of strategies to accommodate habitat spatial shifts

11.4.2 Direct intervention

Direct intervention is more difficult to achieve but may play a role in the short term to conserve particularly vulnerable areas or to mitigate against stochastic events that may occur irregular. Some examples within the marine environment may include:

- Installation of barrage to prevent saltwater intrusion
- Filling in breaches in the coastal dunes after a cyclone to prevent saltwater intrusion
- Restoring island integrity in the short term to preserve nesting habitat of particularly vulnerable species such as sea turtles and seabirds.

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12 The potential effects of climate change on wetlands and freshwater aquatic biodiversity

MM Douglas[1] & LW Traill[2]

12.1 Introduction

The freshwater habitats of Kakadu National Park (KNP) are some of the most valuable in the Park. They contain an abundance of bush tucker, are a focus for tourism and are internationally recognised for their high biodiversity and conservation values. They are some of most iconic habitats of northern Australia. But these habitats are also likely to be among the most vulnerable to the adverse effects of climate change.

A number of studies have considered the potential impacts of climate change on Kakadu, including the freshwater habitats (Bayliss et al 1997, Bartolo et al 2008, Hyder Consulting 2008). There is general agreement that climate change will likely result in a rise in sea level, higher average temperatures and more frequent hot spells and more intense tropical cyclones. However, it is unclear how climate change will affect rainfall patterns (Bartolo et al 2008) and very difficult to predict how the interaction between rainfall, temperature and evaporation could affect patterns of river flow and wetland hydrology.

In this paper we consider the likely negative effects of climate change on aquatic habitats resulting from the more certain changes: elevated temperature and sea level rise. We use magpie geese as case study of the potential impacts on faunal populations and make recommendations for management responses and highlight key knowledge gaps.

12.2 Potential threats

12.2.1 Elevated temperature

The warming effects of climate change are likely to have the greatest negative effects on cold-blooded animals living in tropical regions. Although predicted temperature increases maybe relatively small, tropical animals are relatively sensitive to changes in temperature and are currently living close to their optimal temperature (Deutsch et al 2008). In Kakadu, increased temperatures are likely to have consequences for aquatic species that show strong temperature sex determination such as salt and freshwater crocodiles (*Crocodylus porosus* and *C. Johnsoni*) (Webb et al 1987) and turtles. For example, the breeding of pig-nosed turtles (*Carettochelys insculpta*) is highly sensitive to changes in temperature. The temperature to which eggs are exposed has a strong effect on the sex of hatchlings and an increase in temperature of just 1°C can change the sex ratio of hatchlings from all males to all females (Young et al 2004). Such changes in the sex-ratio of turtle populations has been observed in Papua New Guinea (Georges, unpublished data), but the effects can be ameliorated to some extent by adaptation in the choice of nesting sites (Doody et al 2006).

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12.2.2 Sea level rise

The most widespread effect of climate change on freshwater habitats will result from the increase in sea level and consequent saltwater intrusion. The low-lying coastal wetlands and floodplains are extremely vulnerable to sea level increases (Bartolo et al 2008). There is uncertainty regarding the proportion of wetlands that would be lost to saltwater inundation and the timeframe over which this would occur but it seems likely that at least 60% of wetlands may be lost over the next 50 years (Bartolo et al 2008).

Saltwater inundation of these habitats, as has been seen on parts of the Mary River (Whitehead et al 1990), will result in a massive reduction in floodplain productivity and the loss of freshwater plant communities, including large stands of woody species such as paperbarks (*Melaleuca* species) as well as a reduction in the fauna associated with these habitats. Many of the fish and waterbirds found on coastal wetlands and floodplains move to other habitats in the dry season, so the loss of these habitats is likely to have negative consequences for other ecosystems such as upstream river reaches and estuarine systems. As an example, we provide detailed case study of magpie geese below:

12.2.3 Case study – magpie geese (*Anseranas semipalmata*)

Magpie geese are the sole members of the family Anseranatidae, and are endemic to Australia and New Guinea (Frith & Davies 1961). Numbering up to 3.5 million birds across the Northern Territory (Bayliss & Yeomans 1990), geese are culturally important to indigenous Australians as a food-source (Whitehead et al 2000), are popular with recreational shooters (Whitehead et al 1988) and are ecologically important through their sheer abundance (Whitehead 1998).

The Alligator floodplains of KNP host vast aggregations of geese and principally during the late dry season, when birds gather on floodplains to grub for the root tubers of the sedgeplant *Eleocharis dulcis* (Whitehead 1998). A noted pattern of association exists between geese and *E. dulcis* (Figure 1), and with geese migrating in response to plant tubers, and foraging on these until the drying of floodplains forces migration. Magpie geese also utilise sub-coastal floodplains and inland billabongs in KNP for nesting following the monsoonal rains (Frith & Davies 1961).

Principal threats to magpie geese in KNP and across the Northern Territory (NT) are infectious disease (Tracey et al 2004, Traill et al 2009), potential overharvest (Brook & Whitehead 2005), poisoning by spent lead shot (Whitehead & Tschirner 1991) and habitat loss to introduced plants and saline water intrusion (Eliot et al 1999, Lonsdale 1994). Moreover, the synergistic interactions between these threats under climate change (Brook 2008) are likely to be worse than the impacts of these acting alone.

Saline water intrusion through sea level rise has received attention for almost two decades (Eliot et al 1999, Mulrennan & Woodroffe 1998). Shifts in wetland salinity will alter plant communities, and toward those better adapted to saltwater (Whitehead et al 1990). Important foodplants (to magpie geese), and especially *E. dulcis* thrive in fresh-brackish water and are very likely to be lost to shifts in floodplain water regimes (Midmore 1998).

Loss of *E. dulcis* will likely drive a gradual decline in geese abundance across the NT and in addition to increased human pressures (land use and harvest), and habitat loss to competitive invasive plants. Although not likely to go extinct, a relic magpie goose population in KNP will have implications for traditional harvest and the tourism industry. Pre-emptive conservation action (see for example Whitehead et al 1992), and as outlined in the symposium workshops, should work toward the maintenance of *Eleocharis*-dominated floodplains in Kakadu (at least for the next 50–100 years).

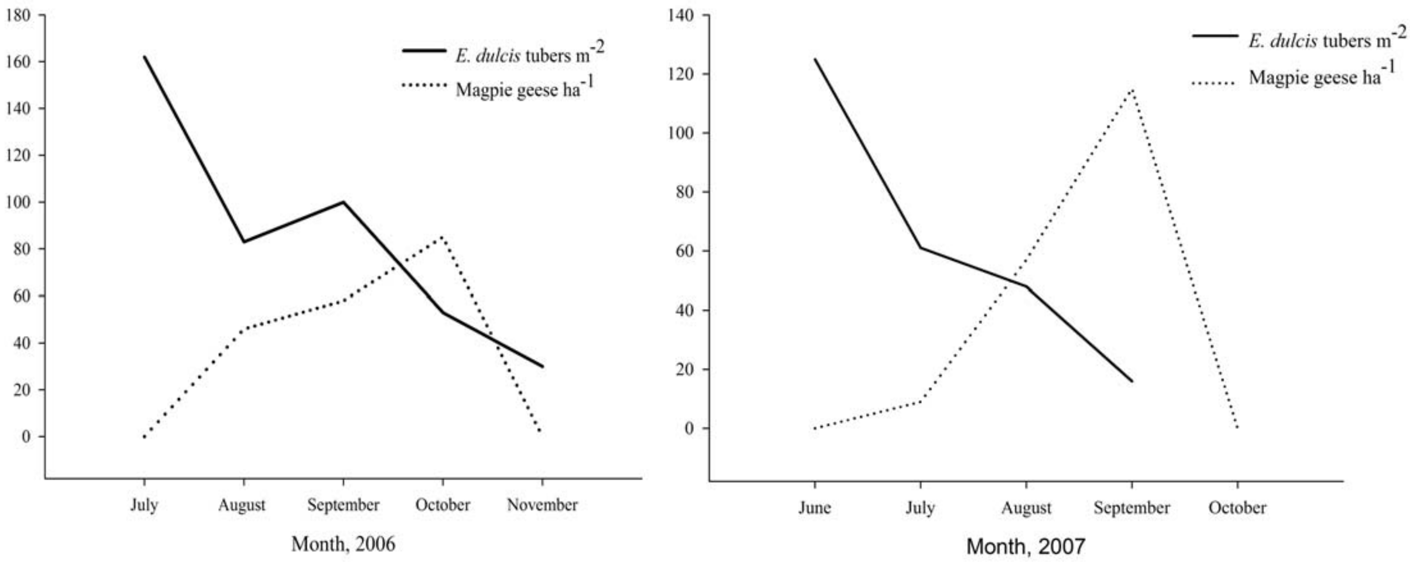

Figure 1a, b Decline in root tuber abundance of *E. dulcis* as the dry season progresses, and for 2006 (a) and 2007 (b). Also shown are the aggregative response of magpie geese in response to tuber density and access. *E. dulcis* taken as mean tuber density m^{-2}, and geese abundance taken as mean individuals ha^{-1} and per month.

12.3 Management issues

There are a number of management responses that follow from the potential threats to freshwater habitats outlined above:

1 Identify critical refugial habitats: Modelling of potential saltwater inundation should be undertaken as a priority to identify potential areas that may provide a ‘refuge’ for floodplain and wetland biodiversity. Not all freshwater wetlands are connected to the tidal rivers and these upstream habitats will be critical refuges (Bayliss et al 1997). It should be noted, however, that not all plant species found on floodplains will be represented in upstream habitats (Bayliss et al 1997).

2 Maintain resilience of refugial habitats: Park management should focus resources to ensure that the areas of freshwater wetland (least likely to be affected by saltwater inundation) are managed to maintain their resilience. Resources should focus on the control of weeds, feral ungulates and ensure correct burning practice. Identifying areas most at risk of saltwater inundation will also assist in identifying areas where continued management of other threats may not be warranted and will assist in reallocation of resources to refugial habitats or local mitigation efforts (see 3 below).

3 Local mitigation of high values sites: Although halting saltwater intrusion onto all of these low-lying habitats is not a feasible option, local mitigation is possible. For example,

one approach is to retard saline water intrusion through the construction of barriers or barrages. Such effort could only be justified in areas of high ecological or cultural significance (such as the South Alligator floodplains).

4 Monitoring and adaptive management: The condition of refugial habitats and the effectiveness of mitigation efforts (if applied) need to be monitored and there needs to be feedback to management responses if necessary.

12.4 Knowledge gaps

Our ability to respond to the potential threats of climate change would be greatly improved with a better understanding of the likely changes in climate for the region, particularly rainfall. Current climate models do not provide very reliable predictions of rainfall at a scale that would allow predictions of the implications for hydrology. For these reasons, we have not discussed the implications of potential changes in hydrology – such as increased river flows or changes in the length of the dry season – but such changes would be critical for freshwater habitats.

Developing a higher resolution digital elevation model for Kakadu's floodplains is a critical step in improving our ability to identify those areas most (and least) at risk of saltwater inundation.

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13 Interactions between invasive species and climate change in a Kakadu context and national priorities for their management

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13.1 Introduction

Invasive alien species (IAS) – species that have spread beyond their native range to cause harmful environmental, economic and societal impacts – are one of the top three threats to global biodiversity. The Intergovernmental Panel on Climate Change recognises that invasive species in the form of pests, weeds and diseases will increase in range (towards the poles), abundance (with increased temperature) and spread (with increased extreme events and associated disturbance (IPCC 2007). As a result the compound impacts of climate change (CC) and invasive organisms accelerate and exacerbate the environmental impacts of either process alone. Society is unlikely to dramatically mitigate current predictions for climate change, therefore direct effective and targeted management and mitigation of the impacts of invasive organisms becomes urgent to prevent such compounding of impacts from biological invasions under climate change. The International Union for Conservation of Nature (IUCN 2005) has recognised that invasive species, climate change and habitat destruction present a 'lethal cocktail' for global biodiversity requiring urgent action. Australia has so far failed to act.

Feral animals already pose the dominant threat to native Australian mammals and bird biodiversity on Australian islands and are a top three threat to wildlife in wetlands and riparian zones (Australian Biosecurity Group 2005). Foxes and cats are implicated in the extinction of 22 native marsupials in the last century. Invasive weeds already cost Australian agriculture in excess of $4 billion p.a. (Sinden et al 2004) 20% of which is borne by the consumers in increased commodity prices. There are equally massive, but currently unquantifiable weed impacts on Australian biodiversity. Weeds are currently the top threat to Australian World Heritage sites. Most of the threatened ecological communities and many of the rare and endangered species listed under the *Environment Protection and Biodiversity Conservation Act 1999* are considered to be directly threatened by invasive plants (J. Scott CSIRO, pers comm). Furthermore the natural environment is also under direct attack from new diseases both in the country (eg Tasmanian Devil facial tumour disease or tree dieback disease caused by *Phytophthora cinnamomi*) or threats near our borders (eg Eucalyptus rust, *Puccina psidii*).

As a national icon site, Kakadu National Park is managed jointly by the Federal Department of the Environment, Water, Heritage and the Arts (DEWHA) through the Director of National Parks and its Aboriginal traditional owners. Park management strategies are therefore framed by national priorities for biodiversity management developed by DEWHA. This paper builds on two excellent papers at the previous workshop on feral animals (Bradshaw 2008) and

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invasive weeds (Walden & Gardener 2008) in and around Kakadu National Park (KNP) to a) reviews the potential future threats from invasive species under future climates and associated extreme events and the implications for invasive species management in KNP (and more generally northern Australia). b) briefly summarise National understanding on the impacts invasive species under future climates on biodiversity and the resulting priorities for research and development, c) summarise the degree to which these activities have so far influenced national policy in DEWHA and higher levels of government and d) set out a potential framework to develop a strategy for prioritising management of invasive species under climate change for KNP.

13.2 Interactions between climate change and invasive species

In this section we outline the potential for increased impacts from invasive alien species under future climate scenarios within a KNP context. First we highlight some of the research underway to predict the changes in species distribution, abundance and impacts under future climate scenarios that will help focus priorities for management. Second we describe the range of mechanisms that feral animals and then weeds will increase their detrimental impacts within KNP through interactions with increased temperature and more frequent extreme events that with indirectly result from climate change.

13.2.1 Changes in species distributions

Increasing temperatures and changing rainfall patterns with climate change will first affect species distributions. This is already started being observed in temperature change sensitive parts of Australia for certain feral animals. For example in the Australian alps, with shorter duration of the snow cover, rabbits are moving earlier to higher altitudes and foxes have started to follow increasing predation pressure on native mammals. Similarly hares, horses, house mice and weeds are increasing their presence at higher altitudes (Pickering et al 2004).

Various studies have tried to predict species distributions based on climate and how these might change under climate change using climate driven biological models. Two notable examples are two studies that predict the final distribution of cane toads across Australia under current climate (Urban et al 2007) and under future climates (Sutherst et al 1995). These two studies, based on models incorporating different environmental drivers, show similar distributions in the north, but differ in their prognosis for the south. The current climate predictions of Urban et al (2007) suggest coastal and southern Western Australia and South Australia are already quite suitable, while under future climates Sutherst et al (1995) predict coastal NSW becoming generally more suitable. The latter study is based on CSIRO's CLIMEX software that has been more recently extended to allow predictions of changes in density and therefore impact (D Kriticos, CSIRO, pers comm).

For invasive plants, similar types of study have been undertaken for two Weeds of National Significance, prickly acacia (*Acacia nilotica* spp *indica*; Kriticos et al 2003a) and rubber vine (*Cryptostegia grandiflora*, Kriticos et al 2003b), that affect savanna country in northern Australia. The *Acacia* study predicted that prickly acacia will increase in abundance in areas of increased soil moisture and movement south will increase its distribution in Australia, especially into xeric areas under increased CO_2 and water-use efficiency. Northern Territory, however, will generally become less favourable in the drier parts (D Kriticos, CSIRO, pers comm), illustrating that the future weed threats to KNP may not be the species of current concern.

Within the Park invasive species are less likely to show significant changes in abundance and distribution due directly to changes in temperature, moisture and CO_2, because future climate predictions are not massive changes in temperature and humidity for this part of the Northern Territory. Factors most likely to affect the impacts of invasives are the indirect impacts of climate change such as changes in sea level, fire regimes and other extreme events like cyclones and the ways these interact with certain invasive species to increase impacts overall.

13.2.2 Feral animals

There are a range of ways that feral animals may increase their detrimental impacts through interactions with the indirect effects climate change will have on the environmental conditions in the Park.

Buffalos could continue to undermine Park resilience to climate change. Although these were subject to eradication campaigns through the 1980s and 1990s they remain quite widespread in the Park and tolerated because of their value to the traditional owners (B Salau, KNP, pers comm). As saltwater incursion risks increase with associated annual average 8 mm sea level rises (E Valentine, CDU, pers comm) and rainfall driven flooding the northern part of the Park risks becoming a saline wetland (Hughes 2003). The role of buffalos in exacerbating such threats are also expected to increase (Skeat et al 1996). The movement of the buffalos throughout the Park, and particularly their creation of swim channels through the flood plain waterway system increases connectivity between the estuarine and freshwater areas (Mulrennan & Woodroffe 1998). This will assist saline incursion and the likely threats that inland salinity, and the new organisms this will encourage, will have on the Park's flora and fauna. The *Melaleuca* paperbarks are highly saline intolerant as are the lotus and wild rice communities that are extremely important for Park wildfowl. Saline incursions open up opportunities to a shift in new weeds of significance to those that show substantial salt tolerance. Also at the freshwater wetlands become more isolated, the impacts of pigs is these areas (Bowman & Panton 1991) may have greater consequences on the Park's biodiversity. Pigs have also been implicated as 'amplifier hosts' for certain diseases, such as Japanese encephalitis that threaten northern Australia under climate change (Bradshaw 2008).

Feral cats remain the top predator of native mammals in the Park. Cats are notoriously hard to census because of the lack of exposed scats left, a way of estimating fox density further south, but they are likely to always be associated in some way with currently observed declines in native mammals across the Park (Bradshaw 2008). Hotter temperatures in the Park are expected to lead to more frequent fires. More frequent fires result in less vegetation cover and in turn less cover is expected to cause higher predation rates (Gill et al 1999) compounded by the direct effects on the native fauna of increased fire frequency. Higher predation pressure leads to decreased range size for the natives and populations become isolated from suitable habitat patches. Arid zone marsupials are particularly at risk and the interaction between climate change effects and predation by feral pest animals has been postulated as a possible driver of the next wave of extinctions in Australia's marsupial fauna. It will be vital for future Park management to clearly identify the potentially complex causes of native mammal declines being observed in order to prevent any chance of this.

The Park's waterways will also be increasingly under threat from exotic fish incursions and increased flooding under climate change may exacerbate this. While nationally the threats and impacts to northern river systems have focused on cane toads, feral fish may be coming in the back door. A publication by the Australian Biosecurity Group (2005) shows that the fish pet trade has been responsible for 22 of the 34 most recent exotic fish incursions Australia wide and that exotic freshwater fish make up 11 of the last 12 vertebrate incursions into Australia.

Mosquito fish, *Gambusia* sp (Bradshaw 2008) and tilapia (*Oreochromis* and *Tilapia* spp) are potentially the most concerning species for the Park. For example, tilapia in Queensland has recently jumped the Great Dividing Range and is now invading rivers that feed into the Gulf of Carpentaria (J Russell, QDPIF, pers comm). The spread of other feral fish, including carp in the Murray-Darling river system, has been associated with particularly wet year of 1974 (Biological Diversity Advisory Committee 2008). Increasing temperatures and flooding associated with cyclones or indeed deliberately redirected water courses to counter water shortage will all assist the spread of these ferals that have large impacts of native fish numbers. Latent threats will exist in exotic aquiculture and outdoor ponds on flood plains stocked with exotic fish and it will be important to educate the public where exotics are considered good for recreational fishing.

More generally zoos, aviaries other exotic species breeding facilities will pose risks if occurring in cyclone country. Five deer species escaped from Babinda farm in Queensland during cyclone Larry (Kaufmann 2006) and now an eradication campaign for deer is underway in far north Queensland.

13.2.3 Invasive plants

Walden and Gardner (2008) comprehensively explore the impacts of weeds in the Park and the means by which such weeds may interact with climate change. Clearly the biggest threat from invasive plants comes from 'transformer species' these are weeds that alter ecosystem function as part of the invasion process that prevents recolonisation or survival of native species that predominated the invaded community. Such species (13 out of the 20 Weeds of National Significance are 'transformer species') and alter ecosystems through nitrogen fixation (eg mimosa, *Mimosa pigra*, and parkinsonia, *Parkinsonia aculeata*), altering fire regimes and intensity (so called 'fireweeds' eg gamba *Andropogon gayanus* and mission *Pennisetum polystachion*, grasses), propagule pressure assisted with the aid of cyclones and associated floodwaters (mimosa, salvinia, para grass, *Brachiaria mutica*, and olive hymenachne, *Hymenachne amplexicaulis*) or through native animals exploiting seeds and fruit (eg *Miconia* spp in rainforests), or by climbing and smothering the existing communities (eg rubber vine).

The Park already spends $1.2M on weed prevention and control (Walden & Gardner 2008), but one of the major new threats to the Park is olive hymenachne through its ability spread fast and turn up in new areas where it wasn't expected (B Salau, KNP, pers comm). Worsening threats associated with climate change impacts for the Park are likely to be the 'fireweeds', saline tolerant weeds that will follow the saline infiltration of the northern half of the Park and weeds that more generally exploit flooding and cyclones to invade pristine native communities.

The high biomass introduced African savanna grasses (eg gamba and mission grass) change ecosystems by altering fire regimes. Their tall growth, late season dry off and dense fuel load lead to hotter more intense fires that will be compounded by more frequent high fire risk days in the Park. Tall growth leads to high flames that wick the fire into the savanna tree canopy, which under the well documented grass fire cycle (D'Antonio & Vitousek 1992, Rossiter et al 2003) releases stored carbon and changes savanna woodland into tree free exotic grass-dominated savanna permanently altering the nutrient/water/carbon cycles. In the dry season herb layer rich vegetation in water courses can also wick the fire into new areas. Although these grasses are quite effectively under control in the Park, the adjoining private land is rich with these grasses that under a hotter climate and more sporadic rainfall and associated more frequent fires will find it easier to invade and reinvade.

The weeds that will accompany saline infiltration of the Park may not yet be known and some form of risk assessment of current sleeper species might be of value along the coastal reaches of the Park. Indeed coastal native species eg mangroves may themselves become invaders further inland as sea levels rise, while current priority weeds in the Park such as mimosa may decline in importance (Walden & Gardner 2008). The interactions between these changes in fire frequency, cyclone damage, flooding frequency and saline incursion will provide a host of new sets of disturbance conditions that will open new opportunities for current and future plant invaders in the Park. It will be important for Park staff to be on the lookout for rapid increases in species abundances that will be symptomatic of these changes and adapt and respond accordingly.

A recent study, http://products.lwa.gov.au/defeating-weeds-menace/projects/modelling-climate-change-impacts-sleeper-and-alert-weeds, has shown that Australia's current national list of alert weed species (www.weeds.gov.au/weeds/lists/alert.html – invasive alien plants already in the country and expected to spread under current climates) will become rapidly outdated. This is particularly true for the Top End as many on the list are already southern and eastern in distribution. The general southward spread of these threats means that under 2070 future climate scenarios nearly all the Top End will have no threats from the current list (JK Scott, CSIRO, pers comm). It will be important therefore that the alien plants from the current exotic flora that will pose the future environmental threats for the Park are identified and added to the list. In the context of KNP, future threats seem most likely to result from drought and saline resistant current sleeper weeds and garden plants.

13.3 National research and development priorities and policy documents on the impacts of invasive species under climate change

This section broadly summarises the available information and understanding nationally on the impacts of climate change and invasive species on biodiversity and the priorities for research and development that have come out of these activities. We also summarise the degree to which the urgency for action appears rather worryingly to have had little impact on national policy priorities so far.

Many national research initiatives, workshops and their published reports, both within Australia and abroad, support the more urgent threats invasive species will pose under future climates and the need for urgent action to mitigate increased future impacts (Howden et al 2003, Buckley 2007, Hilbert et al 2007, Taylor & Figgis 2007, Biological Diversity Advisory Committee 2008, US Environmental Protection Agency 2008). Two of these reports recommend national research and development priorities for Australia (Hilbert et al 2007, Biological Diversity Advisory Committee 2008). These are relevant for the development of an invasive species management strategy under climate change for KNP. In a Kakadu context these priorities would include:

- Development of climate change relevant risk assessment protocols for prioritising invaders that have not yet arrived or are already present (sleepers) in the region.
- Using this to develop revised lists of invaders based on their potential to have exacerbated effects through interaction with climate change for:
  - national surveillance
  - alert and sleeper species
  - future Weeds and Pests of National Significance

- Development of ecologically-based spread and detection models for new invaders eg olive hymenachne
- Undertake preparedness research to understand climate change and extreme event increasers eg ‘fireweeds’, water dispersed and saline weeds
- Identify the potential for further indirect interactions between climate change and invasive alien species (eg like the buffalo example) by through discussions with Park Rangers and traditional owners
- Prioritisation of key locations/communities within the Park vulnerable to the broader impacts of climate change and develop associated management strategies
- Determine and understand the community resilience/collapse thresholds for these communities with respect to invasion and climate change.
- Identify native species increasers under climate change and associated impacts (extreme events and salinity) and how these may threaten key native communities in the Park.

At a policy level, the Federal government department, DEWHA, presents its intentions to respond to climate change impacts on national icon sites and biodiversity through its National Biodiversity and Climate Change Action Plan: www.environment.gov.au/biodiversity/publications/nbccap/.

The Action plan in turn feeds into the National Climate Change Adaptation Framework (www.coag.gov.au/coag_meeting_outcomes/2007-04-13/docs/national_climate_change_adaption_framework.pdf) through COAG, the Council of Australian Territory, State and Federal Governments. The 2004–2007 National Biodiversity and Climate Change Action Plan contained very little about the impacts on invasive species under climate change. What was included is captured under objective six (see Table 1).

The plan did not capture how the components in Table 1 will be achieved, the scientific impediments to achieving them or many of the underlying actions that have since come to light and identified as priorities in many recent scientific reviews already mentioned. This appears to be reflected in the slight information concerning the impacts of invasive species under climate change that appeared in the most recent Prime Minister’s Science Engineering Innovation Council 2007 report ‘Climate Change in Australia: regional impacts and adaptation, managing the risk for Australia’ (www.dest.gov.au/NR/rdonlyres/CE5D024E-8F58-499F-9EEB-D2D638E7A345/17397/ClimateChangeinAustraliareport.pdf), where all that is evident are statements raising the potential for some crop pests to move south. It will be important that stronger goals and outcomes are adopted in future Action Plans through greater engagement of scientists with government.

At the moment it appears that a major impediment to DEWHA and the Director of National Parks investing resources in the mitigation of the major negative consequences of the impacts of invasive species under the direct and indirect effects of climate change may be a lack of recognition at a high level of this urgency. The strong focus of the current government for the environment is investment in climate change adaptation rather than mitigation of impacts risks. This risks dropping the ball on how invasive species will interact with climate and greatly exacerbate the damage that is starting to be seen. A stronger and more urgent focus on invasive species impact mitigation (and indeed habitat loss) now should provide a huge payout on preventing major future environmental damage from invasive species under climate change.

Table 1 2004–2007 National Biodiversity and Climate Change Action Plan, Objective 6: To minimise the impact of invasive organisms on biodiversity in future climates; Strategies and Actions

Strategy 6.1	**Building capacity to predict the effects of climate change on the distribution of new and established alien invasive organisms.**
Actions 6.1.1	Incorporate current and potential future climate change scenarios into alien invasive species modelling.
6.1.2	Incorporate the modelling of alien invasive species under climate change into risk assessment procedures and protocols (for alien invasive species).
Strategy 6.2	**Considering implications of native species becoming invasive, and incorporating this information as appropriate into invasive species and threatened species programs**
Actions 6.2.1	Analyse potential impacts of native species becoming invasive as a result of climate change and incorporate into relevant management strategies (as per 6.4.1 and 6.4.2).
Strategy 6.3	**Preventing the establishment of new alien invasive organisms in Australia, which could be attributed to climate change**
Actions 6.3.1	Incorporate climate change considerations in preborder risk assessment in a national system to reduce the risk of introduction of alien invasive species and vectors for disease
6.3.2	Incorporate climate change considerations into import risk analyses and the development and review of import conditions
Strategy 6.4	**Reviewing priority alien invasive organisms for management action and re-evaluating alien invasive organism management strategies, taking into account the potential effects of climate change on their distribution.**
Actions 6.4.1	Update the Weeds of National Significance (WONS), Alert List for Environmental Weeds and priority lists for alien invasive organisms (including plants, animals and diseases).
6.4.2	Update alien invasive organism management strategies, including threat abatement plans and strategies, for example to manage WONS and Alert List weeds.

13.4 Prioritising invasive alien species and climate change actions

In this section we attempt to highlight a process for prioritising management activities to mitigate the impacts of invasive species under climate change that has relevance in the context of KNP. Any management strategy designed to manage the impacts of invasive species under climate change will need to prioritise actions based on cost and benefit. Table 2 provides an attempt at prioritising such activities.

13.5 Conclusions

In this paper we have tried to scope the currently understood likely impacts of invasive species under climate change on KNP and the ways in which the science of species impact prediction and risk analysis under climate change can help set priorities for the development of a KNP management strategy. We have also summarised the research and policy linkages at a national level that provides DEWHA with the guidance it needs to invest in mitigating invasive species and their impacts on biodiversity under climate change. These linkages still remain surprisingly weak and there remains a major risk that sufficient investment in mitigating the impacts of invasive species on our national icon sites under climate change will not be made.

Table 2 Boston square diagram suggesting a prioritisation of example invasive alien species actions under climate change based on cost and benefit

Benefit	Cost	
	Low	High
High	• invest in prevention of new identified threats • process for finding and removing CC increasers • eradicate ferals on islands so these can provide native refuges • fauna recovery plans (long-term cat/toad control) • buffalo eradication for salinity threatened RAMSAR sites • environmental hygiene actions for emergency crews and equipment • environmental stewardship programs for adjacent lands	• community awareness activities on interactions between IAS and extreme events eg 'Transformer spp' • risk assess permitted species & emerging threats for CC (extreme event) interactions • national and NT policy and strategies for a) tropical fire grasses b) biofuel biosecurity c) extreme event preparedness • develop local IAS and CC interaction Threat Abatement Plans • remove zoos/exotic plant gardens from extreme event prone areas
Low	• coastal defences against saline incursion with sea level rise • undertaking weed/pest eradication programs without science based feasibility analysis	• ignoring the interactions of IAS with CC in current adaptive strategies

At a national level there are already two strategies under the Australian Biosecurity System (AusBIOSEC) that aim to address the impacts of invasive species. These are the Australian Weeds Strategy www.weeds.gov.au/publications/strategies/weed-strategy.html and the Australia Pest Animal Strategy www.environment.gov.au/biodiversity /invasive/publications/pest-animal-strategy .html through which some local invasive species under climate change threat abatement plans are being considered. Management of invasive species always focuses on mitigation while the Department of Climate Change's approach at a system level is more focussed on climate change adaptation in the face of too little too late. Without a stronger focus on IAS mitigation under future climates there is much less chance that the climate change adaptation approaches will succeed. Adaption strategies risk failing as invasive species will end up being the joker in the pack.

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14 Climate change adaptation: coasts and biodiversity activity at the national level

J Morley[1, 2] & L Dovey[1, 3]

14.1 National Climate Change Adaptation Framework

The National Climate Change Adaptation Framework (the Framework) was endorsed by the Council of Australian Governments (COAG) in April 2007 as the basis for government action on adaptation over the next five to seven years. The Framework includes a range of actions to assist the most vulnerable sectors and regions, such as agriculture, biodiversity, fisheries, forestry, settlements and infrastructure, coastal, water resources, tourism and health, to adapt to the impacts of climate change. It also includes actions to enhance the knowledge base underpinning climate change adaptation.

In December 2007, COAG agreed to accelerate the implementation of the Framework and recognised that work should begin immediately to develop a national approach to guide long-term adaptation to climate change.

14.1.1 Australian Government support for adaptation research

A number of National Adaptation Research Plans are currently being developed under the Framework and due to be completed for early 2009. The Australian Government has established the National Climate Change Adaptation Research Facility and announced seven adaptation research networks (Box 1).

14.2 National Coastal Vulnerability Assessment

One of the actions identified in the Framework is a National Coastal Vulnerability Assessment (NVCA). In undertaking the preliminary or 'first pass' NCVA, the Department of Climate Change is looking to support decision-makers through:

- identifying areas in Australia's coastal zone with high, medium and low potential impact from climate change;
- linking biophysical and socio-economic analyses so that decision-makers can better understand the vulnerability and potential costs of climate change in the coastal zone;
- providing analysis of policy and governance of relevance to governments, and outlining priority research areas and national data gaps.

The 'first pass' assessment will involve a preliminary analysis on the risks facing Australia's coastal zone and key assets (coastline, biodiversity, settlements and infrastructure) through the development of, and interrogation of new and existing national data sets. The 'first pass' assessment is acquiring a mid-resolution Digital Elevation Model (DEM) for the entire

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Australian coastline and islands greater than 600 m^2. The DEM will be provided through a National Elevation Data Framework (NEDF) negotiated through the Spatial Information Council, ANZLIC (www.anzlic.org.au/) and made available to government agencies at all levels. This work is being augmented through the provision of a higher resolution DEM for urban areas of the coast, through the Cooperative Research Centre for Spatial Information (http://spatialinfocrc.org/).

Box 1 Developing National Adaptation Research Plans

The Australian Government has provided $126 million towards the implementation of the National Climate Change Adaptation Framework, including the establishment of a Climate Change Adaptation Research Facility, which will lead Australia's researchers in generating robust biophysical, social and economic information that decision makers need to manage the risk of climate change. The Facility is hosted by Griffith University in partnership with seven other universities and the Queensland Government. Foundation Director of the Facility Prof Jean Palutikof, an internationally renowned climate change expert, will lead the Facility to synthesise knowledge, coordinate research activities, broker research partnerships and provide information for decision makers in a form relevant to their sectoral or regional needs.

This national effort to enhance the knowledge base for adapting to climate change is supported by up to $30 million in funding for national climate change adaptation research to build understanding and adaptive capacity to reduce sectoral and regional vulnerability to the impacts of climate change. Up to $10 million is being provided to a number of Climate Change Adaptation Research Networks. Networks include Terrestrial Biodiversity (led by James Cook University), Water Resources and Freshwater Biodiversity (led by Griffith University), Marine Biodiversity and Resources (led by University of Tasmania), Settlements and Infrastructure (led by University of NSW), Disaster Management and Emergency Services (led by RMIT University), Social, Economic and Institutional Dimensions (led by University of Melbourne) and Health (led by Australian National University).

The Australian Government Department of Climate Change and the National Climate Change Adaptation Research Facility are leading the development of a number of National Adaptation Research Plans for each of the Network topics. These Adaptation Research Plans will identify critical gaps in the information needed by decision-makers, industry and the community, set research priorities based on these gaps, and identify capacity that could be harnessed to conduct priority research.

Further information can be obtained from the DCC website www.climatechange.gov.au/impacts/about.html and from the Facility website: www.nccarf.edu.au

A new, more accurate representation of Australia's coastal high water mark will be provided in a new digital product, Smartline. Under development for the NCVA by Geoscience Australia in collaboration with University of Tasmania, Smartline will include nationally consistent digital information on geology, geomorphology, landforms and vegetation and will allow levels of exposure to erosion to be identified. Models for predicting recession and inundation of the coastline are also under development, and will be applied to the Smartline coastline to give an indication of likely changes to the coastline under various climate change scenarios.

The vulnerability of coastal biodiversity to climate change is also being explored in the 'first pass' NCVA. The known extent of ten broad coastal habitat types has been compiled from existing mapping, and the vulnerability of each habitat type is being evaluated by CSIRO Division of Marine and Atmospheric Research.

The 'first pass' NCVA will also explore national coastal management and governance issues, making recommendations in the light of climate change adaptation responses.

The final report on the 'first pass' NCVA is due for completion in May 2009. This will be followed by extensive consultation on the results of the work and on directions for the future.

14.2.2 Coastal case studies

To provide further local scale examination of coastal adaptation issues, six case studies are underway around Australia:

- east coast Tasmania
  - southern Rock Lobster fishery
- Kakadu National Park, NT
  - climate change impacts on river system dynamics, wetlands
- Pilbara coast, WA
  - oil and gas infrastructure
- Yorke Peninsula, SA
  - settlements and planning
- Pimpama River, QLD
  - coastal river system with a fishery in a high urban growth area
- Central and Hunter Coasts NSW
  - impacts on estuaries, their foreshores and ecosystems and the implications for human settlements

The Kakadu case study will be valuable for on-going management of Kakadu National Park. It will develop a hydrodynamic model for the Park that can be improved over time. For the rest of Australia, the Kakadu case study is an exceedingly valuable exploration of the issues around coastal adaptation. Kakadu is a worlds-best example of low-lying coastal wetlands and their management issues: the river system hydrodynamics (salt water intrusion, extreme events) are complex, as too are the planning, management and policy environments. Importantly, Kakadu has had a solid history of research and data collection by organisations including Parks Australia, ***eriss***, Charles Darwin University and the NT Government that will enable the case study to go further into the issues than could be done elsewhere.

14.3 Other relevant climate change adaptation initiatives

From within the Prime Minister's portfolio, the Department of Climate Change is the Commonwealth Government agency leading on developing an effective response to climate change issues and for Australia to play an active and constructive role in international climate change negotiations. The department's functions align with the three pillars of the Government's climate change policy framework of:

- reducing Australia's greenhouse emissions
- adapting to the impacts of climate change we cannot avoid
- helping to shape a global solution.

The department manages the Australian Climate Change Science Program, which supports improved understanding of the likely impacts climate change for Australia. New climate change projections for 2030 and 2070 were released in October 2007. These projections were the first prepared for Australia as a whole and updated the previous national projections issued in 2001. For the first time, they included information on the probability of future temperature and rainfall changes. Information on future climate is essential to support effective adaptation.

The department is also leading a series of national vulnerability assessments, including the national coastal vulnerability assessment mentioned previously and the national biodiversity vulnerability assessment. Due to be completed in early 2009, this latter assessment will synthesise current knowledge about the impacts of climate change on Australia's biodiversity. It will also highlight the implications for integrating climate change adaptation in biodiversity conservation. Led by the Department of Climate Change, in consultation with the Department of the Environment, Water, Heritage and the Arts, and with states and territories, an Expert Advisory Group chaired by Professor Will Steffen of the ANU's Climate Institute was established in 2007 to drive the assessment process.

14.3.1 Reports available or in preparation

Many completed assessments led by the Department of Climate Change have also been undertaken collaboratively with Parks Australia and other parts of DEWHA. Publications of particular relevance to Kakadu include:

- Cost-benefit analysis of Mary River salinity mitigation (2003)
- Impacts of climate change on Australian marine life (2006)
- Climate Change in Australia (2007) – CSIRO and Bureau of Meteorology projections as mentioned above
- Climate change and the Great Barrier Reef: a vulnerability assessment (2007)
- The impacts and management implications of climate change for the Australian Government's protected areas (2008)
- Implications of climate change for Australia's National Reserve System - a preliminary assessment (2008), and a summary overview booklet
- Managing Australian landscapes in a changing climate – a climate change primer for regional Natural Resource Management bodies (2008)
- Variability and trends in the Australian wave climate and consequent coastal vulnerability (2008), and
- Implications of climate change for Australian fisheries and aquaculture – a preliminary assessment (2008).

These and other publications are available from the Department's website: www.climatechange.gov.au/publications/index.html. Hardcopies can be obtained by request.

A number of other relevant projects are nearing completion, including:

- A strategic assessment of the vulnerability of Australia's biodiversity to climate change (as mentioned above),
- The impact of climate change on fire regimes and biodiversity in Australia – a preliminary assessment,
- A preliminary assessment of climate change impacts on Australia's aquatic ecosystems,
- Implications of climate change for Australia's world heritage properties: a preliminary assessment.

Reports of these projects will also appear on the departmental website once released.

Other projects underway but at an early stage of particular relevance to Kakadu includes a second phase of work further examining the implications of climate change for Australia's National Reserve System, involving a range of biome-based regional studies, as well as a synthesis of available information on potential climate change impacts and implications for NRM regions and regional priorities.

15 Effect of extreme events in the Kakadu region

D Jones[1]

15.1 Introduction

The role of the Supervising Scientist Division is to provide independent Australian Government oversight of uranium mining in the Alligator Rivers Region (ARR), including planning for rehabilitation and closure – and predicting how the long-term integrity of the rehabilitated sites will be affected over periods of hundreds of years. Hence the interest of the Division in long-term landscape processes that will either directly impact the mine sites or effect landscape baseline conditions around them. Over the longer term, the occurrence of extreme events will be one of the major drivers of landscape change – both for the mine sites and the ecosystems of Kakadu National Park (KNP).

The wet-dry tropics are already a region of extremes – intra-seasonally, intra-annually and inter-annually. A key question is whether climate change will result in an increase of the magnitude of events beyond that which has already occurred in the contemporary climate record, or indeed the geologic record. Evidence for large flood events over the past 10 000 years has been provided by a study of cores from the Magela floodplain (Wasson et al 2010) and links are being made to specific climate indicators (eg the Southern Pacific Oscillation and El Nino indices) reconstructed over this period. A related question is that of event frequency.

The resilience and ability to recover (to the previous condition) of ecosystems will be a function of both the magnitude of the event and the recurrence interval (that is, the time period that elapses before the re-occurrence of an extreme event in the same geographical area). The larger the event, the longer the recovery period that will be required before another event can be accommodated without systemic change occurring. Analysis of the long-term historic record may ultimately increase our predictive capacity for the magnitude and frequency of future extreme events.

Current climate change projections for the Top End for the next 30 years indicate that: mean temperature may rise by up to 2ºC; mean sea level may increase some tens of centimetres; there may be slightly less rain; the landscape water balance may become more negative as a result of increasing temperatures; weather events (cyclones and storms) may become more intense; and there may be a higher frequency of cyclones (Hennessy et al 2004). A summary of potential impacts of climate change on KNP is provided in Bartolo et al (2007).

In this paper an extreme event is considered to be an occurrence that causes, within a very short period of time (hours/days), a sharp change from antecedent conditions, the recovery from which could take an extended period (months/years) of time. This distinguishes the effect of such an event from that induced by a (relatively) slowly shifting baseline such as incrementally rising sea level, the rate of which may be sufficiently slow that ecological

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systems can progressively adapt. Extreme events will be discussed in the context of water, wind and temperature.

For wind and water, the focus will be on the immediate impact and aftermath of recent extreme events (Cyclone Monica – 2006 and the intense rainfall event of February/March 2007 centred over the ARR). These events provide actual learnings – rather than having to rely on hypothetical scenario analysis or computer simulations – about landscape impacts and responses. Studying the aftermath of these events on the landscape enables the timeframe of recovery to be established and, perhaps more importantly, can lead to the identification of processes that may either impede or prevent recovery.

15.2 Water

15.2.1 Rainfall and river flow

The monthly data for lowest, mean, and highest rainfall recorded over the past 37 years at the Jabiru airport are shown in Figure 1. There is clearly a large spread in monthly rainfall, from the lowest to the highest. Compounding this aspect of variability is the fact that the lowest rainfalls and the highest rainfalls do not necessarily occur in the driest and wettest years, respectively. For example, the lowest monthly rainfall occurred in January 2007, whilst the highest monthly rainfall for February and March occurred in the same wet season.

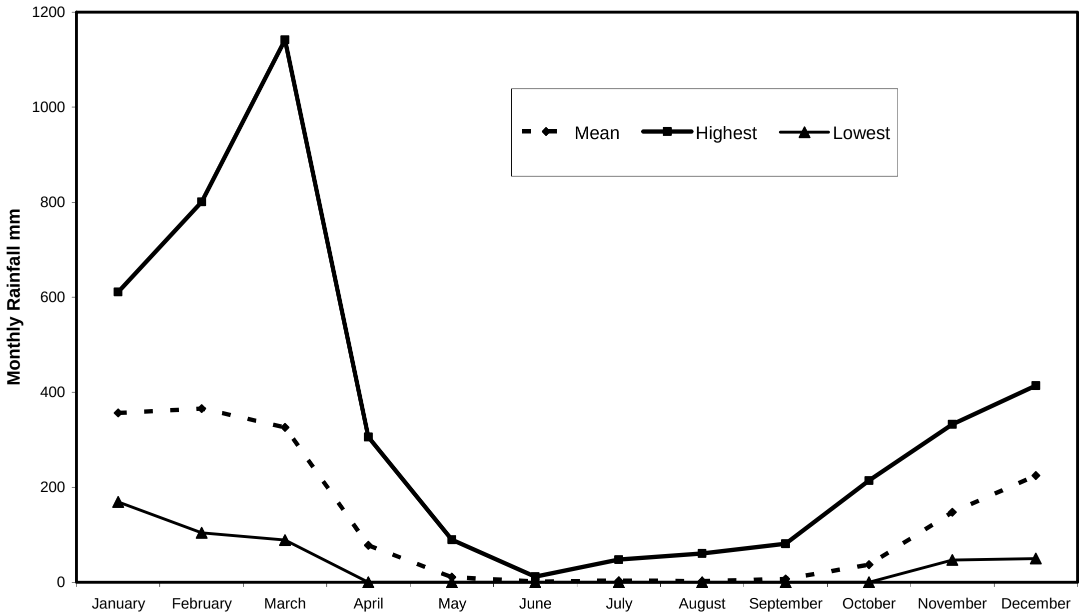

Figure 1 Monthly data for the lowest, mean and maximum rainfall amounts derived from the 37 year record available from the Jabiru airport (source – Bureau of Meteorology)

Recent analysis of the historic rainfall and stream flow records by Bayliss et al (2007) indicates an approximately decadal cycle, with the cycle being 180 degrees out of phase with the corresponding wet and dry periods in southern Australia (Wasson et al 2010).

This level of existing variability will make it extremely difficult to discern any developing climate change signature in the rainfall pattern.

The time series data for annual flow in Magela Creek (measured at GS 812009 downstream of the Ranger mine) show a similar high degree of variability (Figure 2). However, there is a very good linear correlation between total annual flow and total annual rainfall (Figure 3), indicating a high degree of confidence in being able to predict annual flow from annual rainfall, despite the high variability in monthly rainfall. The highest data point in Figure 3 corresponds to the 2006–07 wet season, which contains the largest flood event on record.

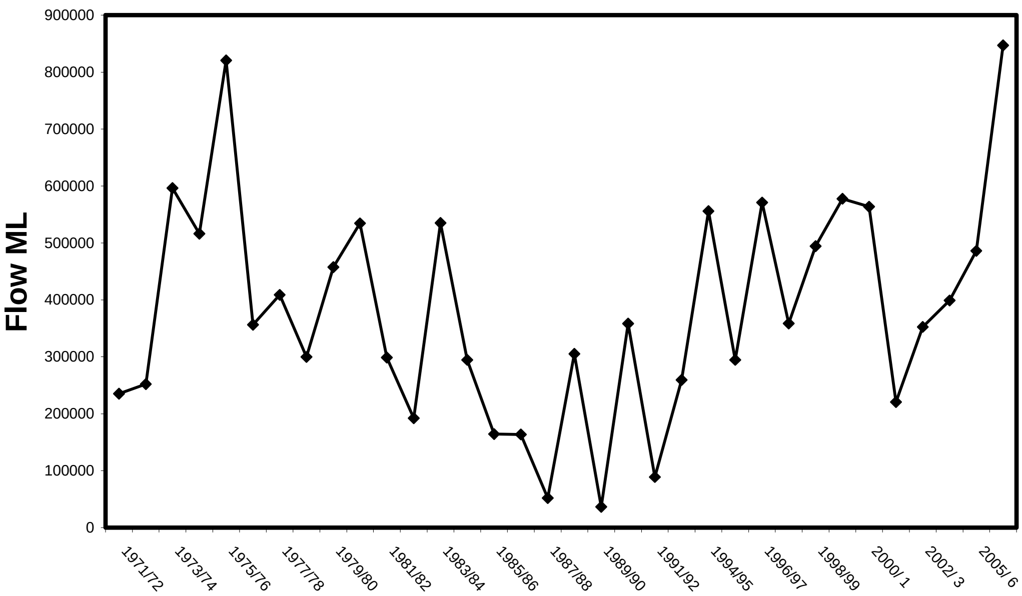

Figure 2 Annual flow record for Magela Creek since 1971–72

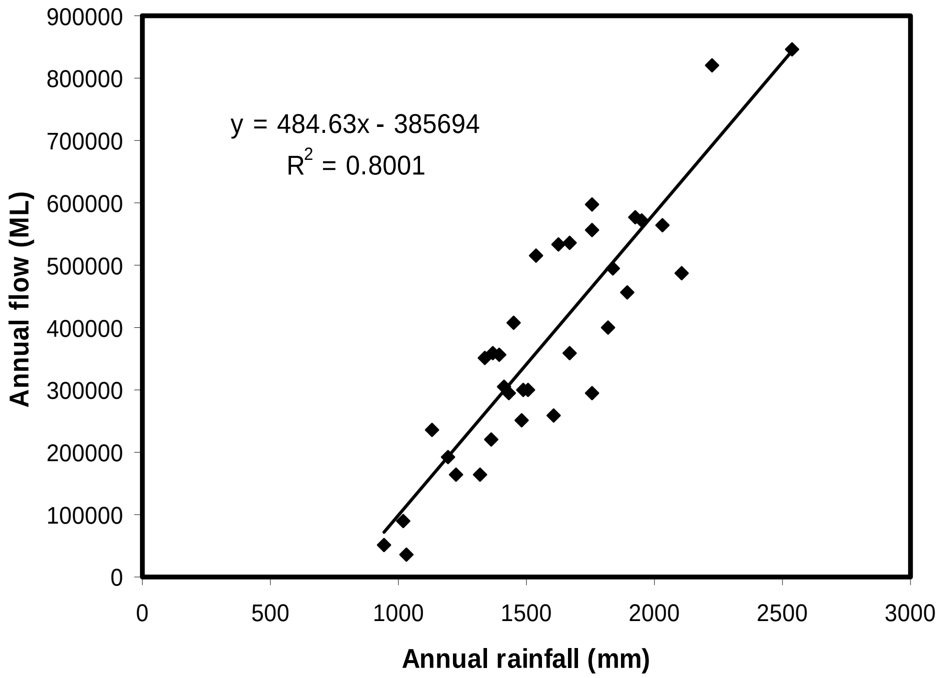

Figure 3 Correlation for the period 1971 to 2007 between annual flow in Magela Creek and annual rainfall measured at Jabiru airport

There is one other important point to note in Figure 3. Extrapolating the line of best fit to the left implies that there might be no surface flow in Magela Creek if there is less than 800 mm of rain. Current predictions are that climate change is unlikely to result in a significant decrease in annual rainfall (Hennessy et al 2004), unlike large areas of southern Australia, so lack of sustained surface flow in Magela Creek may not be a potential outcome of climate change. However, it must be noted that these predictions are based on a very coarse grid (approx 250 km^2) that may not adequately capture more localised effects. Whilst the CSIRO has been contracted to refine climate change predictions to a more appropriate regional grid size, the veracity of such predictions may be less robust than in other areas of Australia owing to very poor coverage of the central Arnhem Land area by weather stations.

15.2.2 Floods

The largest flood event in the history of contemporary flow records for the ARR occurred at the end of February 2007. Over a three day period approximately 800 mm of rain was recorded in the vicinity of Jabiru. The result was a one in several hundred year flood event in Magela Creek and other river systems in the region.

The immediate effect in Magela Creek was a substantial rise in water level, with a flood peak sustained over several days. Peak discharges along the main channel were approximately eight times the mean annual flood discharge and more than double the 1:100 y flood event discharge (Moliere et al 2007). Whilst this event, in itself, would be ranked as extreme, the longer term legacy of that 3-d event on the landscape and Magela Creek also needs to be considered.

The prolonged period of heavy rain triggered 14 landslips in a weathered dolerite intrusion (Oenpelli dolerite) in the upland (escarpment country) of Magela Creek (Supervising Scientist 2008). An example of a landslip is shown in Figure 4. The weathered dolerite is characterised by a distinct red colour (as a result of high iron content) and fine-grained particle size distribution. This highly erodable material was subsequently washed into Magela Creek during the 2007–08 wet season and its effect was manifest by the occurrence of five ‘red mud’ events. Although the total area of the landslips represents only 0.3 km^2 out of a total of 650 km^2 of catchment area upstream of the SSD monitoring location, the landslip source accounted for approximately 50% of the total load of fine suspended sediment carried by Magela Creek through the 2007–08 wet season (Supervising Scientist 2008).

Figure 4 Landslip on weathered Oenpelli dolerite located in the upper catchment of Magela Creek (photo by Mike Saynor)

Increased delivery of sediment is of importance from two dimensions. Firstly, for the accretion of sediment through time on the Magela floodplain. Secondly, from the impact of suspended sediment on aquatic ecosystems, such as by smothering benthic organisms, clogging of gills or by shading the water column, thereby depressing primary productivity.

The aftermath of the landslips will likely continue to be manifest for several more years until the exposed areas are stabilised by a combination of exhaustion of erodable fine particles and establishment of a vegetation cover. The occurrence of more extreme rainfall events in the future would result in accelerated erosion of the existing landslip areas, and likely lead to new landslips. Slope and pattern analysis of the dolerite areas is currently being conducted using remote sensing imagery to identify likely future landslip areas.

The East Alligator River also experienced a major flood event at the same time as Magela Creek. In this context it should be noted that 15 landslips occurred in the component of the dolerite intrusion reporting to the East Alligator River, although in this case the subsequent contribution to fine sediment load was not measured,

Along the gorge parts of the East Alligator River, vegetation was removed and large amounts of sediment were redistributed along the channel. In particular, large amounts of sediment were deposited downstream of the lower gorge, approximately 1 km upstream of Cahills Crossing. This resulted in a significant reduction of the distance that was trafficable by local indigenous tour boat operators and hence negatively impacted on their operations. The advice provided by SSD to the tour operators was that this was the result of a natural process (ie a pulse of bedload moving through the catchment) and that it would clear in time (at least several wet seasons) as it had in the past. Dredging of the material was not recommended as a viable solution, since it would be a long and inefficient processes as sediment would be distributed and re-deposited along the dredged sections.

15.2.3 Storm surge

Saline intrusion per se is not considered an extreme event for the purposes of this paper since, with the possible exception of catastrophic sea level rise as a result of rapid melting of continental ice sheets, it is one of the inexorable and steadily increasing consequences of sea level rise. In contrast, saline intrusion caused by a cyclone generated storm surge and superimposed wave action would be classed an extreme event, with both immediate and potentially long term severe consequences.

Coastal ecosystems (both terrestrial and freshwater) would suffer an immediate insult from the physical surge of water and acute exposure to high salinity. Salinisation of the soil profile and shallow coastal groundwater systems can be the long term legacy of such an event. Indeed, residual soil salinisation after the storm surge caused by Hurricane Hugo in South Carolina is estimated to have caused subsequent tree mortality of the same order as the immediate mortality caused by the strong winds (Michener et al 1997). It should also be noted that secondary effects of salinity can potentially extend much further inland than the surge zone as a result of wind-blown sea spray (Michener et al 1997).

A 1.5 m storm surge was recorded for Cyclone Tracy, and this caused little apparent damage compared with that caused by wind. In dramatic contrast, the storm surge for Cyclone Monica was estimated to have been 5–6 m in height, reaching up to 9 km inland. There has been no follow-up work done on the persistence and effect of residual salinity from the Cyclone Monica storm surge. This aspect would be worth investigating to provide an indication of what impact future climate change enhanced storm surges could have on the low lying freshwater floodplains and terrestrial vegetation areas in KNP.

No specific storm surge modelling has yet been published for the Top End. In common with assessing the impacts of sea level rise, storm surge prediction for KNP is hampered by the current lack of a high resolution digital terrain model. Since the height of a storm surge will depend on both bathymetric and geographic (ie precise shape of the coastline and topography of the land) conditions, different storm surge prediction scenarios would need to be run at a range of locations for different mean sea levels. In the event that engineered barriers are considered for local mitigation of sea level rise, then the height of such barriers should accommodate the storm and waves surges produced by high intensity tropical cyclones. The most downstream location might not be optimal in this context.

15.3 Temperature

Temperature is likely to be one of the key landscape stressors in terms of extreme events. There are two types of temperature-triggered extreme event. Firstly the landscape water balance will become more negative throughout the year as a result of an increase in the rate of evaporation/evapotranspiration (Hennessy et al 2004). This decreased water balance will likely be especially critical towards the end of the dry season when both terrestrial and aquatic systems are already at maximum stress. Figure 5 shows the current monthly average water balance (rainfall minus evaporation) using data from the Jabiru airport. The net effect of higher temperatures will be to shift the line downwards, increasing the length of time through the year that the landscape is subjected to a negative water balance. It is estimated that the net water balance over the dry season may decline by up to 75 mm by 2030, and 50–250 mm by 2070 (Hennessy et al 2004).

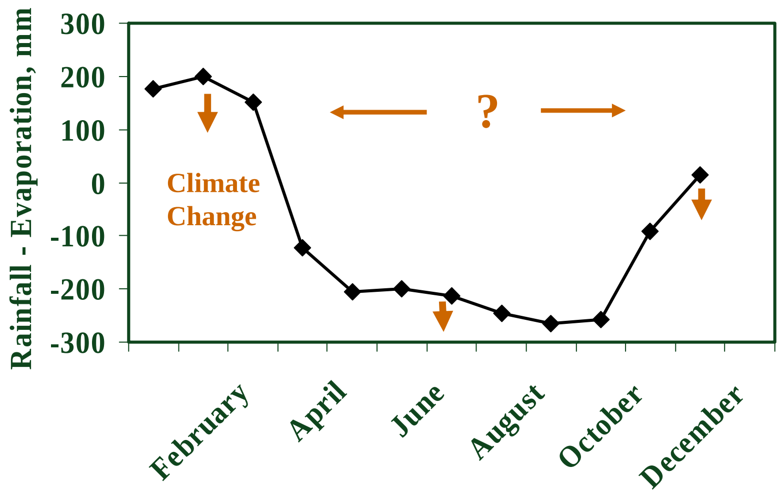

Figure 5 Difference between monthly average rainfall and evaporation, showing net monthly water balance (data – Bureau of Meteorology). Higher average temperatures will increase evaporation rate and make the balance more negative. It is currently not known if distribution of rain through the year will shift (marked by ?)

Evaporation leads to an increase in the concentration of salts in the water, since ions such as magnesium, calcium and sulfate will be conserved as the water evaporates. Thus, aquatic organisms can be exposed to a wide range of electrical conductivities (EC – a measure of salinity) over the seasons (Figure 6). In the event that the start of the wet season is delayed then more evaporation occurs and higher EC results. It is possible that the tolerance range for the more EC sensitive aquatic species could be exceeded in this event.

Waterbody refuges that do not currently completely dry out may do so in the future, with profound implications for those species that currently rely on these refuges for interseasonal survival. Creation of engineered aquatic refuges, or supplementation of existing water bodies are possible management actions that could be taken to mitigate this impact.

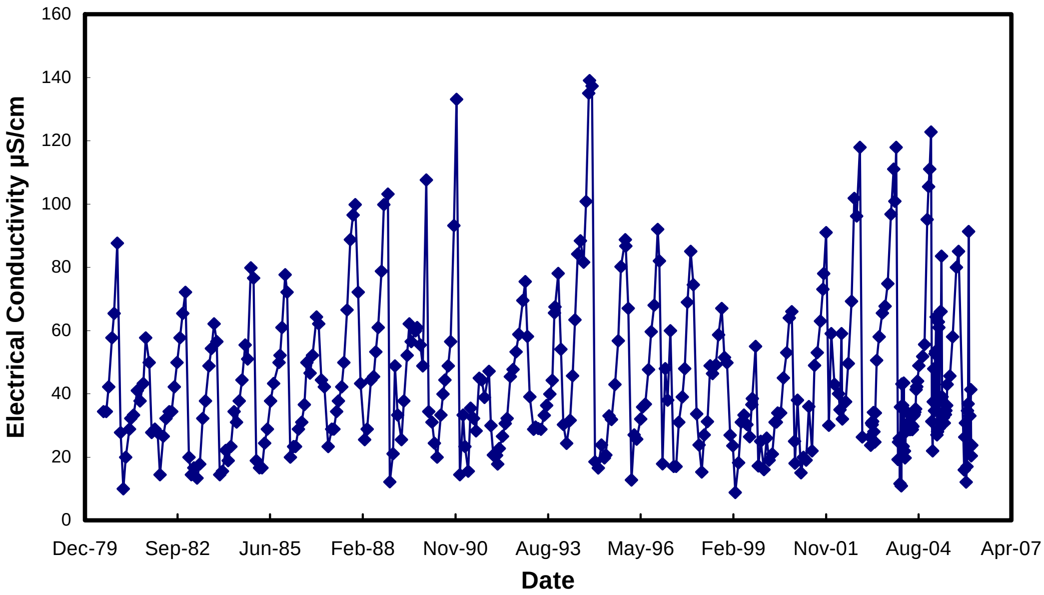

Figure 6 Annual variation of electrical conductivity in Georgetown Billabong, KNP. The lowest values correspond to flushing with rainwater during the wet season. The peak values show the effect of evaporative concentration of residual water through the dry season. The highest values correspond to late starts to the wet season (Jones et al 2006).

The second type of an extreme event driven by temperature is the number of contiguous days for which the temperature exceeds a maximum threshold. Climate change projections indicate a major increase in such hot periods in the second half of this century. Whilst the flora and fauna of the wet dry tropics are adapted to quite high temperatures, their thermal tolerance to an increase in contiguous high temperature days are not well understood. One exception is reptiles (especially crocodiles and turtles) where higher nest temperatures are known to result in a change in sex distribution of hatchlings. In particular a two to three degree rise could lead to almost exclusively female hatchling. This displacement in the sex ratio would have devastating consequences for the survival of the species. There may be many other terrestrial and aquatic species (including plant species) that are quite finely attuned to temperature for reproduction, and which may be approaching the upper range of thermal tolerance.

Both the water balance and thermal tolerance aspects of climate change could substantially influence the seasonal availability of bushtucker. This issue needs specific investigation since it could significantly impact on the carrying capacity of the land for indigenous people.

15.4 Wind

The immediate impact of high winds will be damage (from defoliation through to uprooting and death) to overstory and mid-story trees, and removal of canopy cover. In the intermediate to long term, this damage can provide opportunities for establishment of invasive weeds, result in increased erosion via disturbances to the soil surface and removal of trees along river channels, and lead to changes in landscape biodiversity. Of these three, invasion by introduced weed species is a contemporary factor that, if uncontrolled, could significantly impact on the ability of the natural landscape to recover after an extreme event. In particular, reduction in canopy cover can provide an opportunity for grasses to expand their range of coverage and thus compromise the return of the previous vegetation assemblage. Mission and Gamba grasses are two examples of this. Such species are introduced (and spread) by anthropogenic vectors and are typically associated with focal points of disturbance (towns, minesites, cattle grazing areas).

Over the past three years, two high intensity wind events have impacted areas of KNP and Arnhem Land. The first of these events was a presumed tornado that cut a 3 km long path through the bushland close to the Mary River Ranger station (Andersen et al 2008). The second was the category 5 Cyclone Monica that crossed the coast near Maningrida and tracked SW across Arnhemland to Jabiru (Cook & Goyens 2008, Staben & Evans 2008; Figure 7).

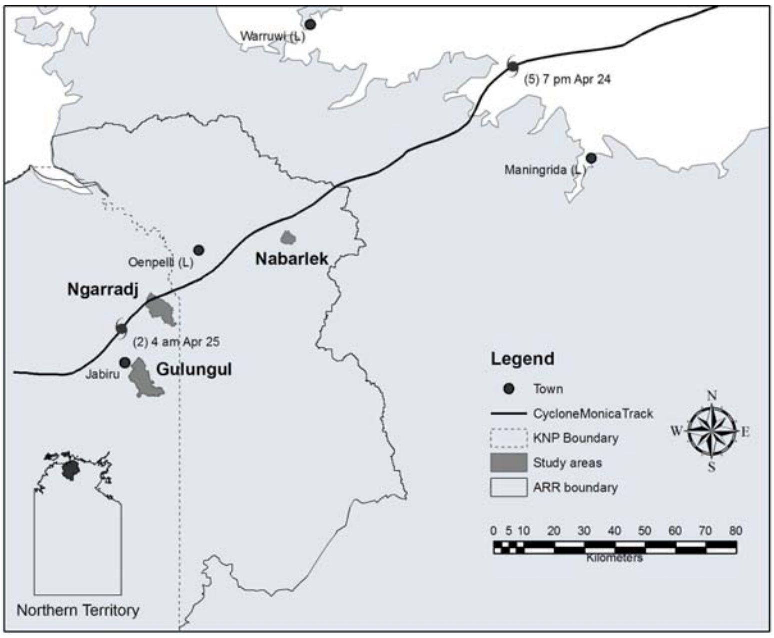

Figure 7 Estimated track of cyclone Monica across the ARR (from Staben & Evans 2008)

Analysis of the recovery of vegetation in the scar left by the tornado has shown that there has been substantial elimination of annual sorghum (Andersen et al 2008). This is a very significant finding since annual sorghum is a major component of the monsoonal savannah that makes a substantial contribution to annual fire loads. It is proposed (Andersen et al 2008) that the reason for the decline at the tornado site is destruction of the seed bank caused by longer fire residence times associated with the burning of a relatively high concentration of fallen trunks and branches leading to sub-surface soil temperatures lethal to annual sorghum seeds. This situation resulted from the increase in density of the on-ground fuel load of fallen tree trunks and contrasts sharply with the 'usual' situation of high intensity – but much shorter exposure durations – fires fuelled by the above ground dry biomass of the sorghum itself.

Analysis of the data obtained in the aftermath of cyclone Monica has provided the opportunity to correlate the extent of tree damage with wind intensity as the system degraded from category 5 at landfall to category 2 at Jabiru. Cook and Goyens (2008) developed a model that enabled an estimate to be made of wind velocity as the cyclone tracked over land. A series of transects along the track were measured to determine the extent of damage to the trees – and the extent of the damage was correlated with wind velocity. This work indicated a critical velocity of about 41 m/s (140 km/h) above which the extent of damage of terrestrial trees increased sharply.

Riparian zones and inundated areas in the Gulungul Creek and Swift Creek (Ngarradj) catchments (Figure 7) closer to Jabiru suffered much greater loss of tree canopy cover compared to terrestrial and upland areas (Staben & Evans 2008), indicating that already saturated areas of the landscape are likely to be much more susceptible to wind damage. This latter observation has implications for riparian vegetation in the context of removal of vegetation that stabilises channel banks.

It was hypothesised that the uprooting of trees caused by the cyclone could have led to increased susceptibility of the landscape to erosion. Accordingly, a specific investigation was carried out to quantify the load of fine suspended sediment being transported through two impacted catchments (Gulungul and Swift Creeks) in the wet season following the cyclone. The conclusion from this work was that there was no substantive increase in the load of fine suspended sediment as a result of the cyclone. However, it should be noted in this context that Cyclone Monica occurred at the very end of the 2005–06 wet season, and the 2006–07 wet season started relatively slowly (January 2007 had the lowest monthly rainfall on record). Hence, there was an opportunity for groundcovers and grasses to become established, and thus partially stabilise the land surface, prior to the onset of the main part of the wet season.

Work is continuing to monitor the recovery of the canopy cover in the Gulungul and Swift Creek catchments. Analysis of Landsat images acquired from before, and through the two after the cyclone has indicated about a 30% recovery in canopy cover. However, it should be noted that no specific follow up work in being done in these catchments with respect to weeds, owing to resource constraints.

15.5 Discussion

Whilst the time of occurrence, location and magnitude of extreme wind events cannot currently be predicted with any level of certainty, and nothing can be done to prevent the immediate impact of such events, it is possible that either antecedent or post-event landscape management practices or strategies could be implemented that would assist recovery of the biological diversity of impacted areas. In particular, the proactive control of hot spot infestations of weeds should be considered since these stand to be the biggest beneficiaries of high wind events and consequential ‘tipping point’ modifiers of the recovering landscape.

Increased numbers of hot days could have a serious impact on both flora and fauna as a result of thermal tolerances being exceeded. However, unlike floods or cyclones, there is no contemporary precedent for this stressor, from which an observational response record could be obtained. Ecosystem level effects would likely be impossible to simulate experimentally, with work being restricted to individual species. Current knowledge indicates that reptiles are at risk. However, there is no knowledge about how an increase in the frequency of contiguous periods of hot days could impact on plant species.

An increase in average temperature, coupled with (the as currently predicted) no change in annual average rainfall will result in a net annual decrease in water balance of the landscape. In particular this could mean the drying out of waterbodies, that currently maintain a water supply throughout the year, at the end of the dry season. Such drying out could severely impact the carrying capacity of the land for all those organisms that depend on these aquatic refugia for interseasonal survival.

It is recommended that a proportion of climate change research effort be focussed on assessing the potential impact of a more negative water balance on regional aquatic refugia located above the predicted maximum sea level elevation, since these will become critical components of the landscape in the event that the majority of the current freshwater floodplain areas are lost. Indeed it is possible that climate change intervention in this context could involve the creation of engineered waterbodies designed to sustain a water supply throughout the year. Such intervention could be considered in limited areas for maintaining critical habitat for ecosystem protection or sustenance of bushtucker organisms for indigenous people.

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16 Workshop summaries: priority issues for management, knowledge gaps and ways forward

M Ibbett[1]

16.1 Focus summary

Participants at the Kakadu Climate Change symposium were asked to consider how climate change might impact on a number of key social and environmental services in Kakadu National Park.

Some of the key issues discussed included:

- The need to develop clear and defensible objectives, and to identify appropriate attributes or indicators for measuring and monitoring the effects of climate change;
- The importance of cross-agency and cross-jurisdiction collaboration in the development of strategies to deal with the effects of climate change;
- The need to engage with indigenous communities to improve their awareness of climate change and how it may affect their environment and to involve them in the development and implementation of responses to climate change;
- The capacity of current infrastructure within the Park (including power and water supplies, the Jabiru airport and housing), to meet the needs of the population in light of climate change effects needs to be assessed;
- Fire management is going to remain a key issue for biodiversity management, and the management of grassy weeds is an important component of developing and implementing appropriate fire management strategies;
- There are going to be some winners and some losers as a result of climate change. Adequate baseline information and ongoing monitoring is required to enable us to decide who the winners and losers should be.

Suggested management responses and some potential ways to progress these issues were also discussed.

16.2 Introduction

The aim of the Kakadu National Park Climate Change symposium was to share the considerable body of existing information about how climate change is likely to impact Kakadu, and to discuss the types of issues and management responses that should be considered during the development of a climate change strategy for the Park. The symposium was designed to consider a range of social and environmental issues, which of course in many cases are

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interlinked. Following a series of presentations and discussions, participants at the Climate Change Symposium undertook workshop activities to discuss how climate change will affect a number of key areas in Kakadu National Park including indigenous communities, infrastructure, industry and community services, and various components of the Park's biodiversity. This paper outlines the issues that were identified in those workshops and includes suggestions for possible management responses as well as identifying knowledge gaps.

16.2.1 Potential impacts of climate change on Indigenous communities

16.2.1.1 Issues

- Impacts of climate change may pose major challenges to the management of people's health in indigenous communities eg. Increase in risk of infectious diseases carried by mosquitoes, rise in temperature and humidity leading to increased heat stress. Health services may be placed under even greater pressure than they are today.
- Increase in the frequency and intensity of extreme weather events, particularly cyclones and associated storm surge, may pose major challenges to the sustainability of some communities, particularly those in low-lying and coastal areas.
- Changes in the environment, particularly loss or modification of some vegetation types, loss of turtle nesting habitat and floodplain habitat may result in a loss of access to traditional hunting grounds and bush tucker, as well as potentially impacting on significant cultural sites.
- Climate change may offer some potential benefits to indigenous communities, through employment opportunities in land management and monitoring to measure and monitor the impacts of climate change and to undertake remedial and mitigation activities. There may also be opportunities for economic gain through participation in carbon trading programs.
- Rising costs of servicing remote communities, and the increase in demand of services for those communities, may encourage people to stay in those remote communities rather than flying in and out.
- Income generating activities related to tourism and bush tucker may be negatively impacted by climate change.
- Community awareness is important, and educating people about the causes and implications of climate change should be a priority. This will empower people who are actively managing their country to identify threats such as weed incursions.
- Is the science being communicated to people? For example, the need to focus burning activities in the early dry season, and the impacts of not doing so, particularly on the declining fauna.

16.2.1.2 Suggested management responses

- Collaboration between agencies and communities in responding to climate change is central. Indigenous communities must be involved in developing and implementing responses on their country and in their community.
- Education programs and community awareness initiatives need to be instigated to inform indigenous people of key issues and threats related to climate change.
- A risk assessment should be undertaken to determine the likely impacts of climate change on significant sites and important hunting grounds to determine the likely impacts of climate change and the best approach to managing them in the future.

16.2.2 Potential impacts of climate change on tourism, employment and health

16.2.2.1 Issues

- Perception of the impact of climate change on Kakadu may deter tourists
- Change in rainfall and temperature may change the duration of the tourism season (for better or for worse).
- Rising costs of fuel and other amenities may impact negatively on tourism.
- Impending effects of climate change may be a selling point for tourism (eg. Come and see Kakadu before climate change alters it).
- Rising temperatures may have an impact on staff (heat stress and other related issues).
- Employment opportunities may increase in areas related to monitoring and responding to effects of climate change.
- Longer retention of water and change in geographic distribution of some disease carrying mosquitoes may lead to greater risk of infectious disease. The potential for vector carried disease may carry with it a stigma that might affect tourism and ability to attract workforce.
- Health issues for indigenous communities may be increased as a result of climate change.

16.2.2.2 Suggested management responses

- Look positively at opportunities generated by climate change eg more employment opportunities for indigenous population in monitoring and remedial activities.
- Develop strategies for managing tourism in the event of more extreme weather events and changed climate conditions, including emergency response plans and marketing strategies.
- Work with other agencies to investigate strategies for managing health risks likely to evolve as a result of climate change.
- Assess Occupational Health and Safety requirements for staff under changed temperature and rainfall conditions (ie prolonged periods of slightly hotter days).
- Greater collaboration between agencies to identify ways to tackle with changes in tourism, employment and health issues relating to climate change.

16.2.2.3 Knowledge gaps

- Future of the township of Jabiru and how the town will be serviced (what will the demography of the town be, will there be adequate housing and services?).
- Future demand on accommodation and other tourism facilities (is this likely to increase or decrease as a result of climate change?).
- Will there be an increase in health management facilities in Jabiru and will this be able to cope with the potential threat of disease and other medical emergencies resulting from extreme weather events and other climate change impacts?

16.2.3 Potential impacts of climate change on infrastructure in the Kakadu region

16.2.3.1 Issues

- Resilience and suitability of infrastructure in light of impending climate change, especially increase in extreme weather events and changes in rainfall and temperature patterns.

- Does the Park have the capacity to monitor the impacts of climate change on infrastructure across the Park (some areas are inaccessible during the wet season and this problem may increase in the future and after extreme events).
- Is there adequate infrastructure in the Park to cope with future conditions eg. Does the airport have the capacity to deal with likely increase in demand as a result of more flooding, can energy demands be met with current approach to supply, how will waste be managed and will there be an adequate supply of drinking water (bore or tank?).
- Is there an appropriate strategy in place for the development and maintenance of appropriate infrastructure in a climate change environment that is going to be highlighted by more frequent and intense extreme weather events?
- Should the Park be considering increasing the use of renewable energy technologies and more fuel efficient vehicles and buildings to decrease contribution to climate change?
- Kakadu needs to work co-operatively with other stakeholders (Defence Force, West Arnhem Shire) in regards to responding to the impacts of climate change, particularly disaster response.

16.2.3.2 Suggested management responses

- Carry out an audit/inventory of assets to identify: which are crucial, what threats they may be vulnerable to, which need updating/upgrading, which need to be relocated and which will be unsuitable in the future climate change environment.
- Review the capacity of key infrastructure for likely scenarios resulting from climate change: eg can the Jabiru airport handle a likely increase in traffic, how will roads and bridges be managed and maintained in the face of more flooding etc.
- Construction and building codes for Park assets need to be reviewed to ensure that infrastructure will be able to cope with the likely effects of climate change eg extended periods of inundation, saltwater intrusion.
- Develop a counter disaster plan that will cope with a range of scenarios. This should be informed by the experience of other agencies in dealing with a range of extreme events .

16.2.3.3 Knowledge gaps

- What is the future of the town of Jabiru and other infrastructure related to the Ranger Mine (particularly power generation)?
- What is the future demography of Kakadu going to be and will current infrastructure be able to service that population?
- Life expectancy of current infrastructure is in some cases unknown.

16.2.4 Potential impacts of climate change on fire and vegetation

16.2.4.1 Issues

- Increase in the number of hot days will mean that fire intensity will increase.
- Invasive species, particularly grassy weeds, will make fire management harder.
- Importantly, people are in control of the fire regimes of the north, not rainfall or other weather conditions, therefore they also have the potential to manage the impacts.
- Monitoring has shown that some components of biodiversity, particularly small mammals, sandstone heath communities, some iconic plant species such as *Allosyncarpia*

- Increased atmospheric carbon availability may be leading to increased woody vegetation on the floodplains, expansion of rainforest pockets and increased density of woody vegetation in woodlands.
- Fire management as a carbon sequestration and emission abatement strategy.

16.2.4.2 Suggested management responses

- Focus must be on burning early in the year and reducing the frequency of fire.
- There must be clear management objectives and the Park's ability to meet these objectives must be assessed through ongoing monitoring. At present, some components of the monitoring are institutionalised, but not all. There is no long term commitment to maintaining all aspects of monitoring.
- Need to clarify the position of KNP in regard to carbon sequestration and emissions abatement and trading policies: can the Park engage in this forum?

16.2.4.3 Knowledge gaps

- Need to continue monitoring to be able to assess changes in vegetation and fire as climate change is occurring.
- Funding uncertainty in relation to fire monitoring.
- How do we go about changing fire regimes to ensure sustainability of vegetation communities, particularly fire sensitive communities, in light of encroaching fire promoting weeds and changes in temperature/rainfall patterns?

16.2.5 Potential impacts of climate change on terrestrial biodiversity

16.2.5.1 Current threats and how they will be impacted by climate change

- Fire: climate change may affect the severity and extent of fires through changes in fire weather conditions eg hotter and drier for longer periods = longer fire season.
- Temperature: higher temperatures may be lethal to some terrestrial species.
- Water: change in timing, duration and variability of wet season may have major impacts on some species.
- Extreme weather events: more frequent extreme events, particularly cyclones, will affect vegetation through tree loss, and the extent of this damage and the rate of recovery of habitats will determine impacts on terrestrial biodiversity.
- Sea level rise: some components of the terrestrial biodiversity have strong links with freshwater systems so may be affected by sea level rise.

16.2.5.2 Suggested management responses

- Need to get fire management right. Fire management is seen to be improving in the Park, but there needs to be a greater sense of urgency in the efforts to get it right. Climate change may also lead to a shift in the 'early burning' window, so fire management must be adaptive in this regard.
- Need to identify and protect refugia for terrestrial biodiversity. We are currently unsure of what a 'refuge' will be, so perhaps should consider focussing on moister components of the landscape.

- Continue to seek to prevent further incursions of weeds, particularly grassy weeds, and manage existing species as effectively as possible. The interplay between grassy weeds and fire regimes may be exaggerated as a result of climate change.

16.2.5.3 Knowledge gaps

- Thermal thresholds for key components of terrestrial biodiversity need to be identified.
- Understanding of ecological responses to temperature and rainfall changes needs to be improved, including how these changes might affect ecosystem processes and functions (eg surface water persistence in ephemeral waterways).
- The level of dependence of terrestrial biodiversity on freshwater systems needs to be investigated.
- The impacts of cyclones on terrestrial systems needs to be investigated beyond the current focus on trees (eg impacts on fauna, soil biology).
- The impacts of climate change on the endemic flora and fauna of the sandstone country needs to be investigated.

16.2.6 Potential impacts of climate change on marine and coastal biodiversity

16.2.6.1 Current threats and how they will be impacted by climate change

- Increase in temperature: rising temperatures may impact on reptiles with temperature dependent sex-determination (eg turtles) with a resultant increase in the number of female offspring; there may be decreased productivity of sea grass communities and increases in the incidence of coral bleaching.
- Coastal erosion: climate change may result in an increase in coastal erosion leading to loss of nesting beaches for turtles and shorebirds and may lead to increased sediment loads in inshore and estuarine waters.
- Sea level rise: rising sea levels as a result of climate change may lead to the loss of beach habitats (eg for nesting), but may also lead to an increase in other habitats (eg the extension of mangroves); may alter the distribution of habitat for some species; and may lead to the loss of corals and seagrass beds as a result of depth increase and increased sediment load.
- Changes in sea water chemistry: climate change may lead to acidification and may alter freshwater flows.

16.2.6.2 Suggested management responses

- Recognise the value of Kakadu’s marine environments and undertake assessment of it’s cultural and ecological values
- Investigate habitat management options to ensure sustainability of some species eg replanting of shade trees on turtle nesting beaches, creation of artificial reefs.
- Manage human impacts to alleviate additional pressures that they may impose on habitats already stressed by climate change.
- Seek to obtain a better understanding of processes affecting coastal erosion and deposition patterns.

- Seek to improve collaboration with other agencies in order to improve understanding of the processes affecting marine and coastal biodiversity.
- Assess fishing pressure in Kakadu and implement appropriate management of this pressure.

16.2.6.3 Knowledge gaps

- Baseline data currently not available in order to assess the impacts of climate change on Kakadu's coastal and marine biota, and on cultural sites.
- Need to document traditional ecological knowledge and significant sites in coastal and marine habitats.

16.2.7 Potential impacts of climate change on wetlands and freshwater aquatic biodiversity

16.2.7.1 Current threats and how they will be impacted by climate change

- Saltwater intrusion: tidal wetlands will be under greater threat as a result of climate change.
- Extreme weather events: likely to become more frequent as a result of climate change and this may result in increased removal of vegetation, a reduction in bank stability in waterways, increased erosion and sediment loads and changes to hydrological processes.
- Boating activities: climate change may increase the risk of saltwater intrusion into upstream billabongs via boating channels.
- Fire regimes: climate change may result in changed fire weather and affect the intensity and timing of fires which could in turn lead to the loss of riparian and floodplain vegetation.

16.2.7.2 Suggested management responses

- Develop a better understanding of the potential extent of saltwater intrusion through detailed regional level predictive modelling, spatial risk assessments and cost-benefit analysis to assess the appropriateness of a range of responses including mitigation works.
- Assess and improve the ability of infrastructure to cope with extreme weather events and develop appropriate response procedures to promptly assess and respond to impacts.

16.2.7.3 Knowledge gaps

- Need to obtain appropriate high resolution digital elevation models and hydrological models to predict the extent of saltwater intrusion. Also need to undertake population viability analysis for key components of freshwater biodiversity (eg barramundi, magpie geese) to assess regional impacts.
- Regional scale modelling of weather impacts, including rainfall and damage zones from storm surges and flooding will be useful.

16.2.8 Potential impacts of climate change on invasive species.

16.2.8.1 Current threats and how they will be impacted by climate change

- Dispersal of weeds by natural processes: increase in extreme weather events may increase this threat and expand problem species into new areas.
- Invasion by new weeds and feral animals: new invasions may be possible if temperature/rainfall changes alter potential geographic distribution of some species.
- Effectiveness of biocontrol agents: some may be more effective, some less effective as a result of change in rainfall/temperature/seasonality.

- Changed fire regimes: the potential increase in a number of weed species, particularly grasses, may lead to more destructive fire regimes (major issue for biodiversity conservation).
- Ongoing conflict resulting from the status of introduced pasture grasses as a valuable resource to some and pest to others: climate change may facilitate new infestations of these species but is unlikely to change these perceptions.
- Lack of regional co-ordination: likely to remain unchanged as a result of climate change.
- Response to high priority weed species: capacity to respond likely to be stretched as a result of increasing number of high priority weeds as a result of climate change.
- Interactions between feral animals/weeds and the environment: climate change may lead to more complex interactions with ecosystem processes and introduced species.
- Effectiveness of control: increase in extreme weather events may compromise the effectiveness of control activities and result in wasted resources and efforts.
- Lack of high quality mapping data: effects of climate change on species distributions (actual and potential) is likely to continue to challenge capacity in this area.
- Loss of biodiversity, particularly small mammals: current declines not linked to climate change, but there may be an effect on the distribution and abundance of cats as a result of climate change.

16.2.8.2 Suggested management responses

- Need to develop and implement evidence-based approaches to the assessment and management of invasive species, including adequate and defensible risk assessment procedures.
- Need to develop management thresholds that when reached, will initiate a pre-determined management response.
- Need to establish response mechanisms to cope with the impacts of extreme weather events on invasive species distribution and abundance.
- Need to ensure that there is an adequately skilled and resourced workforce available to deal with invasive species in a climate change environment.
- Need to develop the capacity to prioritise (and reprioritise efforts) after extreme weather events and as the effects of climate change become apparent.
- Fire regimes need to be managed in the climate change environment: frequency, timing and extent need to be carefully managed and monitored, especially in relation to the distribution and abundance of introduced grass species.
- Control agents (including biocontrol and chemical control) need to be appropriate for climate change environment: monitoring of the effectiveness of control activities is required to ensure appropriate and effective methods of control are in use across the Park.

16.2.8.3 Knowledge gaps

- Which weeds are going to become issues for the Park as a result of climate change, and where are they likely to occur?
- As yet there is no clear strategy for managing the likely increase in demand placed on staff and resources as a result of changing weed priorities associated with climate change.

- What will be the best fire management strategy in light of changing weed issues and climate change?

16.2.9 Measuring and monitoring the effects of climate change.

16.2.9.1 Issues

- Measurement and monitoring of the effects of climate change must be driven by clear and defensible objectives and should focus on significant processes, systems and species in Kakadu. The identification of appropriate spatial and temporal scales for monitoring is also important.
- A coherent set of baseline parameters is required for effective monitoring of the effects of climate change. This should include climatic, geomorphological, hydrological, ecological and social information.
- Commitment to monitoring should be accompanied by an equivalent commitment to improving capacity to manage (and maintain), analyse and utilise data over the long term. The lack of commitment to long-term data collection is considered a major impediment to managing the impacts of climate change (and other threatening processes) in the Park.
- Methods used to measure and monitor the effects of climate change need to be appropriately sensitive and capable of detecting the types of changes that are going to occur. The use of appropriate indicators is central to this process, as it will almost certainly be impossible to measure all components of interest within Kakadu. Monitoring infrastructure (including field equipment, data storage facilities etc) need to be able to withstand extreme weather events likely to occur as a result of climate change.

16.2.9.2 Suggested management responses

- Develop 'adaptive management' projects to test the suitability of techniques for measuring and monitoring climate change.
- Initiate collaborative activities with other agencies and institutions to help clarify needs of management and to match complementary capabilities across these organisations.
- Optimise the use of existing baseline information by improving communication and data sharing between organizations.
- Optimise the use of new and existing technologies to ensure best practice measuring and monitoring of the effects of climate change.
- The development of programs for measuring and monitoring the effects of climate change should include explicit measures for communication of outcomes between research institutions, management organisations and the broader community.
- Make Kakadu more research friendly. The current perception of many researchers is that Kakadu is not a good place to undertake research.
- Work to improve the technical capability of Kakadu, including increasing the technical capacity of the Park in relation to employee skills (GIS, remote-sensing, field monitoring capabilities) and organisational capacity to store and manage the data that is going to be accumulated as a result of monitoring activities (examples of large amounts of lost data from a number of workshop participants highlight the urgent need to improve this area).

16.2.9.3 Knowledge gaps

- Lack of good long-term climate, geomorphology and hydrological data.

- Lack of understanding of links between terrestrial and coastal ecosystems in the light of climate change projections.
- How will the impact of climate change affect Kakadu's World Heritage values (both cultural and natural)?