The dynamics and management of the northern Australian environment

A Doctor of Science thesis

University of Queensland

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December 2012

Volume 1

Dedicated to Helen whose love and prayers made this all possible.

With thanks to Mum and Dad whose support set me on this path.

For Anna, Joel, Eliza and Alice.

1. STATEMENTS OF CONTRIBUTION AND ORIGINALITY

This thesis documents my contribution to understanding the interactions of the physical, biological and human environment of northern Australia and the implications for management.

It contains a comprehensive introduction to my work which summarizes the significance and impact of the scientific papers. In the Introduction, I describe my work under six themes, some with subthemes. The publications are included after the introduction, and arranged according to themes and subthemes.

All publications are the original work of the authors.

Most of the publications represent the work of a team. Where I am the lead author, I led that team's research and wrote most of the paper. In other cases, I contributed ideas, data, analyses and varying numbers of words.

Material included in the paper by Cook, So and Dalal (1992) was submitted as part of my Doctor of Philosophy thesis.

There once was a system, savanna
Defined in a nebulous manner
To include everything
That Australia could bring
And confuse ev'ry management planner!

Garry Cook (1990) Journal of Biogeography 17: p. 551

FIGURE 1: AUSTRALIAN TROPICAL SAVANNA, FAR NORTH QUEENSLAND

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2. OVERVIEW

In the late 1980s, when my colleagues and I commenced the Kapalga Fire Experiment in Kakadu National Park, Northern Territory, Australia, the landscapes of northern Australia had been described in terms of their agricultural productivity and potential for development, but little research had been conducted on their dynamics and management for environmental services and conservation of biodiversity. Since then, my research, in collaboration with numerous colleagues, has allowed land managers in the region to be much better equipped to understand and manage the challenges of a regime of frequent extensive fires in the context of invasive species, climatic variability and mounting concerns about greenhouse gas emissions and threats to biodiversity.

We concluded from our work at Kapalga that much of the biota was highly resilient to fires, but riparian ecosystems and small mammals were severely affected by very frequent fires. At the time the fire regime was poorly quantified, but frequent, extensive fires were inevitable across much of northern Australia because of the very low human population density, the lack of barriers to fire spread across the landscape and the long dry season following reliable wet seasons. Indigenous people, who own much of the region had moved off traditional estates into larger settlements through the effects of colonisation and had scant resources to implement traditional fire management on their land.

My research into greenhouse gas emissions from fires at Kapalga ultimately led to resources being available for improved fire management in northern Australia. As part of my research, I collaborated with atmospheric chemists to measure the emissions from savanna fires. We contributed to the development of methods for evaluating savanna and agricultural burning emissions for Australia's National Greenhouse Gas Inventory. The emissions of the strong greenhouse gases methane and nitrous oxide from savanna burning represent 13 % of Australia's emissions from the Agriculture sector – a uniquely high proportion in the developed world. I argued that the greenhouse gas emissions from savanna fires could be mitigated through the use of low intensity early dry season fires.

Following much further research into the dynamics and management of northern Australian ecosystems, Indigenous people are now receiving payments for reducing greenhouse gas emissions across tens of thousands of square kilometres.

For this thesis, I have grouped my research papers into six major themes each with subthemes. Firstly, in Chapter 3, I provide a context to my research by summarising the historic interactions between science and policy in Australia's north and giving an overview of environmental dynamics and management in the region from the perspective of a number of review papers that I led or co-authored. My contributions are then grouped into themes dealing with climate (Ch 4), landscape dynamics (Ch 5), fire and vegetation (Ch 6), carbon dynamics (Ch 7) and greenhouse gas assessment and management (Ch 8). In each chapter, I briefly review the papers in logical, not necessarily chronological order and list the relevant papers. At the end of the thesis, the papers are grouped into the themes and subthemes, and bound.

3. HISTORY OF INTERACTIONS BETWEEN SCIENCE AND POLICY IN NORTHERN AUSTRALIA

The current focus on Indigenous management of natural landscapes for the provision of environmental services (Cook et al. 2012: see Section 7) contrasts strongly with the focus of land management policy and research for northern Australia throughout most the 20th century. Government policy was for densely settled intensive agriculture based on both cropping and livestock raising (Cook 2009). In the absence of successful pioneering efforts, science was relied upon after the Second World War to lead the way in developing viable intensive agricultural industries. About the time I commenced my research career in Darwin in 1988, this era was drawing to a close as researchers finally concluded that the vision of dense agricultural settlement across northern Australia was not going to be fulfilled.

During the first decade of the 21st century, severe drought compounded by over allocation of irrigation water in southern Australia led to renewed speculation about the agricultural potential of northern Australia. Hence, in 2009, the Australian Federal Government commissioned the Northern Australia Land and Water Science Review. I contributed an analysis of over 150 years of science and policy regarding northern development (Cook 2009), and summarized five historic pushes for agricultural development in which government led research efforts assumed that once the science was in place, agricultural development would follow. However, private and government investment in intensive agriculture in the north invariably failed. I argued that in the past quarter-century, the paradigm was shifting away from intensive agriculture being seen as the logical endpoint of land development towards recognition of Indigenous land management and environmental stewardship. My research career spans that period of shifting paradigms and focuses on understanding the natural ecosystems as a basis for their improved management, and particularly by Indigenous land holders.

FIGURE 2: THE ABANDONED LAKEFIELD DOWNS AGRICULTURAL DEVELOPMENT IN TROPICAL QUEENSLAND

By way of introduction to northern Australia, I include overviews by my colleague Dick Williams and myself of the savanna landscapes of northern Australia, and their fire regimes. My overview of global trends and fire management, published in 2001 foresaw many issues that have now been addressed for the region, as described in other chapters of this thesis.

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4. CLIMATE VARIABILITY AND ITS ECOLOGICAL IMPACTS

Tropical savannas dominate the landscapes of northern Australia. Globally the tropical savanna biome occurs where there is a seasonally wet and dry climate. A systematic understanding of the climatic variation and variability is fundamental to predicting the dynamics of natural ecosystems across northern Australia as a basis for their better management.

RAINFALL VARIABILITY: ITS ASSESSMENT AND IMPACTS

Typically mean annual rainfall is used to describe the rainfall regime of a region. However across the wet-dry tropics of the world mean annual rainfall is confounded with the length of the wet season (Cook and Heerdegen 2001). Liedloff and Cook (1997) used the Flames model to disentangle the ecological effects of rainfall amount from the length of the rainy season. We showed that rainy season length rather than total amount has the greater impact on vegetation production and stocks. Cook and Heerdegen (2001) developed an algorithm to describe rainy season length and showed that the rainy season length declined over 10° of latitude (c. 100 km) from 221 days in the north to 83 days in the south. In an invited contribution to a book on modelling tropical savannas, Liedloff and Cook (2010) compared the seasonality along rainfall gradients in western Africa, southern Africa and northern Australia. We showed that the high rainfall (>1000 mm) parts of northern Australia were characterised by much longer dry seasons and greater inter-annual variability than equivalent parts of western and southern Africa. In contrast, the arid systems of Australia showed much less summer dominance than arid systems bordering the Sahara and Namib deserts in Africa. We argued that these differences in rainfall regimes could account for many of the structural differences in vegetation between the regions.

The savanna *gymnosperm Callitris intratropica* is one of the few trees that produces rings in northern Australia and can give some information about historic climate variability. Through my experience in both climatic variability and vegetation ecology, I contributed to two studies investigating the potential to use this species to study past climate. We showed that because of spatial correlation, historic data from northern Australia, such as provided by tree rings, should be useful to document changes in the Australasian monsoon (D’Arrigo et al. 2008). However, a detailed analysis of the production of individual rings indicates the need for caution in interpreting the tree ring record due to the very different responses of isolated trees to those in groves (Drew et al. 2011).

FIGURE 3: WET SEASON OVER THE FLOODPLAIN OF THE SOUTH ALLIGATOR RIVER, KAPALGA RESEARCH STATION, NT

CYCLONES: THEIR IMPACTS AND HAZARD ASSESSMENT

The impacts of cyclones on vegetation in the wet tropics have long been recognised but few have studied their impact on savannas of the seasonally wet-dry tropics. Following the impact of Cyclone Monica in Arnhem Land in 2006, Cook and Goyens (2008) produced the first systematic evaluation of the effects of cyclones on Australian savanna trees. Cyclone Monica was the most intense cyclone ever recorded to make landfall in the southern hemisphere. We analysed its wind fields to determine the relationship between gust speed and the proportion of damage to trees. This approach is critical to evaluating the role of cyclones in the carbon dynamics of Australia's tropical savannas.

While investigating the return period of particular gust speeds, I realised that the current understanding of the tropical cyclone wind recurrence as embodied in the Australian wind standard was not consistent with the occurrence of Cyclone Monica nor with the occurrence of three other Category 5 cyclones over the past two decades. According to the Australian wind standard, Cyclone Monica was nearly a one in a million year event. On examining the analyses that were used to develop that standard, we realised that it was far more likely that those analyses had simply led to a misinterpretation of wind hazard. By overlooking the impacts of cyclones prior to mid-1950s the analyses were biased towards a low wind hazard. Reanalysing historical data, together with data modelled using Kerry Emanuel's cyclone model, we produced a new gust speed recurrence interval curve for the region (Cook and Nicholls 2009). This had considerable implications for the built environment of Darwin and other northern Australian settlements. This was rebutted by a group of engineers who had developed the previous understanding of cyclonic wind recurrence. We refuted their claims (Cook and Nicholls 2012) and stood by the conclusions of our original paper. Our defence draws attention to flaws in the interpretation of historical wind speeds that have been built into the Australian Standard.

FIGURE 4: TROPICAL CYCLONE MONICA PRIOR TO LANDFALL IN THE NORTHERN TERRITORY. SOURCE: NASA

CLIMATE CHANGE AND GEOENGINEERING

In considering the potential impact of climate change on Australia's wet-dry tropics, (Williams et al. 1995), we found that, at the sub-continental scale, migration of species due to shifting climate zones was likely to be constrained where highly heterogeneous species' assemblages abutted more homogeneous regions. We identified three such bands across the Northern Territory and discussed the implications for fauna and flora.

Climate change will affect fire regimes across Australia (Williams et al. 2009). There is evidence that already the fire danger is increasing in south-eastern Australia. In northern Australia, where fire regimes are determined by fuel or ignition rather than fire weather, the impacts are not likely to be as great.

In Kakadu National Park Indigenous communities are likely to be particularly affected by rising sea levels, which would endanger the extensive coastal wetlands (Cook and Woodward 2010). These wetlands are critical resources for the Indigenous communities. There is, however, potential for Indigenous communities to benefit from engagement in land-based greenhouse gas abatement activities.

In all likelihood, the global community will not be able or willing to respond sufficiently to avert climate change. In that case the possibility of directly intervening in the global climate may be a solution. In a discussion of the potential climate interventions, we concluded that their use was undesirable and their efficacy largely unknown (Pearman et al. 2010).

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5. THE DYNAMICS OF LANDSCAPES, NUTRIENTS AND SOILS IN NORTHERN AUSTRALIA

CYCLING OF NITROGEN AND OTHER NUTRIENTS

My early work in the tropical savannas showed that one of the dominant groups of grasses in the high rainfall belt – the annual sorghums – were too low in nitrogen throughout most of their lifecycle to support grazing mammals (Cook and Andrew 1991). This leads directly to the prevalence of fire in the region and the relative lack of success of commercial grazing enterprises. Quantifying the losses of biomass, nitrogen and other nutrients during fires, I showed that a substantial proportion of the macronutrients within the dead grass and leaf litter is transferred to the atmosphere in each fire (Cook 1992; 1994). This raised questions about the sources of nitrogen in this grass and tree dominated system. Collaborating with French colleagues who had worked in West African savannas, we used stable isotope ratios to show that the various herbaceous legumes in the system were most likely fixing nitrogen, and the grasses were either associated with free living nitrogen fixers or were very tightly controlling nitrogen cycling (Mordelet *et al.* 1996).

I further developed the use of stable nitrogen isotopes, expressed as δ^{15}N values, to interpret savanna dynamics through investigating the changes along the rainfall gradient south from Darwin (Cook 2001). I showed that fire frequency was a major factor affecting the interpretation of δ^{15}N values and countered previous work suggesting that grazing pressure was a major cause of variation in openness of the nitrogen cycle in northern Australia by presenting evidence that fire frequency had the dominant effect.

Working in central Australia, we investigated the flows of nitrogen and carbon through banded Mulga systems with groves of trees interspersed with grassy or bare areas (Cook and Dawes-Gromadzki 2005). We showed that the groves were the dominant sources of fixed nitrogen, with plants in the intergroves being strongly conservative in their use of nitrogen. By comparing the δ^{15}N values of termites with their food plants, we showed that two species of termite were fixing nitrogen, which occurs via their gut fauna.

Natalie Rossitor-Rachor, whose PhD thesis I co-supervised, followed up on my earlier work on nitrogen losses with fire, by comparing the introduced tall African grass *Andropogon gayanus*, with native grasses. This grass is one of those introduced under the Commonwealth Plant Introduction scheme (Cook & Dias 2006), but which has subsequently been declared a noxious weed. Our work showed that invasion by *A. gayanus* increases nitrogen losses from fire compared to native systems (Rossiter-Rachor *et al.* 2008). Further, it substantially alters nitrogen cycling probably though stimulating ammonification and inhibiting nitrification in the rooting zone. This favours its own growth, since it prefers ammonium as a nitrogen source compared with the native species which prefer nitrate (Rossiter-Rachor *et al.* 2009). To our knowledge, this is the first time this mechanism has been proposed as one that facilitates the success of an invasive species.

LANDSCAPE PROCESSES: THEIR ASSESSMENT AND MANAGEMENT

A quantitative index of land condition was developed and applied to pastures across northern Australia (McIvor et al. 1995). The lower herbage productivity on the poorer sites results in lower livestock carrying capacity. Synthetic Aperture Radar represents a tool that, in the early 1990s showed promise for monitoring such changes in land condition (Williams et al. 1997). In Williams et al. (1997), we provide a general overview of the disturbance processes affecting vegetation in northern Australia, and their implications for land management. In Australia's tropical savannas and semi-arid to arid rangelands, management of land condition must aim at maintaining soil processes that underpin the productive ecosystems. This requires a focus on the fertile landscape patches (Cook et al. 2004). Vegetation patchiness is affected by land condition, and we identified an underlying trend that fine scale patches decreased in size with increasing rainfall along the north-south rainfall gradient across the tropical savanna biome (Cook et al. 1999; Ludwig et al. 1999).

Small intermittent streams are important wildlife habitats in the northern savannas. On the Kapalga Research Station, we showed that the sedimentary soils along these streams date from 7 to 21 thousand years before present (Cook et al. 2000). We concluded that climate variation was more important to sedimentation processes than the substantial changes to erosional base levels along the major rivers downstream.

WEED MANAGEMENT

Inspired by the acclimatization societies and botanic gardens of the 1800s, and by the efforts of the US Department of Agriculture in the early 1900s, Australian scientists conceived the idea to replace Australian vegetation at a continental scale with exotic pasture species. Australia's pasture plant introduction scheme constituted the world's largest movement of genetic material in two of the world's largest plant families: Poaceae- the grasses and Fabaceae – the pea family. However, until I recognised the magnitude and legacy of this program (Cook & Dias 2006), it had never been described in its entirety nor had its impacts analysed. Together with our librarian, Lesley Dias, I analysed the full records of the importation of over twice as many grass and legume species as occur naturally on the entire continent of Australia – more than 20 % of all the world's species of grasses and legumes. We showed that not only did many become declared noxious weeds, but that the weed science community was almost completely unaware that pasture agronomists were deliberately introducing these species. Similarly most pasture agronomists expressed no awareness of the negative impacts of their introductions. I concluded that much of the problem lay in the narrow focus of the researchers involved in this program over its 70 to 80 year history. Our analysis followed ground breaking work by Lonsdale (see Cook and Dias 2006), but we showed that his analysis had barely started to address the full magnitude of deliberate plant introductions to Australia.

Theoretical studies in the late 1980s had convincingly demonstrated that while most weed control endeavours focused on major infestations and worked outwards towards small new infestations, far better control and use of resources would be achieved by reversing those priorities. I led an analysis of the control of the wetland weed *Mimosa pigra* in Kakadu National Park (Cook *et al.* 1996), and showed that this paradigm shift in allocation of weed control resources had successfully kept many thousands of square kilometres of potential habitat free of the weed, in marked contrast to areas outside the park. Working with a range of stakeholders, I applied the principles of these scientific advances to develop a new strategic approach to the management of *Mimosa pigra* across northern Australia (Cook 1997, 1998). This approach integrated biological control with chemical, mechanical and ecological, together with a research strategy. I found through a re-examination of historical records that it was highly likely that *Mimosa pigra* had been introduced as a potential forage plant (Cook 2008).

STRUCTURAL STABILITY IN CRACKING CLAY SOILS

For my Ph.D. thesis, I showed that structural stability of cracking clay soils declined under cropping and that this was associated with declining organic carbon levels and with increasing exchangeable sodium levels. Both factors are often associated with structural stability, but disentangling the two, I showed that exchangeable sodium was the causal factor in these high clay soils. Further, soil erosion and the progressive exposure of deeper soil layers was the likely cause of the increasing sodium levels and for the clays to be increasingly dispersive, which reduced the rates of water flow through the soils. I developed a new index of soil sodicity which allowed a general relationship to be developed between soil structural stability and sodium levels, whereas previously these relationships were soil type specific (Cook and Muller 1997). My Ph.D. supervisor followed up my development of methods of assessing structural stability of cracking clay soils and I contributed to two methodological papers (So & Cook 1993, So, Cook & Raine 1997).

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6. THE DYNAMICS OF FIRE AND VEGETATION IN NORTHERN AUSTRALIA

THE KAPALGA FIRE EXPERIMENT

The Kapalga fire experiment was conducted in the early 1990s, when fire in northern Australian savannas was poorly understood by European land managers and policy-makers. We introduced this experiment in a review paper that described the context and approach of what was possibly the largest replicated experiment in the world (Andersen *et al.* 1998). The book that that synthesized the Kapalga results - Fire in Tropical Savannas was the first major text on fire ecology in northern Australia (Andersen *et al.* 2003). This work was revolutionary in that it was multi-disciplinary, used a landscape scale replicated experiment, and had as its primary focus the conservation of natural ecosystems, in marked contrast to decades of previous scientific research in northern Australia which focused on agricultural development. I was lead author of the chapter describing the field site and the experiment (Cook and Corbett 2003) and my chapter on biogeochemical cycling set the scene for a revolution in fire management in northern Australia (see section 8). There, I argued that patchy fires could reduce greenhouse gas emissions (Cook 2003). The synthesis chapter examined the effects of fire on catchment processes, vegetation structure and fauna and brought attention to the deleterious impact of the regime of very frequent fires across northern Australia (Andersen et al. 2003b). Our paper summarizing the implication of the Kapalga experiment (Andersen *et al.* 2005) concluded that much of the savanna biota is remarkably resilient to fire, even of high intensity, with the exceptions being riparian vegetation and associated fauna as well as small mammals. The provision of long unburnt habitats was critical to conservation of small mammals which are in decline across northern Australia. This remains a conservation challenge.

FIGURE 5: EARLY DRY SEASON FIRE AT KAPALGA

THE MUNMARLARY FIRE EXPERIMENT

The Munmarlary fire experiment was established in the 1970s on a much smaller scale than Kapalga to investigate fire and production forestry within what is now Kakadu National Park. I contributed to a synthesis of results from this research which demonstrated the substantial impacts of fire frequency on vegetation structure and diversity (Russell-Smith *et al.* 2003b). In my earliest studies of fire and vegetation dynamics in northern Australia, I showed that, surprisingly, epiphytic orchids could survive in woodlands exposed to frequent fires, but had a lower density of host trees of which it colonised a smaller proportion, and at fewer sites on each colonised tree (Cook 1991).

GENERAL FIRE ECOLOGY AND MANAGEMENT

Fire suppression has been a dominant paradigm in landscapes colonised by Europeans, but in Williams and Cook, 1998, we describe the changing emphasis towards the use of fire as a key tool for managing natural ecosystems and discuss its impact on trees in Kakadu National Park.

The Top End of the Northern Territory is dominated by the native annual grass *Sorghum intrans*. It senesces promptly at the end of the wet season (Cook & Heerdegen 2001), and produces highly combustible fuel for savanna fires. Fires reduce the proportion of seeds that germinate and establish. When fire intensity is high, such as around fallen trees, the species can be eliminated from small patches (Andersen et al. 2008). However the success of this species is assured by the much greater impact of fires on other species that compete for water, space and light (Cook et al. 1996). The vegetation structure of the mesic savannas of the Northern Territory contrasts markedly with that of areas with the same mean annual rainfall in West Africa (Cook & Mordelet 1997). This may be due to the differences in the seasonality of rainfall – an issue explored further by Liedloff & Cook (2007, 2010) - or due to differences in the biology of the vegetation. For example the dominance of eucalypts in Australian savannas appears to be due to the ability of the fastest growing individuals to escape the fire trap (Bond et al. 2012).

One of the major challenges facing fire management in northern Australia has been the disruption of traditional Indigenous fire management practice since colonisation (Russell-Smith *et al.* 2003c). These problems can be addressed through landscape scale research aimed at delivering multiple benefits (Williams *et al.* 2009).

Studying sites along the north-south rainfall gradient in the Northern Territory, we showed that tree height and density decreased systematically with decreasing rainfall, and increasing soil clay content (Williams et al. 1996). Throughout this region fires are frequent with the smallest and largest trees most affected (Williams et al. 1999). Non-eucalypts are more sensitive to fire than the dominant eucalypts. *Erythrophleum chlorostachys,* a common non-eucalypt in the northern savannas, provides a valuable niche timber, but due to its slow growth rate and fire sensitivity, has a sustainable harvest of only 1.8 trees per km^2 per year (Cook et al. 2005).

I studied the implications of fire exclusion during the rehabilitation process following bauxite mining in northern Australia and found that fuel build up was extreme due to both greater litter fall from trees and lower decomposition rates than typical in unmined ecosystems (Cook 2012). I argued that historic paradigm of fire suppression was leading to an unacceptable fire hazard, and that fire needed to be incorporated into the rehabilitation process to ensure the ability of the vegetation to blend with the surrounding landscape.

FIGURE 6: *SORGHUM INTRANS* IN FLOWER

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FIGURE 7 FIRE IN SPINIFEX AND ACACIA SHRUBLAND

7. ASSESSMENT AND MANAGEMENT OF GASEOUS EMISSIONS FROM SAVANNAS

PRIMARY DATA

I collaborated with atmospheric chemists to provide the first comprehensive quantification of emissions from Australian savanna fires (Hurst *et al.* 1994). This built upon my research into the effect of combustion of savanna fuels on nutrient dynamics (Cook 1994). I contributed to the development of the methodology for accounting for non-Carbon dioxide gases from the Agriculture sector for the newly established National Greenhouse Gas Inventory (NGGI) in 1994, with input to the development of methods for estimating emissions from field burning of agricultural residues as well as from savanna and temperate grassland burning (Cheng et al. 1994). In 2001, we revised the savanna burning methodology for the 1999 NGGI to include improved estimates of areas burnt and of fuel loads (Meyer and Cook 2001).

The emissions of nitrous oxide and methane from savanna fires comprise 13 % of all Australian emissions from the Agriculture sector, and we calculated that the CO_2-equivalent emissions from savanna burning were of similar magnitude to those from all fossil fuel combustion in Australia (Hurst et al. 1994). We showed that savanna fires have less smouldering combustion than southern Australian forest fires, probably due to drier and finer fuels in the savannas (Hurst *et al.* 1996).

In examining the air quality affecting the city of Darwin, we found that savanna burning contributed fine particle pollution with emissions being comparable to the fossil fuel emissions affecting major Australian cities (Denlay *et al.* 2000). Evidence based on overseas data indicated that these savanna fires may also be major sources of carcinogenic dioxin compounds, prompting the Australian government to investigate the problem. Analysing ambient air and fresh smoke samples, we showed that the emissions had been greatly overestimated by relying on emission factors derived from overseas work (Meyer *et al.* 2007a; b).

FIGURE 8: GARRY COOK (RIGHT) AND MICK MEYER (CENTRE), COLLECTING SMOKE FOR ANALYSIS

IMPLICATIONS FOR MANAGEMENT

In a number of papers, I developed the argument that patchy, early dry season fires could be used to reduce the greenhouse gas emissions while achieving other management goals (Cook et al. 1995, Cook 1996, Cook 2003). At the time, the land management community was mostly focussed on fire management for protection of life, property and biodiversity, and the issue of fire management for greenhouse gas abatement was a radical idea. Much further research and lengthy discussions were required for our science to impact northern Australian land management, but the idea has grown to revolutionise the drivers behind fire management across much of remote northern Australia. Meanwhile, our reports to government provided convincing evidence that our research had shown that previous concerns about the magnitude of carcinogenic dioxin emissions from Australian bushfire were unjustified (Gras et al. 2004, Meyer et al. 2004).

The mounting pressure to reduce greenhouse gas emissions became an important means of finding resources to tackle the increasingly recognised deleterious effects of the regime of very frequent fires. This regime had arisen because of the effects of colonization on Indigenous burning practices and the extensive abandonment of land (Russell-Smith *et al.* 2003c). We built an argument in support of Indigenous fire management (Gorman et al. 2007). However, for funding to be provided to support such fire management much work was required to reduce the uncertainty in the estimates of greenhouse gas emissions. We showed that improvements to fire maps and fuel accumulation curves were two critical issues (Russell-Smith *et al.* 2003a). Following much research in remote Indigenous lands, many of these issues have been resolved (Russell-Smith *et al.* 2009).

The mechanism by which specific changes in fire management could lead to reduced greenhouse gas emissions (Cook and Meyer 2009) was based on two key findings. Firstly was the evidence from Hurst et al. (1994) that emission factors did not vary seasonally. This was supported by recent work of Meyer et al. (2012). Secondly, the non-combustion pathways for fuel decomposition produced markedly less methane and nitrous oxide than did combustion. Termite consumption of fuel was the most likely source of methane emissions in the absence of combustion. Work by Hizbullah Jamali, a PhD student whom I co-supervised showed that methane emissions from termites were far less than from fires (Jamali *et al.* 2011a; Jamali *et al.* 2011b).

In an increasingly carbon-constrained world, understanding the interactions between vegetation dynamics, biodiversity, fire regimes and carbon dynamics is becoming increasingly important. In a review paper I led, we showed that after vegetation clearing, and livestock emissions, improved management of the fire emissions and carbon stocks of rangelands and savannas was the next largest potential source of greenhouse gas abatement across most of continental Australia (Cook et al. 2010). We explore the issues of fire management for greenhouse gas abatement across Australia in papers by Williams et al. (2012) and Bradstock et al. (2012).

In the latest volume of Australia'a leading fire ecology text, Flammable Australia, we describe how Indigenous fire management in northern Australia has gone from being ignored by science and suppressed by policy to being actively supported to achieve environmental and social outcomes (Cook et al. 2012). The partnership between western scientists and Indigenous people in conducting the appropriate research was critical to that transition. Heckbert et al. (2008, 2009) showed, through a combination of ecological and economic modelling that improved fire management had considerable potential financial benefits to remote communities across northern Australia.

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8. CARBON STOCKS AND DYNAMICS IN SAVANNAS

MODELLING THE DYNAMICS OF SAVANNA VEGETATION AND VEGETATIVE CARBON STOCKS

I collaborated with an ecological modeller, Adam Liedloff to develop the FLAMES computer simulation model. The model is a synthesis of our understanding of tree water use (Cook *et al.* 2002), the effects of fire on tree survival and carbon stocks (Cook *et al.* 2005), grass and fuel dynamics (Cook 2003) and greenhouse gas emissions (Cook et al. 1995). FLAMES enables extrapolation of the results of the Kapalga fire experiment to other management regimes and locations. Thus it was critical to enabling that experiment to have much greater impact across the region. FLAMES is still the only model of the dynamics of Australian savanna that enables the interactive effects of fire management decisions and rainfall variability to be examined for tropical savannas using robust modelling of tree demography. In our first paper describing the results of the model, we showed that fronting fires, such as are often used by land managers reduce tree density much more than do point source fires that produce an elliptical pattern of fire spread typical of wildfires (Liedloff and Cook 2000). Our next paper showed that as fire regimes become increasingly severe, tree basal area will reduce, and the proportion of more sensitive tree species will decline (Cook and Liedloff 2001). Nevertheless, a regime of one fire every two years on average, as is typical in the mesic savannas of northern Australia, will enable persistence of tree stands.

A key issue in examining the impact of reducing the severity of fire regimes is understanding the ultimate carrying capacity of the landscape. Because the dominant trees in the region are not deciduous, but use water all dry season, it is the dry season water availability that sets the ultimate carrying capacity. We developed new mathematical relationships between stem size and water use to enable scaling up to tree stands (Cook et al. 2002) and showed that the FLAMES model could reproduce the declines in tree stand density observed down the rainfall gradient from about 1600 mm to 450 mm mean annual rainfall (Liedloff and Cook 2007).

In a special issue of Australian Journal of Botany devoted to carbon sequestration in northern Australia, I presented research that I had led on carbon budgets in frequently burnt savannas (Cook *et al.* 2005). The work showed that estimation of carbon sequestration from simple field measurements agreed with estimated derived from considerations of water use efficiency and isotopic discrimination by trees. The estimates we derived were consistent with other derived independently and indicated that there is potential for managing savanna landscapes to increase carbon stocks (Williams *et al.* 2005; Williams *et al.* 2004). Multiple-constraints models are one approach to improving estimates of carbon sequestration potential of these systems (Barrett *et al.* 2005).

Australian savannas are generally intermediate between the neotropics and African savannas in the relative contribution of C_4 grasses to net primary productivity (Lloyd *et al.* 2008). Our modelling showed how the savannas are carbon sinks most of the time, but are much larger carbon sources occasionally (Liedloff and Cook 2011). This demonstrates the need for caution in interpreting the most careful field studies and is critical to correctly predicting the long-term carbon sequestration rates. Recent work suggests that earlier work may have overestimated carbon sequestration rates (Murphy *et al.* 2009). Using the Century soil carbon model, we showed that a fire frequency of one low intensity fire every five years was optimal for storing carbon in soils in the mesic savannas (Richards *et al.* 2011). Improved data on soil carbon dynamics requires a better knowledge of tree and grass root production and distribution. We have shown that there exists considerable lateral variation in root distribution in savannas (February et al. 2012).

We documented the systematic decrease in tree cover and height along the gradient of decreasing rainfall south from Darwin (Williams *et al.* 1996). Although frequently burnt savannas dominate this landscape, monsoon forests exist as an alternative fire-intolerant ecosystem. There is much evidence that the boundaries between these ecosystems have fluctuated, but precise determination of that history is challenging (Bowman and Cook 2002; Bowman *et al.* 2004). An improved understanding of the effects of charring on carbon isotopic ratios will be helpful to improving the use of this tool for determining historical vegetation change (Krull *et al.* 2003).

FIGURE 9: AGING CATTLE YARDS, CAPE YORK PENINSULA, QUEENSLAND

MODELLING THE DYNAMICS OF SAVANNA VEGETATION AND VEGETATIVE CARBON STOCKS.

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