Forgotten impacts of European land-use on riparian and savanna vegetation in northwest Australia

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Abstract

Questions: Fire and livestock grazing are regarded as current threats to biodiversity and landscape integrity in northern Australia, yet it remains unclear what biodiversity losses and habitat changes occurred in the 19–20th centuries as livestock and novel fire regimes were introduced by Europeans. What baseline is appropriate for assessing current and future environmental change?

Location: Australia's Kimberley region is internationally recognized for its unique biodiversity and cultural heritage. The region is home to some of the world's most extensive and ancient rock art galleries, created by Aboriginal peoples since their arrival on the continent 65,000 years ago. The Kimberley is considered one of Australia's most intact landscapes and its assumed natural vegetation has been mapped in detail.

Methods: Interpretations are based on a continuous sediment record obtained from a waterhole on the Mitchell River floodplain. Sediments were analysed for geochemical and palynological proxies of environmental change and dated using ^{210}Pb and ^{14}C techniques.

Results: We show that the present-day vegetation in and around the waterhole is very different to its pre-European counterpart. Pre-European riparian vegetation was dominated by *Antidesma ghaesembilla* and *Banksia dentata*, both of which declined rapidly at the beginning of the 20th century. Soon after, savanna density around the site declined and grasses became more prevalent. These vegetation shifts were accompanied by geochemical and biological evidence for increased grazing, local burning, erosion and eutrophication.

Conclusions: We suggest that the Kimberley region's vegetation, while maintaining a 'natural' appearance, has been altered dramatically during the last 100 years through grazing and fire regime changes. Landscape management should consider whether the current (impacted) vegetation is a desirable or realistic baseline target for biodiversity conservation.

KEYWORDS
Australian monsoon tropics, fire regimes, geochemistry, grazing, human impact, palaeoecology, Potential natural vegetation, riverine vegetation, savanna

1 | INTRODUCTION

Human impacts associated with European colonization beginning in the 15th century profoundly altered ecosystems around the globe. Impacts included the introduction of exotic species, manipulation of fire regimes, deforestation, major land-use changes, displacement of indigenous land management practices and alterations to biogeochemical cycles (Ireland & Booth, 2012; Johnson et al., 2017; Kirkpatrick, 1999). As these impacts preceded a widespread understanding of ecosystem ecology and research, in many parts of the world it is difficult to understand how ecosystems functioned prior to European colonization. This raises questions about how to best manage altered ecologies in an era of rapid environmental change (Johnson et al., 2017).

A common baseline for large-scale ecosystem management is the concept of Potential Natural Vegetation (PNV). PNV takes information from areas of assumed natural vegetation (late successional) and extrapolates to other (impacted) areas with similar environmental conditions (Loidi & Fernández-González, 2012). The PNV approach has been criticized because its predictions sometimes conflict with the fossil record (Abraham et al., 2016; Carrión & Fernández, 2009; Rull, 2015). PNV also fails to account for ecosystem dynamics (Chiarucci, Araújo, Decocq, Beierkuhnlein, & Fernández-Palacios, 2010) and is unable to simulate ecological structure in cultural landscapes (Strona et al., 2016). Despite these constraints, PNV remains an accessible baseline for conservation and management decisions.

Northern Australia is regarded as one of the largest areas of intact tropical savanna worldwide (Bowman et al., 2010; Woinarski, Mackey, Nix, & Traill, 2007; Ziembicki et al., 2015). If this is true, PNV maps for the region should constitute a valuable baseline (Beard, Beeston, Harvey, Hopkins, & Shepherd, 2013; Mucina & Daniel, 2013). Yet the ecosystems of northern Australia have been extensively modified since European colonization through livestock grazing, disruption of Indigenous land curation and the introduction of invasive species, among other impacts (Douglas, Setterfield, McGuinness, & Lake, 2015; Hnatiuk & Kenneally, 1981; Lonsdale, 1994; Radford, Gibson, Corey, Carnes, & Fairman, 2015; Vigilante & Bowman, 2004). Impacts are linked to extinctions, declining native mammal populations, altered stream ecology, eutrophication, erosion and catchment instability (Payne, Watson, & Novelly, 2004; Woinarski et al., 2007; Ziembicki et al., 2015).

Taking a different view, recent research links the recent decline of fire-sensitive species across northern Australia to interactions between fire and flammable grasses (Bowman, MacDermott, Nichols, & Murphy, 2014; Trauernicht, Murphy, Tangalin, & Bowman, 2013). Uncertainties surrounding the causes of recent species losses remain obscure in the absence of reliable historical evidence for 19th and early 20th century environmental change in this sparsely populated region. Such evidence could provide a critical test of ecosystem integrity and reveal long-term drivers of species decline.

Northern Australia is home to high levels of biodiversity, much of which remains undocumented (Barrett, 2013, 2015; Barrett & Barrett, 2011, 2015; Maslin, Barrett, & Barrett, 2013; Moritz, Ens, Potter, & Catullo, 2013). Phylogenetic research reveals extraordinary levels of genetic diversity and endemism, perhaps equal to the recognized biodiversity hotspots of eastern Australia (Moritz et al., 2013). The Kimberley region in NW Australia is internationally recognized for its extensive rock art galleries, which are some of the most ancient examples of human artistic expression globally (Aubert, 2012) and are situated in an ancient cultural landscape created by indigenous Australians (Hiscock, O'Connor, Balme, & Maloney, 2016; Rangan et al., 2015). There is a pressing need to understand and document the region's biological and cultural heritage as economic development pressures on the Northern Australian environment intensify.

In this paper, we confront the assumed natural vegetation of the Kimberley region with fossil evidence, aiming to assess the ecological integrity of the region's tropical savanna and riparian vegetation types. Our data pertain to the savanna woodlands and riparian thickets (Mucina & Daniel, 2013) of the Mitchell Plateau, one of the last areas of the Australian continent to experience European colonization (McGonigal, 1990). We compare pollen data with independent geochemical data to understand the timing, direction and drivers of two centuries of environmental change.

2 | METHODS

2.1 | Study area

The Kimberley Region is situated in NW Australia and constitutes a biogeographically and geologically distinct entity within the Australian Monsoonal Tropics (Pepper & Keogh, 2014). The region is characterized by complex and ancient geology, which has combined with long periods of sub-aerial exposure and weathering to create unique landforms and topography (Pillans, 2007; Tyler, 2016). The Kimberley region is broadly divided into three geological basins: the extensive Kimberley Basin in the north, the Ord Basin to the south and east, and the Canning Basin to the south and west (Appendix S1). These basins are separated by two orogenic belts of metamorphosed and intrusive rocks. The western portion of the Kimberley Basin is dominated by the King Leopold Sandstone (erosion-resistant arenites) and Carson Volcanics (weathered basalts), while the Warton and Pentecost Sandstones dominate the eastern portion. These rocks have been subjected to only minor faulting and deformation since their deposition some 1840–1800 million years ago and thick, erosion-resistant laterites developed over the basalts 70–50 million years ago (Tyler, 2016). Geology has a defining influence on the distribution of soil types and vegetation units, as well as biogeographic and phylogenetic patterns (Barrett, 2015; Barrett & Barrett, 2015; Hnatiuk & Kenneally, 1981; Moritz et al., 2013; Mucina & Daniel, 2013; Pepper & Keogh, 2014).

On the Mitchell Plateau, savanna woodlands on basalt tend to have a ground layer of *Allopteropsis semialata*, *Chrysopogon fallax*, *Heteropogon contortus*, *Sehima nervosum*, *Sorghum plumosum* and many other grasses, with a tree layer of eucalypts (*Eucalyptus bigalerita*, *E. tectifera*, *Corymbia greeniana*, *C. bella*, *C. disjuncta*), ironwood trees (*Erythrophloemum* aff. *chlorostachys*) and terminalia (*Terminalia canescens*, *T. fitzgeraldii*), depending on topography (Mucina & Daniel, 2013). Savanna woodlands on sandstone-derived soils have dominant

Sorghum and *Triodia* grasses and a dominant tree layer of eucalypts (*Eucalyptus tetradonta, E. miniata, E. apodophylla, E. houseana, Corymbia latifolia, C. nesophila, C. torta*) and palms (*Livistona eastonii;* Hnatiuk & Kenneally, 1981; Mucina & Daniel, 2013). Sandstone outcrops have an altogether different flora, having a high proportion of species considered to have Gondwanan heritage, as well as many endemics (Dunlop & Webb, 1991). Key species of these scrubs/heaths include *Acacia gonocarpa, A. kelleri, A. arida, A. tumida, Bossiaea arenitensis, Calytrix brownii, C. exstipulata, C. achaeta, Corymbia polycarpa, Gardenia pyriformis* and *Grevillea agrifolia* (Mucina & Daniel, 2013). Rain forest remnants (vine thickets) occur in fire-protected locations where moisture is available all year (Hnatiuk & Kenneally, 1981; Ondei, Prior, Williamson, Vigilante, & Bowman, 2017). *Albizia lebbeck, Atalaya variifolia, Cochlospermum fraseri, Sersalisia sericea* and *Wrightia pubescens* are important canopy species in these rain forests (Beard, 1976). Wetlands and riparian zones are dominated by *Pandanus* and *Melaleuca* species (*P. aquaticus, P. spiralis, M. leucadendron, M. nervosa, M. viridiflora*). *Nauclea orientalis, Timonius timon* and the deciduous shrub *Antidesma ghaesembilla* are also common in these areas.

The Kimberley region has a dry tropical monsoonal climate, with rainfall seasonality driven by the Indo-Australian Summer Monsoon. Doongan Station, near our study site, receives an average of 1,205 mm annual precipitation, 95% of which falls from November to April (Bureau of Meteorology, http://www.bom.gov.au/climate/data/ accessed 5 Jun 2017). Rainfall events usually occur in the form of prolonged tropical storms and/or cyclones during the humid 'wet' season, flooding the region's water courses (Mucina & Daniel, 2013). A steep rainfall gradient exists across the Kimberley region – on average, over 1,400 mm of precipitation falls annually on the seaward slopes of the Mitchell Plateau, while the southern parts of the Kimberley adjoining the Great Sandy Desert receive less than 400 mm. Maximum daily temperatures average over 30°C in most parts of the Kimberley Region throughout the year (Bureau of Meteorology).

2.2 | Sample collection and dating

A sediment core was collected from a small (~100 m^2) elliptical waterhole on the floodplain of the Mitchell River (15°10′30.5″S, 125°53′29.3″E; Figure 1, Appendix S1) using a mud–water interface corer operated from a floating platform. The site (MP11A) is 150 m from the main river channel and forms part of a complex of lakes and swamps where the floodplain widens as it follows the geological contact between basalt and sandstone. The waterhole is fringed by *Melaleuca leucadendron* to the south and surrounded by savanna woodland on all sides. *Nymphaea violacea* and *Eleocharis* grow in the water, which was ~50-cm deep at the time of core collection.

The core was dated using a combination of ^{210}Pb and ^{14}C techniques (Wright et al., 2017). Eight ^{210}Pb samples were selected from the upper 35 cm of the core. Macroscopic plant remains were removed before the samples were freeze-dried, ground and weighed. Subsamples of >1 g were dated at the Australian Nuclear Science and Technology Organisation (ANSTO) using alpha spectrometry. Radiocarbon (^{14}C) dating was performed on three samples >5 g using

Accelerator Mass Spectrometry at DirectAMS Laboratories (Seattle, OR, USA). Macroscopic plant material was removed prior to further pre-treatment. An age–depth model was constructed using cubic spline regression in Clam 2.2 (Blaauw, 2010).

Surface sediment samples are routinely collected in palaeoecological research to calibrate pollen–vegetation relationships (Morris, Higuera, Haberle, & Whitlock, 2017). In the Kimberley Region, surface samples have been analysed to aid the interpretation of pollen records (Field, McGowan, Moss, & Marx, 2017; Proske, Heslop, & Haberle, 2014), but multi-site calibration has not been attempted. We collected surface sediment samples from ten small lakes and wetlands across the region (Figure 1). Multiple representative stands of the surrounding vegetation were surveyed using a Haglöf HEC-R electronic clinometer (Haglöf, Avesta, Sweden) and a GRS densitometer (Geographic Resource Solutions, Arcata, CA, USA) to estimate canopy height, tree volume and density. Composition was measured on the DAFOR scale (Kent, 2012). Satellite imagery was used to estimate the proportion of each vegetation type within a 100-m radius of the coring site. Stand-based estimates were weighted using these proportions to obtain vegetation estimates for comparison with pollen assemblages.

2.3 | Pollen and charcoal analysis

Seasonally variable environments often have less suitable conditions for pollen preservation than more stable environments (Head & Fullager, 1992), requiring relatively large sediment samples. Samples
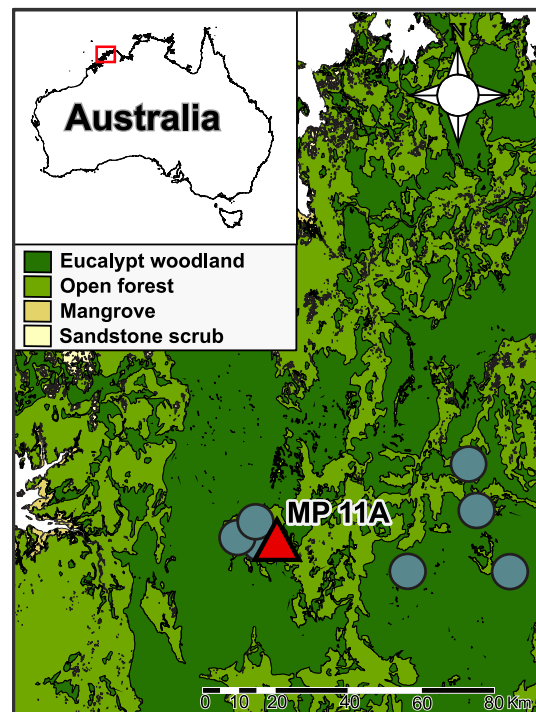
FIGURE 1 Location of the main study site (MP11A - triangle) and surface sampling sites (circles) in relation to regional vegetation structure, NW Kimberley Region, Western Australia. Vegetation units after Mucina and Daniel (2013)

of 5 ml sediment were treated according to standard palynological techniques (Jones & Rowe, 1999), including removal of clays through settling and decantation, sieving to remove large particles (>120 μm), treatment with 10% KOH at 90°C for 20 min to remove humic material, heavy liquid separation (s.g. 2.0) to remove minerogenic material, acetolysis (9:1 mixture of $C_4H_6O_3$ to H_2SO_4), carbonate removal with 10% HCl, HF (50%) to remove fine silica, dehydration in 100% ethanol, and mounting in glycerol on glass slides. *Lycopodium* spore tablets were added early in pre-treatment to enable calculation of pollen concentrations and accumulation rates. Pollen, spores and selected fungal and algal remains were identified at 400× magnification, using the extensive Kimberley collection in the Australasian Pollen and Spore Atlas (Rowe, 2006) and published guides (van Geel & Aptroot, 2006; Macphail & Stevenson, 2004). Identifications were agreed upon by three analysts (JT, SR and SH).

Charcoal particles are an indicator of fire occurrence, with macroscopic particles considered indicative of local fires and microscopic particles indicative of regional burning (Whitlock & Larsen, 2001). Microscopic charcoal was quantified on pollen slides by counting opaque black particles 10–120 μm. Macroscopic charcoal was sieved from a known volume of sediment using a 120-μm mesh and particles identified using a binocular microscope (Stevenson & Haberle, 2005). Results were converted to accumulation rates for comparison with pollen data.

The pollen sequence was divided into relatively homogenous time spans using zonation (CONISS), implemented in Tilia (v 2.0.41, Eric Grimm, http://www.TiliaIT.com). Pollen–vegetation relationships were assessed by comparing the abundance of each pollen type to the abundance of pollen-producing plants within a 100-m radius (the most commonly used sampling radius in comparable studies: Bunting et al., 2013).

2.4 | Geochemical analysis

To examine the relationship between past vegetation and changes in the floodplain environment, we analysed elemental concentrations of 34 geochemical elements. We used the alkaline elements sodium (Na), potassium (K), magnesium (Mg), calcium (Ca) and barium (Ba) to track erosion. These elements are relatively water-soluble and their mobility during erosion processes results in elevated concentrations in water-body sediments (Davies, Lamb, & Roberts, 2015). The lithogenic element titanium (Ti) was used as a control for the mobile elements as it is geochemically stable and hosted by resistant minerals (Davies et al., 2015). The element phosphorus (P) was used to track livestock grazing. Cattle directly affect the local P cycle because the phosphorus they consume is returned to the environment as dung (Parham, Deng, Raun, & Johnson, 2002). This increases P concentrations in the soil and ultimately contributes to P enrichment in water bodies and sediments.

Sediment samples (33 from the core and ten surface samples) of 0.2 g each were digested using 1 ml HNO_3 (Aristar, BDH, AU) and 2 ml HCl (Merck Suprapur, Darmstadt, Germany) and analysed for metals using an inductively coupled plasma mass spectrometer (ICP-MS;
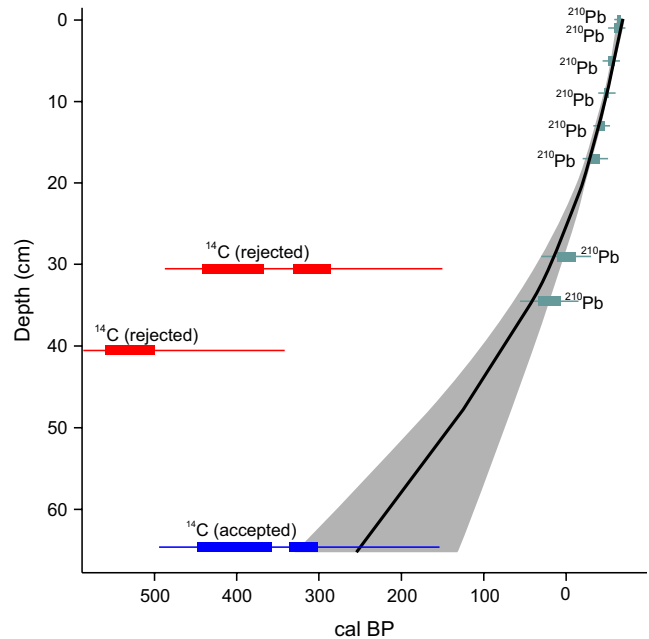
FIGURE 2 Age-depth model for the MP11A sediment core, showing calibrated ages and associated errors from ^{210}Pb and ^{14}C isotopic dating, with smooth spline interpolation

Perkin-Elmer, Waltham, MA, US; model DRC-e) with an AS-90 autosampler (Telford, Maher, Krikowa, & Foster, 2008). Certified reference materials (NRC-BCSS1, NRC-Mess1, NIST-1646, NRC-PCAS1) and blanks were used as to check the quality and traceability of metals. PCA was used to link geochemical variables to pollen assemblages.

3 | RESULTS

Figure 2 shows the adopted age–depth model for the MP11A sediment record with dated levels and associated errors. Two ^{14}C dates were excluded from the model (30.5- and 40.5-cm depth). These samples yielded ages that were the same or older than the lowermost ^{14}C age in the core. Re-deposition of older C by floods is a common problem when dating recent floodplain deposits (Ely, Webb, & Enzel, 1992). The chronology established by ^{210}Pb has low errors and indicates relatively constant sedimentation rates. The apparent increase in sedimentation toward the top of the core is likely to reflect the relatively uncompacted nature of the more recent sediments.

Figure 3 shows key changes in the vegetation of the MP11A site and its surroundings through the last 200 years (see Appendix S2 for complete pollen record). Four main phases were defined by zonation, described below in relation to changes in charcoal and geochemistry:

1. Phase 1 (AD 1823–1907) is characterized by relatively high proportions of *Corymbia*, other Myrtaceae, *Callitris*, *Terminalia*, *Banksia* and *Antidesma ghaesembilla* pollen. Phase 1 pollen assemblages are very different to those of surface samples collected in modern waterholes (see PCA, Appendix S3). Microscopic
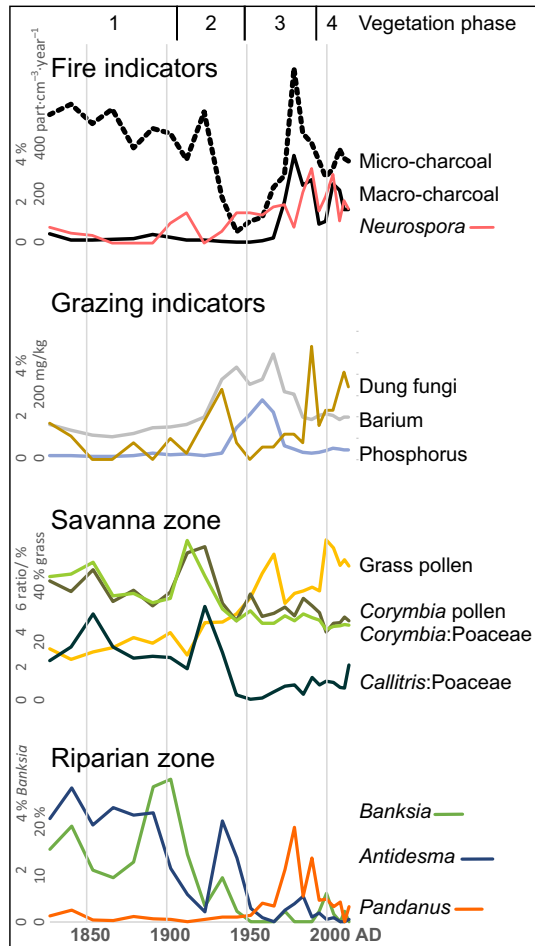
FIGURE 3 Summary of major changes in environmental proxies at site MP11A, Mitchell Plateau, Western Australia (see Appendix S2 for complete palynological and geochemical proxy diagrams)

charcoal accumulation rates were relatively high in Phase 1 compared with later phases, whilst macroscopic charcoal accumulation rates were low (average 4% total charcoal). Geochemical indicators show a dip in concentrations of weathering resistant Ti later in this phase and an increase in silicon (Si).

2. Phase 2 (AD 1907–1948) exhibits a steep decline in *Antidesma ghaesembilla* and *Banksia* pollen. Pollen of the canopy dominants fluctuated, with *Corymbia* and *Callitris* attaining their highest proportions in the entire sequence before rapidly decreasing toward the end of the phase. *Botryococcus* decreased substantially at the same time and *Sordaria* fungal spores increased in abundance. Charcoal declined substantially toward the end of this phase, reaching its lowest concentrations in the entire record. In contrast, the mobile elements (Na, K and Ba) increased while Ti concentrations declined. The end of this phase is marked by a sharp increase in P, reaching levels over ten times background concentrations.

3. Phase 3 (AD 1948–1993) begins with major increases in Poaceae and *Pandanus* pollen. These changes were followed by a major increase in both macroscopic and microscopic charcoal, reaching the highest concentrations in the record. Tree pollen decreased to an

average of 34% (compared to 50% in the previous zone). Phase 3 pollen assemblages are similar to those of surface samples from modern waterholes (see PCA, Appendix S3). Geochemical data show a temporary decline in concentrations of Na, K and Ba and an increase in Ti, Mg and Ca.

4. Phase 4 (AD 1993–2016) is differentiated from the previous phase by a further decline in tree pollen (average: 30%) and the highest levels of Poaceae, *Acacia* and *Dodonaea* pollen for the entire record. Macroscopic charcoal is abundant compared to microscopic charcoal (average 30% total charcoal). *Sordaria* remained abundant through this phase. Geochemical indicators show relatively high concentrations for all elements except P, which decreased.

Figure 4 shows the relationships between major pollen taxa and vegetation parameters for surface samples (Appendix S4). *Corymbia* pollen correlates strongly with area-weighted plant abundance ($r^2 = .87$), savanna basal area ($r^2 = .74$) and savanna canopy cover ($r^2 = .48$). *Pandanus* pollen was less strongly related to abundance ($r^2 = .37$) and had no relationship to savanna basal area (i.e., tree density). Poaceae produced a short abundance gradient (being dominant in vegetation surveys), but displayed an inverse relationship with savanna density ($r^2 = .42$) and canopy cover ($r^2 = .27$). *Corymbia*:Poaceae ratios correlated positively with both *Corymbia* abundance ($r^2 = .64$) and savanna density ($r^2 = .67$).

4 | DISCUSSION

Our multi-proxy results provide a glimpse of historical changes that occurred in the savannas and inland floodplains of the Kimberley Region. A longer record of palaeovegetation change comes from Black Springs, 75 km SW of site MP11A (15°38′S, 126°23′23″E), showing *Pandanus* expansion during Holocene wet phases and aridification cycles linked to weakening monsoons (Field et al., 2017). This record, however, has low temporal resolution (centennial scale) and uncertain dating for recent centuries. The MP11A record provides decadal resolution, revealing a sequence of environmental changes in the upper Mitchell River area since European colonization. The ^{210}Pb chronology shows no signs of flood disturbance (Arnaud et al., 2002). Nevertheless, the assigned ages should be viewed as approximate.

The sequence of events is summarized in Figure 3. An initial decline of the riparian shrub *Antidesma ghaesembilla* began around 1900 (Phase 1), followed by *Banksia* decline a decade later. *Corymbia*, indicative of savanna density (Figure 4), increased around 1912 and *Callitris* followed in the 1920s (Phase 2). At the same time, regional fires decreased (indicated by lower levels of microscopic charcoal) and grazing intensified (indicated a rapid increase in dung fungal spores, such as *Sordaria*). The 1930s brought higher grazing intensity, increasing erosion (indicated by rising Ba and Na concentrations) and a major decline in savanna trees (*Corymbia* and *Callitris*) and regional burning. Eutrophication followed in the 1940s, with a pronounced peak in P lasting until the 1970s (Phase 3). During this interval, grass abundance increased and *Pandanus* replaced *A.*
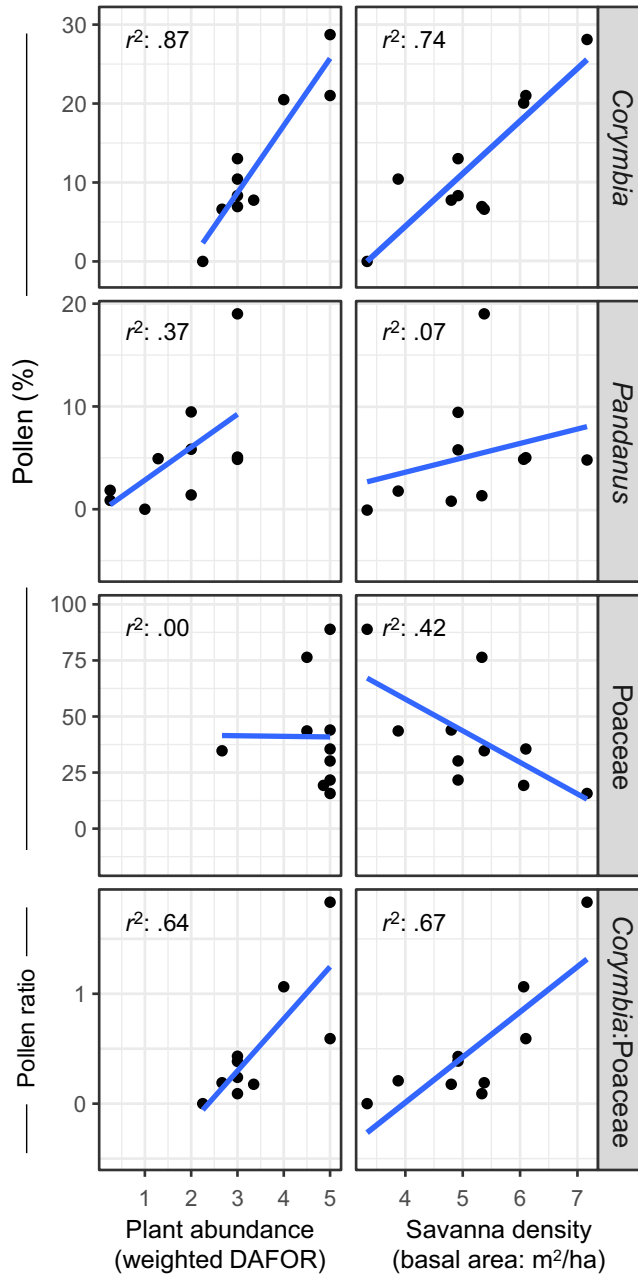
FIGURE 4 Scatterplots of plant abundance and savanna density parameters versus pollen abundances in surface samples

ghaesembilla as the dominant riparian element. Fire occurrence rose substantially in the late 1970s, particularly the local fires indicated by macroscopic charcoal and *Neurospora* fungal spores (van Geel & Aptroot, 2006; Whitlock & Larsen, 2001). This increase in local burning was accompanied by evidence of increased grazing intensity (dung fungi), peaking around 1990. The last two decades have seen further expansion of grasses and a decline in savanna density, as well as the disappearance of *Pandanus* from the waterhole margins (Phase 4).

Observed changes in savanna fire regime, savanna vegetation structure and riparian zone vegetation are discussed in the following sections in relation to major drivers of environmental change.

4.1 | Changes in savanna fire regime

On a global scale, savannas are thought to exist as an alternative stable state to forests, maintained by frequent fire (Bond, Woodward, & Midgley, 2005). Changing fire regimes are implicated in major vegetation shifts across the Northern Australian savanna zone (Bowman, 2003; O'Neill, Head, & Marthick, 1993; Russell-Smith et al., 2003), including the simplification of vegetation structure (Craig, 1997), compositional change (Bowman et al., 2014; Trauernicht et al., 2013), shifting forest–savanna boundaries (Banfai & Bowman, 2005; Hnatiuk & Kenneally, 1981) and negative impacts on native mammals (Radford et al., 2015; Ziembicki et al., 2015). The effects of fire regime change in Australia are not completely understood, given a lack of information on historical fire regimes and fire ecology (Silcock, Witt, & Fensham, 2016). Fire regime change is often linked to the dispossession of Aboriginal peoples of their land and consequent loss of traditional burning practices, followed by the different burning practices of European colonists (Ritchie, 2009; Russell-Smith et al., 2003). Alternatively, fire regime change may stem from the invasion of fire promoting grass species, creating a grass–fire positive feedback cycle (Bowman et al., 2014).

Our data demonstrate profound changes in fire regime around the MP11A site over 200 years. Phase 1 samples are dominated by microscopic charcoal. This suggests that regional savanna fires were common, while local fires in the riparian zone were apparently rare. This agrees with ethnographic evidence (Russell-Smith et al., 1997; Vigilante, 2001). The major reduction in regional burning in the 1930s and 1940s (Phase 2) coincides with the decline of continuous Aboriginal occupation of the Mitchell Plateau, ending in the 1950s (Wilson, 1981). Data from the 1960s onwards (Phases 3–4) show that local fires became more prevalent, impacting both savanna and riparian zones (Figure 3). Historically, Aboriginal fire management is associated with light/early season fires compared to unmanaged areas, where severe dry season fires are more frequent (O'Neill et al., 1993).

The nature of the MP11A site limits the conclusions that may be drawn from charcoal analysis. Fluvial transport is a major source of primary charcoal (direct products of fire) and secondary charcoal (redeposited by erosion: Patterson, Edwards, & Maguire, 1987; Whitlock & Larsen, 2001). Overlapping radiocarbon dates at different sediment depths could indicate contamination by older (secondary) charcoal (Figure 2). However, the macroscopic charcoal record is validated by a similar trend in *Neurospora*, a biological proxy for local fire (van Geel & Aptroot, 2006). Charcoal abundance is not clearly related to erosion proxies (Figure 3) and there is no indication of a major shift in sediment source that explains the dramatic increase in macroscopic charcoal since the 1960s. Hence, the MP11A charcoal record is cautiously interpreted as a reflection of fire occurrence in the riparian zone (macroscopic charcoal) and surrounding savanna (microscopic charcoal). The changes are consistent with a transition from Aboriginal to European fire management (Haberle, Tibby, Dimitriadis, & Heijnis, 2006), but remain to be corroborated at other sites.

4.2 | Changes in savanna structure

A critical question in understanding savanna vegetation dynamics is how global-scale factors interact with the local environment (Case & Staver, 2017). Previous research has debated the role of fire vs local edaphic factors in determining vegetation structure in northern Australia (Bowman, 1988; Craig, 1997; Douglas et al., 2015; Ondei et al., 2017). These studies often used space-for-time substitution or repeat aerial photography to analyse vegetation changes. Space-for-time substitution is limited by confounding variables such as differences in soil type, climate, species pools and land use at different sampling locations. Aerial photography provides long-term data on a broad geographic scale, but has limited temporal scope (usually late 20th century) and provides little detail on changes in understorey vegetation beneath the canopy where the impacts of savanna fire are presumably greatest. Palaeoecological data from small basins, such as the MP11A record, reveal vegetation changes at a small spatial scale over long time scales and are ideally placed to inform debates on vegetation structure (Mariani et al., 2017; Morris et al., 2017).

Our results point to a long-term decline in savanna tree density. The decline is registered in decreasing *Corymbia* pollen abundances and *Corymbia*:Poaceae ratios, proxies strongly associated with savanna basal area (Figure 4). Tree density decline was particularly acute in the 1930s. This evidence, albeit from a single site, contrasts with observations of 20th century 'woody thickening' across northern Australia (Bowman et al., 2010; Tng et al., 2011; cf. Murphy, Lehmann, Russell-Smith, & Lawes, 2014). Observed changes in vegetation density are dependent on the baseline used. The earliest aerial photography for most of northern Australia dates to the 1940s and 1950s. Savanna density change at MP11A since the 1940s has been negligible (Figure 3). Compared to a baseline of the 19th or early 20th century, however, loss has been substantial.

Around MP11A, grass cover increased as savanna density declined (Figure 3). Historically, livestock have caused major changes in grassland species composition in the Kimberley Region (Petheram, Kok, & Bartlett-Torr, 1986). Cattle, sheep, pigs, horses and donkeys were introduced by European graziers from the 1880s (McGonigal, 1990). Livestock numbers increased rapidly from less than 100,000 cattle in the 1890s to more than 600,000 in 1914 (Bolton, 1953), and were linked to environmental degradation from the 1930s (Payne et al., 2004). Cattle grazing can trigger a transition from perennial to annual grasses in Australian savannas (Ash, McIvor, Mott, & Andrew, 1997; Fensham & Skull, 1999). The same type of transition is linked to increasing fire frequency (Bowman et al., 2014). The histories of grazing and fire at MP11A are so long and intertwined that a single cause of recent savanna structural change is unlikely to emerge.

Perennial *Triodia* grasses, if left unburned for long periods, can gain significant size and density, providing habitat to a range of vertebrates and invertebrates. Old tussocks, often exceeding 2 m in height and 5 m in breadth, were frequent along the Fitzroy Crossing Road until the mid-1980s. Recent changes in fire regime have greatly reduced the extent of unburned *Triodia* tussocks, a change that may be linked to the decline of small mammals in the region. Pollen data cannot be used to interrogate the history of specific grass species because different species produce pollen that is morphologically indistinguishable. Analyses of phytoliths or ancient DNA may help address this shortfall.

Callitris intratropica has been the target of considerable research into fire impacts in northern Australian savannas (Bowman & Panton, 1993; Bowman et al., 2014). *Callitris* pollen is morphologically distinct, and the MP11A pollen record provides insight into the recent history of this fire-sensitive conifer. *Callitris* apparently experienced a major decline in the 1930s and has since recovered slightly. *C. intratropica* trees were not sufficiently abundant in our vegetation surveys to permit a quantitative test of the grass–fire cycle hypothesis (Bowman et al., 2014). Theoretically, if the expansion of grasses is linked to *Callitris* decline, the ratio of *Callitris*:Poaceae pollen should decrease over time. Instead, there is an increase since the mid-20th century at MP11A (Figure 3). The purported link between fire and grass cover finds little support in our data, with charcoal and Poaceae pollen following different trajectories. Our data cannot answer questions about grazing–fire–grass interactions on a regional scale, but point to a profound legacy of 20th century grazing and fire impacts in the Mitchell Plateau savannas.

4.3 | Changes in the riparian zone

Data from the MP11A waterhole provide strong evidence for the 20th century deterioration of a riparian shrub layer comprising *Banksia* and *Antidesma*. *Banksia* pollen represents *B. dentata*, the only *Banksia* species extant in the Kimberley region. This non-serotinous species occurs in seasonally inundated areas and swamp margins on sandstone bedrock, where it grows alongside *Eucalyptus apodophylla* (Hnatiuk & Kenneally, 1981). Extensive aerial surveys across the Kimberley confirm this almost exclusive habitat restriction (R. Barrett, personal observation). Our data suggest that *Banksia dentata* also occupied riparian zones in the past (i.e., *Melaleuca leucadendron* alliance of Hnatiuk & Kenneally, 1981; Riparian Thickets group of Mucina & Daniel, 2013).

Antidesma ghaesembilla is a fire-sensitive riparian shrub that bears edible fruits and is known to expand rapidly in areas of unburned woodland (Bowman, Wilson, & Hooper, 1988; Russell-Smith et al., 2003). It occurs frequently along the Mitchell River floodplain today. The MP11A pollen record suggests *A. ghaesembilla* was dominant around this site until the early 20th century. Its decline follows a peak in macroscopic charcoal, implicating local fires as the cause. According to ethnographic sources, Aboriginal people avoided burning riparian vegetation (Russell-Smith et al., 1997; Vigilante, 2001). Post-fire recovery may have been impeded by grazing, as *Antidesma* species are more palatable to cattle than browse- and burning-resistant *Pandanus*.

Riparian and wetland zones are where cattle and feral animal impacts in the Kimberley are most acute (Legge, Murphy, Kingswood, Maher, & Swan, 2011). Grazing and trampling have had significant detrimental impacts on riparian 'bamboo' (*Phragmites karka*), once common in the Kimberley, but now listed as a species of conservation concern in western Australia. Enhanced erosion is attested geochemically by increased concentrations of mobile vs immobile elements (Bierman

et al., 1998). At MP11A, mobile Na, K and Ba increased as relatively immobile Ti decreased during the 20th century. Erosion is further indicated by *Pseudoschizaea* palynomorphs (López-Marino, Martínez Cortizas, & López Sáez, 2010), which peak in Phases 3–4. Grazing may cause P enrichment from faeces and losses of Ca and Mg from urine patches (Early, Cameron, & Fraser, 1998; Parham et al., 2002). In the MP11A record, the early–mid 20th century is characterized by an increase in P (Figure 3) and a decrease in Ca and Mg (Appendix S5). With the additional support of proxies for livestock dung (Figure 3), these geochemical changes may be linked to grazing impacts.

Some of the changes witnessed in the MP11A record could be explained by other environmental shifts occurring in the Mitchell River catchment. Larsen, May, Moss, and Hacker (2016) demonstrated how the geomorphic process of knick-point migration caused riparian forest loss in Australia's Northern Territory. Sand slugs released by upstream erosion cause long-lasting impacts on downstream ecosystems in many Australian rivers (Prosser et al., 2001). These explanations seem inadequate in the case of MP11A – aerial photographs of the study area in 1949 and 2017 show no obvious change in riparian forest and floodplain geomorphology (Appendix S6).

There are no major flooding events corresponding to the time of peak impact at MP11A (Gillieson, Smith, Greenaway, & Ellaway, 1991; Wohl, Fuertsch, & Baker, 1994). Meteorological records indicate some higher-than-average rainfall years in the 1940s and 1950s, but much higher values in recent decades (Bureau of Meteorology), part of a wetting trend across northern Australia (Bowman et al., 2010). The decades-long environmental transformation evident at MP11A cannot be explained by a single disturbance event. Agreement between geochemical and biological proxies for grazing and fire, alongside clear evidence for the loss of savanna tree density and the shrub stratum within the riparian zone, suggest geomorphic processes are an unlikely cause of historic vegetation changes in the study area.

4.4 | Implications for conservation and vegetation mapping

Our evidence casts doubt on the notion that northern Australia's landscapes and ecosystems are intact and unmodified (Bowman et al., 2010; Woinarski et al., 2007; Ziembicki et al., 2015). Just as the intact canopy of 'Australian' eucalypts disguises a savanna flora with strong SE Asian affinities (Haynes, Ridpath, & Williams, 1991), the same canopy may disguise the pervasive ecological transformations that have occurred over the last 100 years. The forgotten impacts of early 20th century fire and grazing have profoundly altered savanna and riparian ecosystems on the Mitchell Plateau, and perhaps more widely.

Our data call for caution in adopting mid-20th century baselines for assessing ecological change, given that the impacts of European colonization often manifested themselves much earlier. Potential Natural Vegetation (PNV) maps have similar limitations. Because PNV maps are populated from data collected in the current (impacted) environment, there are likely to be knowledge shortfalls in reconstructing pre-European vegetation (Beard et al., 2013). Given the duration and magnitude of historical impact, it could be asked whether restoration to pre-European conditions is desirable or realistic.

There is a clear need for replication beyond the single palaeoecological record presented here to better understand spatial and temporal variation in the Kimberley region's ecosystems. It is acknowledged that obtaining palaeoecological data for vegetation types existing under more arid conditions may be difficult (Head & Fullager, 1992). Hence PNV provides a useful 'null model' (Somodi, Molnar, & Ewald, 2012) that can only be improved as better data and new sources of information come to hand.

Failure to recognize the Kimberley Region's historically altered ecological state could place the remaining biodiversity and ecosystems at greater risk than could be expected under truly 'intact' ecological conditions.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Appendix S1. Map of sampling locations, NW Kimberley Region

Appendix S2. Complete pollen and geochemical diagrams, MP11A record

Appendix S3. Principal Components Analysis result

Appendix S4. Pollen and vegetation data from surface samples

Appendix S5. Geochemical data from surface samples

Appendix S6. Aerial photographs of study area in 1949 and 2017

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