



Humans, megafauna and environmental change in tropical Australia

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Humans, Megafauna and environmental change in tropical Australia

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Abstract

Debate concerning the environmental impact of human arrival in Australia has continued for more than a century. Here we review the evidence for human impact and the mechanisms by which humans may have affected the environment of tropical Australia. We limit our review to tropical Australia because, over three decades ago, it was proposed that the imposition of an anthropogenic fire regime upon human occupation of the Australian continent may have resulted in profound changes in regional vegetation and climate across this region. We conclude that ecological processes and vegetation-fire-climate-human feedbacks do exist that could have driven a significant shift in boundary conditions and ecosystem state at the sub-continental scale through the sustained imposition of an anthropogenic fire regime over tens of millennia. These potential feedbacks operate through the inhibition of forest expansion both directly, by targeted burning at established forest edges and newly irrupted forest patches, and indirectly, through lengthening of the dry season as a result of changes to the timing of burning. However, the impact of any such anthropogenic forcing may have been entirely overshadowed by the effects of natural climate change and variability, as well as the generally low nutrient status of Australian soils. A robust assessment of the degree to which the environment of tropical Australia at the large scale has been modified from its 'natural' state as a result of human occupation will require new, coordinated collaborations between indigenous traditional landowners, archaeologists, anthropologists, geochronologists, geoscientists, ecologists, climatologists and modellers.

1. Introduction

‘Oh no, not again’ was the last thought that went through the mind of a bowl of petunias as it fell to the ground on an alien planet in ‘The Hitchhiker’s Guide to the Galaxy’ (Adams, 1979: 103). Whatever else the petunias thought, it is clear that they had been in the same position previously. And so it is with the debate surrounding the environmental impact of the arrival of humans in Australia.

Well over a century ago, it was known that a number of large, now extinct, marsupial species had once been extant in Australia, and so began the debate as to whether climate change or ‘Australoid wielders of clubs and throwing sticks’ (Owen, 1877: cited in Horton, 1980: 86) were responsible for their demise (see Horton, 1980 and Johnson, 2006 for reviews).

Over four decades ago, Merrilees (1968) and Jones (1968) independently postulated that humans were implicated in megafaunal extinction, and Jones (1968: 189) suggested that it was likely that humans had arrived in Australia much earlier than previously thought: ‘For the present an antiquity of 30,000 years is a reasonable claim’. Jones (1969) elaborated on his earlier work proposing that humans had manipulated the environment since arrival through ‘firestick farming’.

Over three decades ago, Kershaw (1974, 1986) first suggested that Aboriginal burning had led to a sustained decline in fire-sensitive gymnosperm taxa and an increase in sclerophyll and grass taxa. This conclusion was based on a pollen record from a single site: Lynch’s Crater on the Atherton Tablelands of north Queensland. Also over three decades ago, Horton (1982: 238) noted that ‘There have been a few criticisms of this general thesis [that humans caused megafaunal extinction]’. On reviewing the information available at the

time, he found little evidence to support human agency in either megafaunal extinction (Horton, 1980) or modification of vegetation through anthropogenic manipulation of fire regime (Horton, 1982).

Over two decades ago, Flannery (1990) proposed that after megafaunal extinction brought about by 'blitzkrieg' over-hunting, humans responded to subsequent increased fuel loads by firestick farming, thereby assisting in the maintenance of biodiversity in medium-sized mammals and some plants. Release from this anthropogenic fire regime upon arrival of Europeans resulted in another 'trophic cascade' of extinctions. Thermoluminescence (TL) and optically stimulated luminescence (OSL) dating was used by Roberts *et al.* (1990, 1994) to push back the proposed date of human occupation of mainland Australia to between 50 and 60ka, while Nanson *et al.* (1992) used TL and uranium-series dating methods to document a number of wet and dry phases in central and south-eastern Australia over the last 300 ka. Miller and Magee (1992) went further and proposed that Lake Eyre is dry in the current interglacial as a result of substantial modification of vegetation across tropical Australia following the imposition of an anthropogenic fire regime.

Over a decade ago, combinations of more robust radiocarbon pretreatment techniques, OSL and other dating techniques continued to suggest occupation of Australia occurred considerably before 40ka (Turney *et al.*, 2001a, Bird *et al.*, 2002, Bowler *et al.*, 2003), with some claims of occupation close to 60ka (Roberts *et al.*, 1998, Thorne *et al.*, 1999). Roberts *et al.* (2001) used OSL and uranium-series methods to date articulated megafaunal remains and their burial sediments at a number of sites to infer that extinction occurred in the interval of 40-51ka. Miller *et al.* (1999) and Johnson *et al.*, (1999) suggested extinction of the large flightless bird *Genyornis newtoni* and large-scale vegetation change was a direct result of human

arrival and the imposition of an anthropogenic fire regime at 45-55ka, perhaps underlain by natural climate change. We observe that, while there is abundant evidence for early human occupation across the tropical north, from the Kimberley to Cape York (Figure 1), there are comparatively few well-dated megafauna sites in tropical Australia. However, the widespread existence of notionally 'Late Pleistocene' megafaunal remains in the region (Field *et al.*, 2008: Figure 12) suggests that they were a significant component of the fauna encountered by humans on arrival.

At each stage of the debate in the twentieth century, claims for earlier arrival of humans on the Australian mainland, as well as the assertion that humans were responsible for megafaunal extinction and/or significant ecosystem modification through firestick farming, have been vigorously contested. Opposition has generally taken the form of disputing the reliability of the dating, the stratigraphic association between dated material and physical evidence, the selective use of evidence, conflicting evidence and/or insufficient evidence, coupled with the general observation that fire was a significant factor in tropical Australia prior to human arrival (Horton, 1980, 1982, O'Connell and Allen, 1998, Bowman, 1998, Mulvaney and Kamminga, 1999).

It is not our purpose to review in detail the development of the debate on the timing of human arrival and megafaunal extinction, though we do summarize debate from the last decade. Rather, we focus instead on the development of two divergent, testable, end-member hypotheses for the impact of human occupation on the landscape-scale ecology and climatology of tropical Australia. In particular:

- (i) that human dispersal through and occupation of tropical Australia had little or no impact on regional ecosystems and climate; or

- (ii) that human dispersal through and occupation of tropical Australia either rapidly or cumulatively over many millennia, resulted in a profound change to regional ecosystems and climate.

We focus on the literature that bears on the development of these hypotheses rather than on making a detailed assessment of the burgeoning literature surrounding the timing of human arrival and human impact on the environment following arrival. We constrain our area of interest to the Australian monsoon tropics as defined by Bowman *et al.* (2010): those areas of Australia that (currently) receive more than 85% of rainfall between November and April.

2. Timing of human colonization

Early human occupation at sites in tropical Australia such as Ngarrabullgan, Nauwalabila 1, GRE-8, Riwi and Carpenter's Gap has been established since the 1990s, although exactly how early remains the subject of debate (e.g. O'Connell and Allen, 2012). In the last decade, further sites with dates interpreted as suggesting human occupation at or before 40ka have been identified across tropical Australia: Nawarla Gabarnmang (David *et al.*, 2011), Parnkupirti (Veth *et al.*, 2009) Nonda Rock (David *et al.*, 2007), and GRE-8 (Slack *et al.*, 2004) (Figure 1) – as well as Papua New Guinea (e.g. Summerhayes *et al.*, 2010). While the absolute antiquity of initial colonization remains contested, there appears to be emerging consensus that humans had arrived in Australia and had expanded 'archaeologically instantaneously' across much of mainland Australia and Papua New Guinea by not later than 44-46ka (Hiscock, 2008, O'Connell and Allen, 2012).

There is little evidence upon which to base inferences as to the number or size of colonization events or the likely population after colonization. Nevertheless, O'Connell and Allen, (2012: 12) contend that after arrival and 'despite their inherent capacity for growth, Sahul populations remained surprisingly small and spatially concentrated in persistent 'sweet spots'. Williams (2012) used 2996 radiocarbon dates from 800 archaeological sites in Australia to explore occupation trends from 40ka to the present. While subject to considerable uncertainty, the results from that study suggest approximately constant levels of occupation from the beginning of the record, with occupation levels increasing into the Holocene (see also Johnson and Brook, 2011).

For the purposes of this paper, we conclude simply that humans had arrived on the Australian mainland by at least ~45ka (Hiscock, 2008, Hiscock and Wallis, 2005), a date now consistent with the timing of migration through mainland and island SE Asia (Higham *et al.*, 2009, Demeter *et al.*, 2012) and Papua New Guinea (Summerhayes *et al.*, 2010). We further conclude that within a few millennia, humans had dispersed throughout mainland Australia (O'Connell and Allen, 2012), with the possible exception of parts of the arid interior (Smith *et al.*, 2008).

3. Megafaunal extinction: The Rasputin Syndrome 7

Recognizing that claims for earlier arrival may be correct, the apparent consensus that humans had arrived on mainland Australia by ~45ka has marginally narrowed the range of debate concerning the timing and cause of megafaunal extinction: humans and megafauna clearly co-existed for a period of time, and hence humans could potentially have been responsible for at least a component of megafaunal extinction. Gunn *et al.* (2011) report the existence of rock art in Arnhemland that appears to depict the extinct giant bird *Genyornis*

newtoni (Figure 2) and Flannery (2012) reports rock art in the Kimberley region that has been interpreted as depicting the extinct marsupial lion (*Thylacoleo carnifex*). Both imply direct co-existence (for other rock art examples see Murray and Chaloupka, 1984). If humans and megafauna did overlap in time, it is difficult to envisage a situation where humans and megafauna could co-exist on the same continent without any form of interaction.

Correlative evidence in the last decade supporting rapid extinction coincident with human arrival has come from Tasmania (Turney *et al.*, 2008, Gillespie *et al.*, 2012) and north Queensland, the latter inferred from the abrupt decline in *Spororomiella* fungal spores – indicative of mega-herbivores – in the Lynch's Crater record at around 41ka, coincident with an abrupt increase in charcoal (Rule *et al.*, 2012). At the site of Cuddie Springs in western New South Wales, claims for survival of megafauna for at least 10 ka after human arrival (Field *et al.*, 2008) have been countered by Grün *et al.* (2010), who concluded from direct electron spin resonance (ESR) and uranium-series dating of megafauna teeth and bones that the Cuddie Springs material had been reworked from older deposits. This evidence is 7 consistent with earlier suggestions of sediment disturbance (Roberts *et al.*, 2001, Gillespie and Brook, 2006).

Arguments against a human-induced extinction 'event' have continued to appear in the last decade (Wroe and Field, 2006, Field and Wroe, 2012). Price *et al.* (2011) used OSL and uranium-series dating techniques to constrain the ages of multiple taxa in the Darling Downs in southeastern Queensland and concluded that 15 taxa disappeared from the local record over a staggered time interval between 122 and 83ka ago. The authors considered that megafaunal extinction was a process underway for some time prior to the arrival of humans, in response to a long-term trend to greater aridity. Faith and O'Connell (2011) re-examined

the data of Prideaux *et al.* (2010) from Tight Entrance Cave in southwest Western Australia and concluded that the evidence was consistent with environmentally-mediated extinction, with uncertainties in the dating making it impossible to exclude the possibility that the majority of megafauna were extinct by the penultimate glacial maximum (MIS-6), but that uncertainties in the dating made it impossible to discriminate between gradual attenuation over the last few glacial cycles and synchronous extinction between about 50 and 40ka. By contrast, Prideaux *et al.* (2010) noted that the MIS-6 had no lasting impact on the regional fauna, which argued against climate change as the sole or primary driver of the extinction. The latter interpretation is also consistent with the only other faunal sequence in Australia with a paired climate record extending back 300ka – namely, Cathedral Cave in South Australia (Prideaux *et al.*, 2007).

The absence of clear evidence of human predation on, or consumption of megafauna, also continues to be advanced as an argument against human involvement in megafaunal extinction (Davidson, 2012), although this issue had earlier been addressed by Brook and Johnson (2006), Roberts and Brook (2010) and, more recently, by Surovell and Grund (2012) who conclude that such evidence in Australia is likely to be very rare even in comparison to evidence from parts of the world occupied by humans more recently (e.g. North America and New Zealand).

Miller *et al.* (2005b), building on their earlier work, concluded that *Genyornis* became extinct as a result of anthropogenic burning between 50 and 45ka. On the other hand, Murphy *et al.* (2010), using the same stable isotope analyses of *Dromaius* eggshell reported by Miller *et al.* (2005b), concluded that ecosystem change began before the arrival of humans and could be better modelled as a gradual change in response to overall decreasing water

availability between 80 and 30ka. Hence, ecosystem change due to the imposition of an anthropogenic fire regime was not necessarily the primary cause of the extinction of *Genyornis*.

Gregori Rasputin, a monk and a controversial member of the court of the Russian Tzar through the early part of the twentieth century, was variously poisoned, shot and clubbed to death in 1916. Which of these violent actions caused his ultimate demise remains a subject of debate and it is also possible that he survived the initial attempts on his life, lingering on for a period before finally succumbing to drowning after being dumped through a hole in the ice on the Neva River. And so it is with megafaunal extinction. The potential drivers of extinction can be summarized as direct human impact in the form of direct predation or selective predation of juveniles (Brook and Johnson, 2006), indirect anthropogenic ecosystem change through modifications to fire regimes, introduced disease or natural climate change (for a review see Johnson, 2009). It has been argued that extinction followed rapidly on the heels of human occupation (Roberts *et al.*, 2001, Miller *et al.*, 2007, Turney *et al.*, 2008, Gillespie *et al.*, 2012) but the possibility cannot yet be excluded that some of the megafauna that were extant at human arrival lingered on for some time (Johnson, 2005, 2006, Field and Wroe, 2012). In that context, it is worth noting that for communities subject to non-pluvial climate regimes there is a strong correlation between precipitation, plant productivity and both total herbivore biomass (Coe *et al.*, 1976) and large herbivore diversity (Olf *et al.*, 2002); Thus it is likely that megafaunal populations were already in decline due to increasing aridity at the time of the first human occupation. Such declining populations would be also be expected to have been more sensitive to anthropogenically-induced changes in environment (or direct hunting pressure) than would have been the case for a

more stable or expanding megafaunal population (Hubbell, 2001). Thus, the two hypotheses are not necessarily exclusive.

Field and Wroe, (2012: 69) conclude ‘that the megafaunal extinction debate in Australia has a long way to go before even the most fundamental of questions are convincingly resolved’. For the purposes of this paper, the details of the mechanism and timing of extinction are not important, except insofar as determining whether human agency was involved. This is because mega-herbivores in modern tropical environments are capable of a significant degree of ‘engineering’ of the ecosystems they inhabit (Asner *et al.*, 2009, Staver *et al.*, 2009, Midgley *et al.*, 2010, Tanentzap and Coomes, 2012). Mega-herbivore browsers are partly responsible, along with fire and other edaphic controls, for the maintenance, and in some cases extension, of open vegetation types. The removal of megafauna from Australian tropical ecosystems is therefore likely to have resulted in some degree of ecological transformation (Johnson, 2009), and this would be considered anthropogenic if humans were responsible, in part or in whole, for megafaunal extinction.

We conclude that the results of Roberts *et al.* (2001), which were based on dating of articulated extinct megafaunal remains only, do indicate that megafauna were dramatically reduced in numbers from, to use the terminology of Johnson (2005), ‘palaeontological visibility’ to ‘archaeological visibility’ during a period of a few millennia following human arrival. As a result, and regardless of whether they became literally extinct at that time, megafauna were thereafter unlikely to be able to exert a significant influence on vegetation structure in tropical Australia. We do not speculate in detail on the likely cause of this reduction in numbers, other than to note that, of the mechanisms identified, climate change as the sole driver of extinction represents the least likely possibility; a conclusion that has

previously been reached by several authors (Owen-Smith, 1987, 1989, Miller *et al.*, 2007, Brook and Bowman, 2004, Prideaux *et al.*, 2007, 2009, 2010, Murphy *et al.*, 2012).

While we acknowledge a long-term trend to increasingly arid conditions in some parts of Australia over the last 300ka (Nanson *et al.*, 1992, Magee *et al.*, 2004, Wroe and Field, 2006, Webb, 2008), there is no evidence for 'sharp, intra-decadal through millennial-scale fluctuations in temperature and precipitation' (O'Connell and Allen, 2012: 7) during the period of interest through Marine Isotope Stage 3 (MIS-3: 28-59ka). High latitude northern hemisphere ice core records and temperate northern hemisphere speleothem records do indicate significant millennial-scale variability associated with Dansgaard-Oeschger (D/O) cycles (e.g. Weninger and Jöris, 2008). However, the expression of D/O events is very muted in the southern hemisphere ice core climate records from Antarctica and the signal associated with D/O events is likely to be even more muted in low latitude locations such as tropical Australia. Hesse *et al.* (2004) concluded that the 'largest changes in circulation patterns [in Australia] over the glacial cycle probably occurred in the location and/or intensity of summer tropical convergence in northern Australia', but there is no evidence to suggest that climate variability in MIS-3 on any temporal scale was more extreme than at any time prior or subsequent to the interval during which extinction occurred.

The discussion above leads us to conclude that human occupation of the continent did play a direct and decisive, if currently unquantified, role in the rapid reduction of megafaunal populations to levels at which they could no longer exert an influence on the vegetation structure of tropical Australia. The possibility cannot be excluded, however, that other environmental factors may have played a role - as yet unquantified - in eventual megafaunal extinction (Roberts *et al.*, 2001, Koch and Barnosky, 2006, Prideaux *et al.*, 2010, Lorenzen *et*

269 *al.*, 2011, Prescott *et al.*, 2012). In the absence of other human impacts, extinction of the
270 megafauna may have itself led to modifications to ecosystem function through changes to
271 the nature and abundance of fuel loads and changes in the density of woody vegetation
272 through release from browsing pressure.

273 4. Ecological and climatological impacts of occupation

274 Much of eastern tropical Australia has been argued to fall into the category of ‘ecosystem
275 uncertain’, where the present-day climate is such that a range of vegetation states are
276 potentially possible (Bond and Keeley, 2005; Staver *et al.*, 2012; Hirota *et al.*, 2012). Although
277 such results have been interpreted as supporting the notion of forest and savanna
278 representing alternative steady states in such climates, with the latter induced and then
279 maintained by fire (e.g., Hoffmann *et al.*, 2012; Murphy and Bowman, 2012), it is important
280 to recognise that factors such as soil cation status which are known to sometimes be
281 substantially higher for forest and savanna vegetation formation types (e.g. Cochrane, 1989)
282 are not accounted for in such ‘climate only’ simulations. Similarly, soils underlying more
283 open savanna formation types also tend to have a lower cation status than for nearby
284 woodier savanna formations (Lopes and Cox, 1977) and given the low fertility of Australian
285 tropical soils in general (McKenzie *et al.*, 2004) edaphic factors may account for much of the
286 region currently being savanna rather than forest. Nevertheless, significant large-scale
287 anthropogenic modification to vegetation cover sustained over many millennia to the
288 present day is at least a possibility. Human occupation could potentially have modified the
289 vegetation cover of tropical Australia in three ways, with all potential mechanisms operating
290 through an influence on the dynamics of tree–grass competition.

291 First, the removal of any browsing megafauna would improve opportunities for
292 establishment of trees and shrubs (Bond and Keeley, 2005, Staver *et al.*, 2009). Second, and
293 alternatively, if the bulk of the megafauna were browsers rather than grazers, then an
294 increased standing crop of herbaceous biomass may have resulted, with increased fire
295 frequencies/intensities ensuing (Flannery, 2012). Third, any deliberate change in intensity,
296 number or timing of fires would also be expected to modify the recruitment opportunities
297 for trees and shrubs relative to grasses (Bond, 2008, Bond and Midgley, 2012, Lehmann *et al.*,
298 2011, Nano and Clarke, 2011, Prior *et al.*, 2009, 2010, Russell-Smith *et al.*, 2010, Scott *et al.*,
299 2012). A shift towards more trees, for example, is thought to potentially result in a positive
300 feedback, leading to further vegetation thickening as a result of the suppression of grass
301 growth and, hence, the ability to carry fire, and vice versa (Sankaran *et al.*, 2005, Bond and
302 Midgley, 2012, Higgins and Scheiter, 2012, Murphy *et al.*, 2012).

303 It is important to note that a change in the timing of fires does not necessarily imply a
304 change in the total burnt area, and hence a change in fire regime may not be reflected in a
305 simple change in charcoal abundance in sedimentary records (Mooney *et al.*, 2011). It is also
306 important to note that any anthropogenic modification to fire regime and land cover would
307 necessarily have occurred against a background of changes due to natural forcing primarily
308 associated with changes in atmospheric CO₂ (Bond and Midgley, 2012, Higgins and Scheiter,
309 2012) and climate from the time of human occupation to the present (Mooney *et al.*, 2011).

310 There is no doubt that the 'indigenous' (anthropogenic) fire regime in tropical Australia is
311 not the same as a 'natural', pre-human fire regime (e.g. Burrows and van Didden, 1991). In
312 the monsoon tropics of north Australia, a natural fire regime would likely have been low
313 frequency due to an absence of significant natural ignition sources (lightning) over most of

314 the seasonal cycle, but of higher severity due to fuel accumulation between the more
315 infrequent fire returns. Most recently, Bliege Bird *et al.* (2012) clearly demonstrated
316 substantial differences in fire regime between areas subject to indigenous fire management
317 and areas that are not subject to management, in the spinifex grasslands of northern Western
318 Australia. Areas under indigenous fire management are subject to more but smaller fires,
319 buffering climate-driven variability in fire size and resulting in increased patch richness,
320 diversity and evenness (Yibarbuk *et al.*, 2001, Yates *et al.*, 2008). Price *et al.* (2012) note that
321 the depopulation of indigenous land custodians from northern Australia in the early to mid-
322 twentieth century resulted in a shift from a larger number of small, early dry-season fires to
323 fewer but larger, more intense wildfires in the late dry season. Release from an indigenous
324 fire regime has also seen considerable additions to forest area across tropical Australia,
325 although this interpretation is complicated by the likelihood that increasing CO₂ or changes
326 in precipitation regime are also contributing to forest expansion (Brook and Bowman, 2006,
327 Donohue *et al.*, 2009, Bowman *et al.*, 2010, Tng *et al.*, 2012).

328 Archibald *et al.* (2012) have recently suggested that humans in Africa successively acquired
329 the ability to manipulate fire frequency and season prior to 100ka and, finally, fuel
330 connectivity with the advent of agriculture/pastoralism around 10ka. They conclude that, as
331 in Australia, a lightning fire regime was characterized by seasonal fire distributions different
332 from modern anthropogenic fire regimes, with major effects on the size and intensity of fires.
333 They also conclude that substantial human impact on total burned area was probably not
334 initiated until the middle Holocene in open landscapes, whereas humans could have altered
335 fire regimes in closed/dissected landscapes by around 40ka.

336 Research into the interactions between fire, indigenous or natural, on ecosystems in
337 northern Australia can directly examine a time window encompassing the last half-century or
338 so (for review see Bowman, 1998). The ecosystems that were present at the time of
339 European arrival are generally considered to be the benchmark for what is 'natural'. The
340 extent to which indigenous fire regimes that had been in place for tens of millennia prior to
341 European arrival had led to the modification of land cover in tropical Australia is currently
342 unknown, but is of critical importance because of the potential feedbacks between land
343 cover and climate that operate on a range of spatial scales and of timescales, from annual to
344 millennial and longer (Beerling and Osborne, 2006, Bond and Midgley, 2012).

345 It has been argued that extensive regional scale tree cover can exert a direct influence on
346 meso-scale climate (Shiel and Murdiyarso, 2009), with tropical forests recycling water by
347 transpiration at higher rates compared to grasslands (Zhang *et al.*, 2001) and extracting water
348 from greater depths within the soil (Hayden, 1998, Beerling and Osborne, 2006).
349 Vegetation–climate feedbacks have been suggested to exist for regions ranging from the
350 Amazon Basin (D'Almeida *et al.*, 2007) to the Sahel (Los *et al.*, 2006). Spracklen *et al.* (2012)
351 found that for 60% of the tropical land surface, including much of central Australia, air that
352 had previously passed over areas of extensive vegetation produced at least twice as much
353 rain as air that had passed over little vegetation in the few days prior to the rainfall. In similar
354 vein, recent studies in Australia have attributed regional reductions in rainfall to vegetation
355 clearing, where conversion of forest to croplands that could function similarly to shallow-
356 rooted grasslands (Pitman *et al.*, 2004, Deo, 2011).

357 Miller and Magee (1992) first proposed that the imposition of an anthropogenic fire
358 regime in northern Australia could have reduced tree/shrub cover across tropical Australia,

359 to the extent that the degree of penetration of monsoonal rains into the continental interior
360 was reduced, resulting in the anomalous comparatively dry state of Lake Eyre in the
361 Holocene (Magee *et al.*, 2004). Miller *et al.* (2005a) later used a modelling approach to explore
362 the potential feedbacks between vegetation and climate in tropical Australia assuming the
363 extreme scenarios of a pre-human landscape of “broadleaf deciduous trees on sandy loam
364 soils and landscape after occupation of “desert vegetation on sandy soil”. The study
365 concluded that tree cover in tropical Australia exerts a significant control on monsoon
366 penetration, with higher amounts of tree cover leading to deeper penetration of monsoon
367 rains into the continental interior. In contrast, Pitman and Hesse (2007), found little
368 response of the monsoon to changes in vegetation, a result subsequently criticized by Miller
369 *et al.* (2007) on the basis that Pitman and Hesse (2007) specified modern insolation for
370 Holocene simulations.

371 In another modelling study, Marshall and Lynch (2006) inferred only a muted response of
372 the monsoon to vegetation change, whereas the modelling results of Lynch *et al.* (2007)
373 suggested that late, high intensity fires could increase monsoon precipitation in modern
374 northern Australia by up to 31%, (although this response was obtained from an artificially
375 high burnt area of 90% and high severity fire events). The most recent and comprehensive
376 simulations to date, (Notaro *et al.*, 2011), assuming only a 20% reduction in vegetation cover,
377 found a non-significant effect of this vegetation change on peak monsoon period
378 precipitation (January to March) but a significant 40mm reduction in rainfall in the pre-
379 monsoon (October to December) season, thus effectively lengthening the dry season.

380 Nevertheless, even a 20% reduction in total vegetation cover as assumed by Notaro *et al.*,
381 (2011) may be not be realistic, as the real driver of change in rainfall is change in latent and

382 sensible heat fluxes associated with the anthropogenically-induced vegetation change (e.g.,
383 Grace *et al.*, 1998). And here we note that, contrary to some claims (e.g., Flannery, 2012),
384 savanna fires tend to accelerate rates of nutrient cycling (van de Vevjer *et al.*, 1999) with net
385 fire-induced nutrient losses usually minimal at a regional scale due to the subsequent return
386 of emitted nutrients through wet- and dry-atmospheric deposition (Delon *et al.*, 2012; Kugbe
387 *et al.*, 2012). Thus, with a stimulation of vegetative growth, if anything, latent heat fluxes may
388 actually be greater for invigorated savanna vegetation regrowing after low to moderate
389 severity fire events (Santos *et al.*, 2003) and even where large effects of long-term fire regime
390 on woody vegetation cover have occurred stand-level evaporation rates are minimally
391 affected (Quesada *et al.*, 2008).

392 The major source of natural ignition is lightning and Kilinc and Beringer (2007) found
393 that lightning strikes in the Northern Territory are concentrated in the wet season and during
394 transition periods between seasons. Very few dry season lightning strikes were observed.
395 They also found that lightning strikes were more common in grasslands relative to woodier
396 ecosystems. This was argued, at least in part, to be due to the higher sensible heat flux from
397 grasslands than surrounding vegetation types within the landscape mosaic and hence a
398 greater potential for convective activity directly above. Bowman *et al.* (2007) noted a link
399 between late dry season fires and rainfall with one explanation being the dynamic effects of
400 aerosols released by burning invigorating convection, with the formation of an enhanced and
401 higher cloud cover than would otherwise be the case: this leading to higher rainfall (Andreae
402 *et al.*, 2004; Lin *et al.*, 2006).

403 On balance, the studies cited above provide some support for the possibility that
404 anthropogenic fire regimes could have, over an extended period and through a number of

405 fire-biosphere-atmosphere feedbacks, resulted in an appreciably different climate and land
406 cover across northern Australia than would be the case had humans not occupied the
407 continent. We explore the mechanisms in the following section, but note the following,
408 inconclusive, evidence supporting this possibility:

409 (i) the most cited evidence for a change in fire regime following human arrival leading to
410 a change in vegetation comes from the record of Lynch's Crater (Kershaw *et al.*, 2007). In
411 this record, a sustained increase in charcoal flux at around the time of human arrival (Turney
412 *et al.*, 2001b, Rule *et al.*, 2012) is accompanied by a dramatic decrease in gymnosperm taxa
413 and concomitant increase in sclerophyll and grass taxa. It is also the case that fire-sensitive
414 *Callitris* species disappear from the record, probably before human arrival, but never to
415 reappear at similar levels of abundance despite having been abundant in the penultimate
416 glacial and last interglacial (Kershaw *et al.*, 2007). This observation has also been made for
417 the Lake Frome region by (Luly, 2001).

418 The interpretation of the Lynch's Crater record as indicative of a broad change in fire
419 regime in northern Australia is complicated by an observation originally made by Kershaw
420 (1976: 492): 'This area is climatologically sensitive and it may be that the vegetation changes,
421 and the climatic shifts implied by them, were exaggerated there as compared with the rest of
422 north-eastern Australia'. The rainforest or rainforest fringe areas that are typical of the
423 Atherton Tablelands are climatically atypical of northern Australia, which is dominated by
424 lowland sclerophyll woodlands and shrublands occurring on vast sand-sheets of low relief
425 (Ash, 1983, Shulmeister, 1992). It is therefore undesirable to extrapolate northern Australian
426 palaeoenvironments solely on the basis of the Atherton Tablelands pollen record as a

427 significant impact on vegetation cover at Lynch's Crater may not equate to a significant
428 impact on vegetation across the majority of tropical Australia.

429 A potentially more representative pollen record for tropical Australia is provided from the
430 marine sediment core (SHI-9014) of van der Kaars *et al.* (2000). This record, from the Banda
431 Sea and therefore sampling a broad area of northern Australia and the Sahul shelf (but also
432 including a southeast Asian component), is interpreted as indicating a significant expansion
433 of grassland and a concomitant decline in *Eucalyptus* in northern Australian and the Sahul
434 Shelf region from 37ka ago, sustained to the present-day. Further evidence for a sustained
435 change comes from the disappearance of *Olea* pollen, indicative of vine thickets, from
436 marine core MD98-2167 at around 45ka (Kershaw *et al.*, 2011). In neither of these cases are
437 changes in charcoal abundance closely associated with the changes in pollen abundance, nor
438 are there abrupt changes in charcoal abundance coinciding with initial human arrival.

439 (ii) As discussed above, the dominantly dry modern condition of Lake Eyre is anomalous
440 in the context of its record of previous episodes of filling under analogous climate
441 conditions (Magee *et al.*, 2004). More recent work on Lake Mega-Frome, which was last
442 connected to Lake Eyre 50-47ka ago and is also currently dry, has suggested a greater
443 importance for Southern Ocean sources, but still posits a significant influence from tropical
444 moisture sources in the Holocene in determining its state (Cohen *et al.*, 2011).

445 (iii) The carbon isotope estimates of the proportion of C₄ grass in the diet of both emus
446 and wombats, which suggested a mixed C₃ and C₄ diet prior to ~45ka and including the last
447 interglacial and penultimate glacial periods, indicate a permanent shift to a lower proportion
448 of C₄ biomass in the diet from 45ka until the present time (Miller *et al.*, 2005b, 2007). While
449 these results derive from more southerly latitudes than tropical Australia, they do imply a

450 large and permanent shift in environmental conditions across tropical Australia at some time
451 after 45ka.

452 (iv) In tropical Australia, tropical dry forest types, with no perennial access to water but
453 often with a measure of fire protection, extend in patches into regions of <600mm rainfall
454 (Fensham, 1996, Miles *et al.*, 2006) and are common but widely dispersed in regions that
455 receive >600mm (Figure 1). These patches have been shown to have both expanded and
456 contracted over adjacent areas in the recent past, suggesting there is no general soil-imposed
457 limit on their potential (local) distribution above 600mm rainfall (Bowman *et al.*, 1994).
458 Murphy *et al.* (2010) conclude that both fire and soil fertility control the relative distribution
459 of mulga and spinifex in the more arid interior.

460 Sankaran *et al.* (2005) has argued that in African savannas areas above 650mm are
461 'disturbance' savannas, where fire and/or herbivory are required to prevent canopy closure,
462 although Lloyd *et al.* (2008) have pointed out that there are other explanations for their
463 observations. Nevertheless, if we accept Sankaran *et al.*'s (2005) thesis, then the observation
464 of Archibald *et al.* (2009) is pertinent – that fires become uncommon in Africa when rainfall
465 exceeds ~800mm and canopy cover exceeds 40%. This is because, in the tropical Australian
466 context, Bond (2008; Figure 1) has demonstrated that, in contrast to African savannas,
467 modern Australian savannas fail to reach an African-type rainfall-determined maximum
468 cover below 650mm. Above this threshold, where closed canopy vegetation should (based
469 on the conclusions of Sankaran *et al.* (2005) for Africa), represent a much woodier stable
470 state in the absence of disturbance.

471 Thus Australian savanna continues to persist to a much higher mean annual rainfall than
472 Africa with one explanation being that long-standing indigenous fire regimes have resulted in

473 large areas of savanna in northern Australia maintained by fire-mediated feedbacks
474 preventing the return of the vegetation to an alternative, forest type, vegetation formation
475 (Warman and Moles, 2009; Lawes *et al.*, 2011; Murphy and Bowman, 2012). Nevertheless,
476 we add a note of caution that whilst the notion of forest and savanna representing two
477 alternative steady states is conceptually attractive but is contested (House *et al.*, 2003,
478 Lehmann *et al.*, 2011). We also note that Fensham *et al.* (2005) examined changes in woody
479 cover in the 500-800mm rainfall zone of central Queensland and found that neither fire nor
480 grazing exerted significant control, with variations in woody cover driven largely by
481 variations in relative rainfall since the 1940s.

482 In summary: (i) it has been suggested by some modelling studies that forest vegetation
483 can potentially exist over a larger area of tropical Australia than is currently the case, where
484 local soil conditions allow; (ii) current climate and fire regime clearly favour the maintenance
485 of open vegetation across much of tropical Australia; (iii) a number of potential feedbacks,
486 some highly non-linear, have been suggested to operate between vegetation and climate,
487 potentially resulting in alternative states of climate and vegetation; (iv) a change in fire regime
488 theoretically provides one mechanism by which one state may be advantaged over another;
489 and (v) there is evidence that fire regime has been manipulated by humans to some degree
490 since their arrival in tropical Australia and across Sahul.

491 **5. Towards testable hypotheses**

492 What is striking in the discussion to date concerning the impact of human arrival is the
493 relative lack of consideration of the dynamic ecological processes that would necessarily
494 underlie any impact associated with human arrival (but see Bowman, 1998, Johnson, 2009).
495 It is clear that many of the landscapes and ecosystems encountered upon European arrival

496 were ‘naturalized’ rather than ‘natural’ (e.g. Bliege Bird *et al.*, 2012). However, the degree to
497 which humans may have affected vegetation and/or climate at more than the local scale in
498 Australia – ‘The Biggest Estate on Earth’ (Gammage, 2011) – remains unresolved after
499 decades of debate.

500 Based on the discussion in the preceding sections, we elaborate below on two testable
501 ‘end-member’ hypotheses concerning the broad-scale impact of an anthropogenic fire
502 regime in the tens of millennia following human arrival, recognizing that a continuum of
503 possible scenarios lies between them.

504 *5.1 One minus one equals zero: no change*

505 This scenario represents the null hypothesis and is straightforward to articulate. The
506 removal or dramatic diminution of megafauna, and particularly browsing megafaunal
507 herbivore populations, removed an impediment to tree recruitment and survival. The
508 increased potential recruitment and survival of trees in tropical Australia was offset by the
509 introduction of an anthropogenic fire regime. The net effect of an anthropogenic fire regime
510 was to more or less maintain the status quo, with changes in the ‘spatial grain’ of ecosystem
511 processes favouring enhanced biodiversity and resource availability at the local scale (Bliege
512 Bird *et al.*, 2008). Whilst, over an extended period of time, this fire regime may have been
513 instituted across a large area, a population probably never numbering more than one million
514 people (Butlin, 1983), and possibly considerably fewer (Atkinson *et al.*, 2008, Eriksson *et al.*,
515 2012), was not capable of significant large-scale influence on ecosystems.

516 The relative areas of ecosystems at the broad scale were determined entirely by natural
517 changes in regional climate, in turn forced by global changes in sea-level and insolation,
518 modulated by the dynamics of the Asian monsoon and regional oceanic and atmospheric

519 variability, overprinted by a long-term trend to greater aridity in Australia (Magee *et al.*, 2004,
520 Webb, 2008, Cohen *et al.*, 2011, Field and Wroe, 2012). A 300ka record of vegetation change
521 from the Timor Sea, northwest and downwind of tropical Australia, provided by Wang *et al.*
522 (1999), shows no evidence of a significant change in the balance between tree and grass
523 pollen, or in charcoal abundance, coincident with human arrival or at any time subsequent to
524 human arrival. Indeed, the records of early explorers suggest that in the arid and semi-arid
525 tropics, indigenous fire may have been infrequent and restricted to intermittent favourable
526 seasons (Silcock *et al.*, 2013).

527 Peaks in charcoal abundance prior to human arrival in core ODP-820 from off northeast
528 Queensland (Moss and Kershaw, 2007) and core GC-17 off Western Australia (van der
529 Kaars and De Deckker, 2002) indicate that this proxy cannot be reliably interpreted as
530 indicative of anthropogenic fire. Indeed, in their review of charcoal records from the region,
531 Mooney *et al.* (2011) found no ‘distinct change’ in charcoal abundance after human arrival in
532 Australasia, though a possible trend to increased biomass burning between 50 and 40ka is
533 one possible interpretation of the composite record. They note, however, the ‘considerable
534 uncertainty’ associated with the chronology of records that lie beyond the limit of
535 radiocarbon dating, and their composite record for Australasia as a whole may also conceal
536 significant trends at finer spatial scales.

537 Modern tree and grass distributions in tropical Australia are largely explained by low
538 nutrient soils, high natural climate variability (Fensham *et al.*, 2003, Lehmann *et al.*, 2009,
539 Fisher *et al.*, 2012) and by the dominance of fire-adapted eucalypts (Lawes *et al.*, 2011, Crisp
540 *et al.*, 2011). Increased atmospheric CO₂ and rainfall on their own can explain the observed

541 forest encroachment and thickening of savannas over the twentieth century (Bond *et al.*,
542 2003, Bowman *et al.*, 2010, Fensham *et al.*, 2005, Lawes *et al.*, 2011, Tng *et al.*, 2012).

543 *5.2 One plus one equals three: profound change*

544 Significant human influence on vegetation in tropical Australia could have resulted from the
545 effects of an anthropogenic fire regime on climate–vegetation feedbacks through two
546 mechanisms. The first is indirect, operating through a change in the timing of burning, while
547 the second is direct, from targeted burning at forest boundaries and of newly irrupted forest
548 patches. Both mechanisms operate cumulatively on centennial to millennial timescales, with
549 landscape-scale change not readily observable across several human generations, although
550 local changes would be observable on decadal timescales, as is currently the case (Banfai and
551 Bowman, 2005). Neither mechanism requires ‘more’ fire than a natural fire regime, simply a
552 change in the frequency, timing and focus of burning. Hence, there is no requirement for a
553 discernible change in biomass burning proxies accompanying human arrival (Mooney *et al.*,
554 2011).

555 Neither mechanism requires a large population. This is because an area under an active
556 anthropogenic fire regime by definition shares a boundary with areas not under active
557 management. Thus, human-lit fires could be expected, under favourable conditions, to carry
558 over into areas not actively managed, thereby leading to change in the timing of burning in
559 areas not actively managed and a more constant source of ignition than provided by
560 lightning alone. In glacial and early post-glacial times, arid conditions may have also served
561 to focus a comparatively small population around forest edges, which would have provided
562 access to a wider resource base and accessible surface water in riparian areas.

563 Bond *et al.* (2003) modelled the impact of low CO₂ and fire and found that, at the CO₂
564 concentrations pertaining at the LGM, seedling growth rates were too slow to ensure
565 growth to a 'fire-escape' height. Over the 25–30ka from human arrival to the LGM,
566 incremental introduction of fire at a higher recurrence interval, early in the dry season and at
567 low CO₂, may have exacerbated a natural trend to stem thinning in open environments and
568 a reduction in forest area in response to drying and cooling of the continent (Hesse *et al.*,
569 2004).

570 After the LGM, climate began to warm, CO₂ began to rise and the monsoon re-
571 established across tropical Australia by ~14ka (Wyrwoll and Miller, 2001). In the absence of
572 humans, this combination of factors, coupled with the absence of browsing megafauna,
573 would have improved the establishment and persistence potential for trees in northern
574 Australia. Given the vast expanse of woodlands across this region, an increase in tree cover
575 would have initiated a positive feedback, increasing the evapotranspirative movement of
576 moisture into the continental interior and enabling tree establishment further towards the
577 centre of the continent (Miller *et al.*, 2005a). Late dry-season lightning fires had the effect of
578 reducing dry season length (Notaro *et al.*, 2011) and/or increasing wet season precipitation
579 (Lynch *et al.*, 2007), further favouring tree establishment. Examination of the current degree
580 of seasonality in precipitation across tropical Australia (Figure 1) indicates that even a 5%
581 change in the proportion of rain falling outside the wet season would dramatically change
582 the climate of much of northern Australia. Once tree cover passed a threshold, equivalent to
583 ~40% canopy cover in Africa (Archibald *et al.*, 2009), the incidence of fire would be reduced,
584 further promoting the establishment of woody vegetation formations across a much broader
585 area than is currently the case.

586 The above scenario was not, however, realised because the anthropogenic fire regime
587 operating in the post-LGM times was characterized by increased frequency of ignitions,
588 decreased return interval and a shift to more common early dry-season fires. This could
589 have had the indirect result of instituting a negative feedback, constraining tree
590 establishment through the maintenance of a longer dry season as well as constraining both
591 the intensity of the monsoon and its penetration into the continental interior. As a result,
592 canopy closure was inhibited and fire, mediated by humans, maintained the system in a
593 relatively open state across a larger area than would otherwise have been the case (Murphy
594 and Bowman, 2012).

595 This indirect negative feedback, hindering forest establishment, could have been further
596 amplified by targeted anthropogenic burning along forest boundaries. Certainly, some forest
597 environments in northern Australia were difficult to exploit, with limited or no occupation
598 of forests in the wet tropics until the Holocene (Cosgrove *et al.*, 2007). This suggests that
599 indigenous populations may have preferred to maintain an open vegetation type in the face
600 of forest encroachment. In the Northern Territory, monsoon forest patches are currently
601 valued for a number of resources, particularly yams in the wet season, and both Haynes
602 (1985) and Russell-Smith *et al.* (1997) found that such forest patches are actively protected by
603 early dry-season burning outwards from their edges. While such a strategy may be effective
604 in protecting existing forest areas, in post-LGM times it may also have limited the expansion
605 of forest area by inhibiting tree seedling maturation beyond forest boundaries (Woinarski *et al.*,
606 2004). Frequent low intensity fires in open vegetation may also have deterred forest
607 establishment through inhibition of irruption of new forest patches in the landscape, as has
608 been demonstrated in the modern environment (Russell-Smith *et al.*, 2004a, b). Indeed, given
609 the relatively slow rates of forest advance by edge progression, generally no more than a few

610 metres per year (e.g. Favier *et al.*, 2004b; Tng *et al.*, 2012), inhibition of the formation of new
611 forest patches across the landscape might be the dominant mechanism by which forest
612 advance could be limited by anthropogenic fire.

613 The net effect of an anthropogenic fire regime applied for tens of millennia on the
614 observed modern vegetation cover, under this scenario, would be a more highly seasonal
615 climate with lower penetration of the monsoon into the continental interior. This may in
616 turn have fed back into (i) a more limited distribution of dry/monsoon forest cover over
617 northern and northeastern Australia, (ii) savannas with comparatively low-density tree cover
618 over much of the tropical north, (iii) the expansion of spinifex grasslands at the expense of
619 shrublands in the arid interior (Miller *et al.*, 2007) and, ultimately, (iv) to the anomalously dry
620 condition of modern Lake Eyre (Magee *et al.*, 2004). This scenario is consistent with results
621 from the long pollen record from core SHI-9014 in the Banda Sea (van der Kaars *et al.*,
622 2000), which shows a significant expansion of grassland and concomitant decline in
623 eucalypts in northern Australia and the Sahul Shelf region from 37ka, sustained to the
624 present-day. Indeed, it is possible that the present link between increased savanna
625 woodiness and increased rainfall in Queensland savannas in the second half of the twentieth
626 century (Fensham *et al.*, 2005) is partly the result of release from an anthropogenic fire
627 regime in the early twentieth century – a trend that may continue for centuries to millennia.

628

629 **6. Conclusions: What is natural in tropical Australia?**

630 There is abundant evidence that the vegetation patterns and biodiversity across tropical
631 Australia at the time of European arrival were, to some degree, anthropogenic (Jones and
632 Bowler, 1980, Johnson, 2006, Gammage, 2011), so the question ‘what is natural?’ is one of

633 spatial and temporal scale. We conclude that mechanisms do exist (supported by limited
634 evidence) to support the hypothesis that human occupation resulted in profound
635 modification to broad-scale vegetation patterns and climate across tropical Australia at the
636 millennial scale. However, human activity, primarily expressed through megafaunal
637 extinction and modifications to natural fire regime, occurred against a background of
638 significant natural climate change and generally nutrient-poor soils that may ultimately have
639 mitigated against any more than local expression of this potential for significant broad-scale
640 anthropogenic change.

641 It is not possible to discriminate unequivocally between the two hypotheses proposed
642 above, or any intermediate between the two, because the data required to undertake a
643 rigorous assessment do not exist. Obtaining the data required to draw a defensible
644 conclusion will require closer collaborations between indigenous traditional land owners,
645 archaeologists, anthropologists, geoscientists, climatologists and ecologists than has been the
646 case to date. The evidence required to discriminate between these hypotheses can potentially
647 come from several avenues:

648 (i) geosciences – the Lynch’s Crater record has existed for almost 40 years, but is not
649 suited to assessing broad-scale human impact across tropical Australia. There is a need for
650 terrestrial records spanning the last interglacial period to the present in the savannas of
651 northern Australia, to examine in detail the trajectory of environmental change across the
652 tropics. The obvious location for such records is in the regions that currently receive
653 >600mm of rainfall each year (Figure 1) – regions that could potentially support a higher
654 forest cover, but which are currently dominated by woodland and open-forest savanna of

655 between 20% to 60% cover with scattered patches of closed forest, including currently
656 flooded continental shelf areas.

657 Two unexplored possibilities exist. The first are large sinkholes, up to 100m in depth that
658 exist across the Top End of the Northern Territory in various stages of infilling, generally in
659 limestone or dolomitic terranes. The second comprises the many swamps created by basaltic
660 volcanism in northeast Queensland over the last several million years (Stephenson, 1989,
661 Whitehead *et al.*, 2007). There are a large number of untested potential targets that are
662 currently in savanna that could, prior to human occupation, have featured a higher woody
663 cover and potentially of non-eucalypt species (Pole and Bowman, 1996). The deposits in the
664 sinkholes and basalt-dammed swamps contain both charcoal and quartz, making them
665 amenable to numerical dating by radiocarbon and OSL. There are new geochemical
666 techniques that can provide carbon isotope fingerprints for both terrestrial carbon and
667 charcoal, to assess any long-term changes in the balance between C₃ trees and C₄ grasses in
668 the surrounding environment (Bird and Ascough, 2012, Wurster *et al.*, 2012). Pollen grains
669 and *Sporomiella* spores can provide information on vegetation and megafaunal abundance
670 over time (Roberts and Brook, 2010, Rule *et al.*, 2012).

671 The most important periods for detailed examination are not the time intervals shortly
672 before and after human arrival, but the comparatively wet periods of MIS-5 and MIS-4, prior
673 to human arrival, and the post-glacial period after human colonization, when climate was
674 broadly similar. The long-term maintenance of savanna vegetation would imply little impact
675 of human occupation, whereas the existence of forest at such sites prior to human arrival
676 would provide further evidence of substantial human impact.

677 A further source of high-resolution climate proxy information is speleothems, and such
678 records might be brought to bear on the issue of climate variability and megafaunal
679 extinction in MIS-3, in particular. Speleothem records have proved remarkably valuable in
680 palaeoclimate studies in southern Australia (e.g. Ayliffe *et al.*, 1998) and elsewhere (e.g.
681 Weninger and Jöris, 2008), but the potential for long-term climate records from tropical
682 Australian speleothems has yet to be extensively investigated.

683 (ii) archaeology and anthropology – testing the two hypotheses presented above requires
684 a more complete understanding of the evolution and distribution of population numbers in
685 prehistory to determine the plausibility of the ‘profound impact’ hypothesis, in particular. It
686 could also require the revisiting of available archaeological information and the material
687 excavated from sites to, for example, determine local vegetation and climate from the
688 geochemical analysis of biotic discard materials (e.g. bones, mollusc shell). There is
689 considerable space for further research into the use of forest edges across tropical Australia
690 in the past, the dynamics of and rationale behind the indigenous fire regime applied at forest
691 edges, as well as the perception of, and response to, decadal-scale change in stem density and
692 tree recruitment in savannas. This implies collaboration with contemporary traditional
693 owners to explore the meaning, uses and value of modern forest and savanna areas across
694 the tropical north (Bliege Bird *et al.*, 2008).

695 (iii) environmental biology – understanding the response of tropical vegetation types to
696 changing climatic conditions on millennial timescales will require a better understanding of
697 plant, animal and ecosystem responses to fire and water stress, the historical biogeography of
698 Australia’s tropical flora and fauna, and a better understanding of the role of soil physical

699 and chemical properties in influencing the structure and function of tropical vegetation
700 formations and how soil properties interact with climate to determine vegetation type.

701 (iv) modelling – there have been significant, but largely separate, efforts across several
702 disciplines to model the interactions between vegetation, climate and fire in savannas, both
703 globally and in Australia (e.g. Archibald *et al.*, 2012, Murphy and Bowman, 2012). There have
704 also been efforts to model the evolution of the monsoon in Australia in the Quaternary, to
705 identify the controls underlying monsoon variability in the past, including the impact of
706 vegetation (e.g. Notaro *et al.*, 2011). The work of Archibald *et al.* (2012), in particular, has, for
707 the first time, explicitly included humans as an agent capable of influencing the fire–
708 vegetation–climate system in prehistory. Africa has been occupied by humans for a much
709 greater length of time than Australia and saw the incremental development of human ability
710 to control fire frequency and season over the last million years with the continued existence
711 of mega-herbivores (Koch and Barnosky, 2006). The human ability to manipulate fire
712 frequency and season was imposed ‘instantaneously’ upon arrival in Australia. Combined
713 with the ensuing rapid loss of megafauna, the resulting trajectory of change in Australia may
714 have been substantially different from that in Africa.

715 Archibald *et al.* (2012) note that anthropogenic fire may have affected forest expansion
716 and contraction in Africa in the past, but, as yet, there have been no integrated attempts to
717 include the potential millennial-scale feedbacks between anthropogenic fire, vegetation and
718 climate in ecosystem models. This would be a challenging undertaking for tropical Australia,
719 but would potentially enable an assessment of the sensitivity of the vegetation–climate
720 system to perturbations, particularly in those boundary conditions potentially capable of
721 modification through the imposition of an anthropogenic fire regime.

722 In conclusion, we are not able, on the basis of the data currently available, to determine
723 which of the two broad hypotheses outlined above better define the actual trajectory by
724 which we arrived at the vegetation distribution we observe across tropical Australia. The
725 degree to which anthropogenic fire regimes in prehistory may have shaped the modern
726 environment is critical to understanding its trajectory under future anthropogenic climate
727 change. The possibility that human occupation resulted in profound environmental change
728 at the very least suggests that phenomena observed to be operating in the modern
729 environment cannot necessarily be extrapolated into the past, as significant anthropogenic
730 impacts on regional climate and vegetation may have considerably more time depth than is
731 currently supposed. As Midnight Oil (1987) noted, '40,000 years can make a difference to the
732 state of things ...'.

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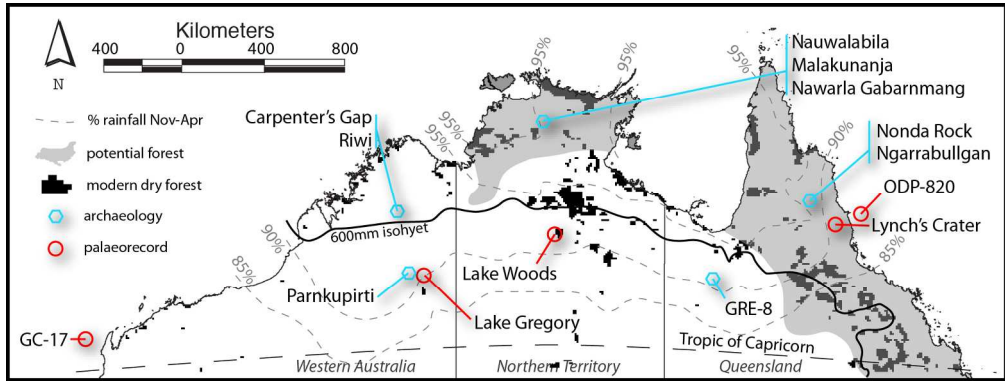
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1180 **Figure 1:** Modern Tropical Australia. Percent of total annual precipitation falling between
1181 November and April shown as grey dashed lines (Bowman, 2002) along with the 600mm
1182 isohyet shown as a solid line. Modern dry forest area taken from Miles *et al.* (2006) based
1183 on 10km grid cells containing a minimum of 40% forest area. Light shading represents
1184 potential modern forest area based on the modelling of Bond and Keeley (2005). Also
1185 shown are archaeological sites and palaeoenvironmental sites mentioned in the text
1186 (locations of marine cores MD98-2167, SHI-9014 and G6-4, all from the seas off
1187 northwest Australia, are not shown).

1188 **Figure 2:** Rock art thought to be a representation of *Genyornis newtoni* from Jawoyn country,
1189 western Arnhemland (see Gunn *et al.* 2011 for discussion). Credit: Ben Gunn and Jawoyn
1190 Association.

1191 **Figure 3:** Example sinkholes in the Northern Territory. Note that scale is variable. (in white:
1192 latitude °S, longitude °E; sinkhole maximum width; land surface elevation AMSL; vertical
1193 distance from land surface to water surface).



184x70mm (300 x 300 DPI)



199x132mm (300 x 300 DPI)



230x154mm (300 x 300 DPI)