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Editorial

Kakadu's wetlands: more change is afoot

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Kakadu National Park (KNP) is iconic in every sense of the word. From its striking sandstone escarpments to its long and vibrant Indigenous culture, KNP has become part of Australia's vernacular and a key tourist attraction for both national and international visitors. Of particular ecological and social significance, and the focus of this Special Issue, are KNP's extensive wetlands. These comprise myriad biomes, including coastal tidal flats and mangroves, hyper-saline salt flats, freshwater wetlands and streams (Erskine *et al.* 2018; Finlayson 2018). The wetlands support a large proportion of the region's quintessential flora and fauna, which are inherently entwined with the local Indigenous communities, providing food, resources and places of cultural significance (Bayliss and Ligtermoet 2018, Dutra *et al.* 2018).

Despite its World Heritage status and Ramsar listing, KNP is typical of high conservation areas around the world in that the simple act of declaring a region 'protected' does not exclude it from the influences of the outside world. Since the establishment of KNP, considerable resources continue to be allocated to programs aimed at controlling the impact and spread of a range of invasive species, including water buffalo and pigs. Of particular concern are weeds: Para grass (*Urochloa mutica*), for example, now covers an estimated 3200 ha of KNP (Adams *et al*. 2015) and poses a significant threat to key environments, e.g. Magpie Goose habitat (Bayliss and Ligtermoet 2018). The continuous need for a diverse range of control and eradication programs is having significant effect on KNP's financial, natural and Indigenous values (Bayliss *et al.* 2018*a*).

An underpinning theme throughout this Special Issue has been the susceptibility of the region to sea-level rise (SLR). The region is particularly vulnerable because of its low-lying and flat topology. Anecdotal evidence, including the recession of mangroves, die-back and the formation of salt-crusted fissures towards the mouth of the South Alligator River (Lucas *et al.* 2018; A. A. Chariton, pers. obs.), suggests that salt-water intrusion is already reshaping the face of Kakadu and its surrounding region. However, the present contribution of SLR is difficult to quantify, as other factors such as historic buffalo grazing are also likely to have contributed to salt-water intrusion, although there is insufficient historical measurements to demonstrate the relative importance of these factors.

Bayliss *et al.* (2018*b*) modelled the extent and frequency of inundation in Kakadu's floodplains for the years 2013, 2030, 2070, 2100, reflecting sea-level rise scenarios of 0, 0.14, 0.7 and 1.1 m respectively. Using a fairly conservative approach based on a 25% frequency of sea-water (over 2 PSU) inundation over a monthly tidal cycle, the findings suggests that although freshwater habitat loss will be marginal (~4%) by 2030, there is a high probability of a threshold effect potentially resulting in an estimated loss of 42% by 2070, increasing to 78% by 2100. The findings of Bayliss *et al.* (2018*a*) also suggest that the extent of loss varies among the floodplains, reaching 80% by 2100 in the most pronounced case. However, it should be noted that the model relies on a 'bathtub-like' SLR effect, meaning that the variable hydraulic friction of the floodplain was not directly incorporated into the model. Hence, although there are some process uncertainties in the prediction of SLR, the modelling outcomes can be considered a reasonable approximation of forecasted impacts over decadal to centennial time frames.

Using the information conveyed in this Special Issue as a template, we briefly postulate the implications of SLR over the next five to eight decades. From a hydrodynamic perspective, the increasing influence of seawater into the system is likely to profoundly alter the morphology of Kakadu's floodplains, resulting in an increase in the upstream deposition of sedimentary material. In addition, we anticipate an increase in the lateral movement of seawater into the floodplain via the existing labyrinth of channels and fissures. The intrusion of saline waters into formerly buffered regions increases the likelihood of dieback and a reduction in soil integrity, thereby creating additional fissures that may further exacerbate the lateral movement of saltwater. Bank collapses in the main channel may also increase due to the additional stress brought about by SLR. This may lead to the formation of lateral channels conveying water onto the floodplain as has been observed in the nearby Lower Mary River wetlands (Williams 2014).

Although saltwater inundation currently plays a vital role in shaping Kakadu's floodplains (e.g. maintaining water chestnuts and the Magpie Geese colonies they support), presently, such events occur 6–12 times per year in environments that are also subjected to seasonal and often sustained freshwater inundation events (Woodroffe *et al.* 1986; Bayliss *et al.* 2018*a*). However, the proposed future scenarios suggest a very different pattern in the timings between saltwater and freshwater exposure, ultimately resulting in increasingly sustained periods of seawater exposure, creating conditions that exceed the physiological limits of a large proportion of the biota (Nelson *et al.* 2015, 2018; Humphrey *et al.* 2018; Pettit *et al.* 2018; Stephenson *et al.* 2018). For much of the ARR's floodplain, the modelling of Bayliss *et al.* (2018*b*) suggests that the system will initially undergo a transitional change, with a tipping point occurring *c.* 2070, where affected areas will make a permanent and unidirectional transition from mostly freshwater to marine-dominated environments.

Although several articles in this issue specifically highlight the effects of salinity on the region's biota, including sensitivities and thresholds of particular taxa and ecological communities, it is emphasised that in some cases this information was obtained from data based on current pulse-saltwater-exposure events, rather than more sustained scenarios. Consequently, extrapolating these findings may be fraught with ambiguity, posing the question: what will the system look like post-2070?

The long-term viability of any remnant floodplains is unclear given the overarching effects of habitat fragmentation, and potential increases in competition between native species and feral animals for dwindling resources. Even if new environments are slowly created upstream, by natural or artificial means, it can be argued that they are unlikely to be at the same scale or support the same level of biodiversity that currently occurs in KNP, potentially jeopardising Kakadu's Ramsar listing.

Clearly, the postulated scenarios have profound and negative social and economic implications. For KNP's Indigenous communities, this is likely to include the loss of hunting and fishing areas, and sites of cultural significance. The decline in tourism will also have financial implications for tourism operators, and the revenue used to support the Park's management activities (Bayliss *et al.* 2018*a*; Dutra *et al.* 2018).

Given the findings of Bayliss *et al.* (2018*b*), it can be argued that Kakadu's floodplains in their current form are unlikely to persist into the next century. Although the true ecological, social and economic implications are difficult to quantify, and indeed are likely to change over the next few decades, there is a critical need for an articulated insight into what lies ahead. This includes identifying what the system will look like, and what measures will be required to either embrace this change or modify its course. For example, given the low sensitivity of Para grass to saltwater, at what point do we stop managing it, or restrict its management to specific areas? Should levies or other structural measures be put in place to restrict the influence of sea-level rise or to protect specific areas of high value? Can new environments be seeded upstream to compensate for habitat loss? Given the current discussions about incorporating facilitated adaptation and technological interventions to assist in protecting the Great Barrier Reef (Albright *et al.* 2016), perhaps similar approaches could be considered for KNP.

Although it is beyond the scope of this paper to provide guidance on how KNP should manage sea-level rise, what we do wish to emphasise is that significant consideration of these matters is urgently required. Over the next few decades, sea-level rise will undoubtedly place increasing pressure on our national economy. Under such conditions, it is inevitable that priority will be given to regions based on potential losses to infrastructure and economic activities. As such, it can be foreseen that funding opportunities for protecting Kakadu and other areas of ecological and cultural value from the effects of SLR will diminish over time. Given that the modelling suggests SLR will initiate with a potentially reversible transitional stage, with a tipping point not occurring until the latter part of the 21st century, there is currently an opportunity to address this issue, noting that cost and effort will increase as decisions are delayed.

The impending influence of SLR on KNP's wetlands parallels the threats facing other regions of high conservation value, e.g. the Great Barrier Reef and Florida's Everglades; emphasising the need to address both localised (e.g. poaching and pollution) and global threats (e.g. climate change) (Bartolo *et al.* 2018; Wolff *et al.* 2018). To address the combined influence of these factors, a profoundly different approach is required. Critically, this must consider both the current interplay between localised and global threats, and forecast how their balance and magnitude will vary over time (Baird *et al.* 2016). Ultimately, success will be determined by timely decision-making and direct actions that reflect the values of KNP's stakeholders and the intentions of national and international policy makers. The former have been engaged in discussions and decisions about managing the impacts of saline intrusion and SLR since the 1980s and 1990s respectively (Bayliss *et al.* 1997; Finlayson *et al.* 1997) and, as shown in this Special Issue, the scientific knowledge-base about the wetlands has increased enormously and is available for informing urgently needed decisions for local remediation and adaptation. The urgency comes from the expectation that Kakadu' wetlands will change and we may see the loss of existing biomes as well as the emergence of novel ecosystems. And all within a policy context whereby the consequences of climate change have been removed from existing responses for reporting on the international status of the wetlands (Finlayson *et al.* 2017). Climate change and SLR may represent a wicked problem, but in this instance we can point to a considerable dividend in obtaining the information to inform decision-makers and local residents alike as they grapple with the best adaptation options.

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