Collaborative Research on the Ecology and Management of the 'Wulo' Monsoon Rainforest in Wunambal Gaambera Country, North Kimberley, Australia

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Abstract: Indigenous groups are increasingly combining traditional ecological knowledge and Western scientific approaches to inform the management of their lands. We report the outcomes of a collaborative research project focused on key ecological questions associated with monsoon vine thickets in Wunambal Gaambera country (Kimberley region, Western Australia). The study mapped monsoon rainforests and analysed the environmental correlates of their current distribution, as well as the historical drivers of patch dynamics since 1949. Remote sensing was used to chart the effectiveness of an intervention designed to re-instate Aboriginal fire regimes according to customary principles. We identified the most vulnerable patches based on size, distance from neighbouring patches, and fire frequency. More than 6000 rainforest patches were mapped. Most were small (<1 ha), occurring predominantly on nutrient-rich substrates (e.g., basalt) and fire-sheltered topographic settings (e.g., slopes and valleys). Rainforests with low fire frequency and no cattle were more likely to expand into surrounding long-unburnt savannas. Frequent fires and cattle did not cause substantial contraction, although the latter affected rainforest understories through trampling. Fire management performed by Aboriginal rangers effectively shifted fire regimes from high-intensity late dry season fires to early dry season fires, particularly in areas with clusters of vulnerable rainforests. The remote sensing methods developed in this project are applicable to the long-term monitoring of rainforest patches on Aboriginal-managed land in North Kimberley, providing tools to evaluate the impacts of fire management, feral animal control, and climate change. The study confirmed the importance of the cattle-free and rarely burnt Bougainville Peninsula as one of the most important rainforest areas in Western Australia.

Keywords: aboriginal natural resource management; Australian monsoon tropics; biodiversity; feral cattle; fire regimes; traditional ecological knowledge; tropical savanna

1. Introduction

The important role of Indigenous People in biodiversity conservation programs has been increasingly recognized internationally [1–5]. This includes the declaration of Indigenous and Community Conservation Areas (ICCAs), whereby indigenous or other communities voluntarily

conserve their lands and waters as protected areas. In Australia, over 70 Indigenous Protected Areas (IPAs), formally recognised by the Australian Government and counted in the National Reserve System, have been declared by Indigenous groups in recent decades, and now cover 65 million hectares, which represents 7% of Australia and 40% of the National Reserve System [6,7]. IPAs, like other protected areas, require management planning, monitoring, and evaluation, and a variety of approaches have been adopted by practitioners [8]. Implementation of management on indigenous lands also requires the integration of the knowledge systems of Indigenous people (including Traditional Ecological Knowledge) and non-indigenous partner agencies and the development of participatory community-based approaches to monitoring and management (including Participatory Monitoring and Management) [9–12].

The Uunguu Indigenous Protected Area was declared by Wunambal Gaambera Aboriginal Corporation (WGAC, Kalumburu, Australia) in 2011 and now extends over 800,000 ha of Wunambal Gaambera country (WGC) in the Kimberley region of Western Australia. The management plan for the Uunguu IPA and wider WGC was developed [13] (and later reviewed [14]) using a local form of the Open Standards for the Practice of Conservation called 'Healthy Country Planning' [15–18] and identified 10 important conservation 'Targets' (assets) to be monitored and managed. In implementing the plan, WGAC has utilised collaborative research projects with external partners to provide Traditional Owners with the opportunity to integrate Indigenous Knowledge and Western scientific methods and approaches, to address key research questions such as monitoring target species (e.g., marine turtles and dugong [19]).

Rainforests, known as 'Wulo' in Wunambal and Gaambera languages, are one of the 10 'Targets' identified as important to Traditional Owners in the Wunambal Gaambera Healthy Country Plan. They are an important source of plant food (e.g., yams, *Dioscorea* spp.) and animal food (particularly bats and birds) and materials such as trees for making canoes (e.g., *Bombax ceiba*) [20]. Some rainforest patches are associated with important cultural sites and feature in cultural stories including links to Gwion rock art [13,21]. These rainforests, classified as monsoon vine thickets and dry rain-green forests, are found across Northern Australia, occurring in regions with strongly seasonal climate at the driest end of the Australian rainforest climatic range. They are characterised by low stature trees, a high density of shrubs and vines, and are a type of tropical monsoon forest [22,23]. Rainforests were first formally reported in Western Australia in 1965 [24], with some initial descriptive studies [25,26] followed by a series of biological surveys in the region [27–30] and finally a dedicated Kimberley Rainforest Survey (KRS) [24]. Despite the relatively small extent they occupy, rainforests contribute 25% of the floristic biodiversity of North Kimberley [31], with some 453 species of vascular plants (93 of which were rainforest specialist trees) and one endemic shrub (*Hibiscus peralbus* Fryxell). Unusually for that period, the KRS team included an indigenous Wunambal Gaambera elder, Geoffrey Mangglamarra (now deceased), who accompanied scientists to a number of rainforests in the WGC and contributed an ethnoecological paper to the study [20].

Key threats to the health of rainforests identified in the Healthy Country Plan included unmanaged wildfires and invasive species. Unmanaged wildfires have been identified as a key threat to natural and cultural values in the Australian monsoon tropics [32–35]. Changes in fire regimes, as observed in Australia with the switch from Traditional Aboriginal burning to European colonisation, are likely to pose a threat to rainforests due to the increased extent and frequency of wildfires [36,37]. This is in spite of the rainforest expansion trends observed in the Australian monsoon tropics in the past years [38,39], which have been linked with regional wetting trends and possibly atmospheric CO_2 enrichment [40–44]. Intense fires can cause direct damage to entire rainforest patches or portions of them, since rainforest species generally present limited fire protection (thick bark) and the ability to resprout after a fire compared with savanna species [45–47]. It can also influence the dynamics of woody vegetation in savanna adjacent to rainforest patches and affect the expansion and contraction of rainforests over time [38,40]. Early rainforest surveys at the Mitchell Plateau identified wildfire impacts and suggested that degradation had resulted in fewer bird records [48]. For example, abandoned

Orange-footed Scrubfowl (*Megapodius reinwardt*) mounds on the rainforest edge can be an indicator of change associated with fire as they are usually located under closed canopy [49,50]. Of the 95 patches visited in as part of the KRS in 1987 KRS, 40 showed evidence of fire damage [35].

The presence of mega-herbivores, such as cattle and buffalos, can result in decreased fire intensity by reducing fuel load through grazing [51]. Nonetheless, unmanaged grazers have a negative impact on rainforests, by increased tree—and particularly seedling—death through wallowing and root compaction, consequently reducing plant recruitment and understorey diversity [52,53]. In the Australian monsoon tropics, feral pigs (*Sus scrofa*) and cattle (*Bos Taurus/indicus*) can damage rainforests through trampling vegetation, particularly affecting small rainforest patches [52,54]. The KRS provided anecdotal evidence of structural changes to a rainforest patch vegetation, including the loss of lower level species, through trampling by cattle [48] and suggested that cattle may have facilitated fire damage through the loss of canopy cover and spread of savanna grass species into the rainforest edge [55].

Invasive grasses have the potential to increase fuel loads and associated fire severity (e.g., gamba grass *Andropogon gayanus* [56,57]), whilst vines such as Siam weed (*Chromolaena odorata*), rubber vine (*Cryptostegia* spp.), and stinking passionflower (*Passiflora foetida*), as well as woody weeds such as neem (*Azadirachta indica*), have the potential to alter the structure and composition of vine thickets [58,59]. Stinking passionflower is currently widespread across the Kimberley; its presence has been recorded in North Kimberley since 1984 [26]. In 1987, stinking passionflower was recorded in half of the surveyed patches [60]. Weeding programs, aimed to contain the spread of exotic invasive species in strategic locations, have been carried out by WGAC and partner agencies since 2010.

This paper reviews the outcomes of a collaborative research project between WGAC and the University of Tasmania, aimed at combining customary and scientific knowledge systems to answer key ecological questions surrounding the management and monitoring of 'Wulo' or monsoon vine thicket rainforests. Drawing together the results of joint field operations, the outputs of a series of research papers [47,61,62] and additional unpublished analysis of remote sensing data, we discuss (Table 1):

(a)　the location and characteristics of rainforest patches, mapped via a combination of an analysis of remote sensing data and targeted field validation [62];

(b)　decadal scale rainforest boundary dynamics, detected using historical imagery and field surveys [61];

(c)　the effects of climate change, fire frequency, and feral livestock occurrence on rainforest and savanna historical expansion trends, inferred using natural landscape ecology experiments [61];

(d)　the use of a field experiment to investigate the effect of fire on rainforest and savanna seedling survival and growth [47]; and

(e)　recent changes in fire regimes following an intervention designed to restore elements of traditional Aboriginal fire management.

Table 1. Summary of methods presented in this paper. Some approaches were undertaken across all of Wunambal Gaambera country (WGC), while others were limited to comparison of two locations or a single location.

Aim	Method	Analysis Extent	References for Full Method Description and Results
Mapping rainforest distribution	Creation of an ex novo map of rainforest patches from 2005 orthophotos using a 30 m × 30 m lattice	WGC	Ondei et al. 2017 [62]
	Patch connectivity index estimated by calculating patch area and average distance from the 5 nearest patches		This paper
Determining rainforest change	Rainforest patch change was estimated by applying 30 m × 30 m lattice to available historic aerial photography (1949 and 1969) and comparing the output with the 2005 orthophoto results.	Two locations: the Bougainville Peninsula & Mitchell Plateau	Ondei et al. [61]

Aim	Method	Analysis Extent	References for Full Method Description and Results
Boundary dynamics and threats to patch health	Florastic and vegetational data collected in 20 transects (each with five 10 m × 20 m plots) spanning rainforest–savanna boundaries. These data were associated with rainforest change data (obtained from the analysis of aerial photos and orthophotos). Feral herbivore occupancy sampled with camera traps placed along vegetation transects.	Two locations: the Bougainville Peninsula & Mitchell Plateau	Ondei et al. 2017 [61] Unpublished data
Sapling survival and growth	Controlled experiment on sapling survival rates and resprouting strategies following fire.	One location: the Mitchell Plateau	Ondei et al. 2016 [47]
Fire regime change	GIS analysis comparing occurrence of fire (MODIS fire scar data) adjacent to rainforest patches before and after fire management intervention. 'Vulnerability index' determined using GIS analysis	WGC	This paper

We combined the abovementioned results with literature on local traditional knowledge and comments from Traditional Owners to consider implications and land management options for Traditional Owners.

2. Materials and Methods

2.1. Study Area

The WGC occupies about 1.2 million ha of land and sea in the North Kimberley region of Western Australia, which is located toward the driest portion of the rainforest range in the Australian tropics [63], and listed as one of the 15 Australian National Biodiversity Hotspots [64]. The WGC is defined by the Wanjina Wunggurr Uunguu Native Title Determination (*Goonack v State of Western Australia* [2011] FCA 516), representing the traditional lands of Wunambal Gaambera Aboriginal people (Figure 1). The majority of WGC has been declared as the Uunguu Indigenous Protected Area. Other conservation estates include the Lawley R National Park, Camp Creek Conservation Park, and parts of Mitchell River National Park, Laterite Conservation Park, and the Prince Regent River National Park.
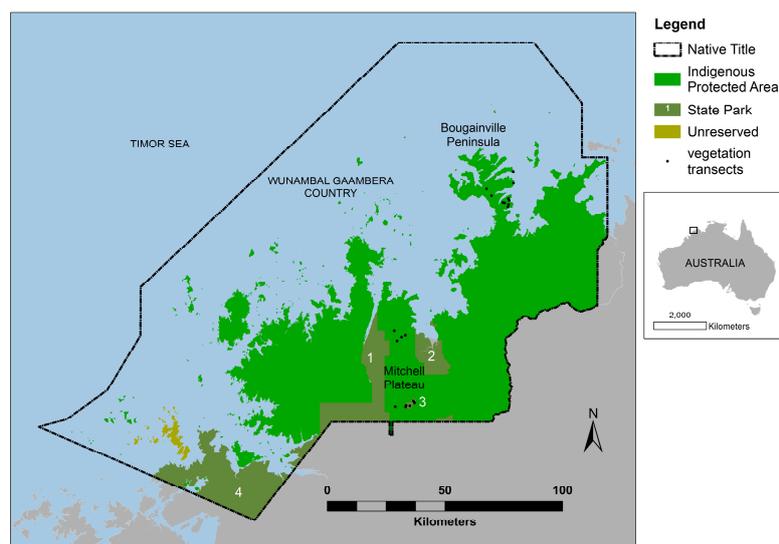

Figure 1. The extent of Wunambal Gaambera country as defined by the Wanjina Wunggurr Uunguu Native Title Determination boundary. The Uunguu Indigenous Protected Area and co-existing State Parks including 1. Mitchell River National Park; 2. Lawley River National Park; 3. Camp Creek Conservation Park; 4. Prince Regent National Park.

The WGC lies within the Kimberley, a dissected plateau of deeply weathered Precambrian sandstones with interspersed areas of Precambrian basalt, occasionally capped by mid-Cainozoic laterite [65]. The climate is tropical monsoonal, characterised by a short summer wet season (November to April) during which most of precipitation occurs, while the rest of the year is virtually rain-free [65]. Mean annual rainfall currently ranges from 1000 to 1400 mm, and average maximum temperatures are equal or higher than 30 °C all year, while average minimum temperatures vary from 20 °C or more in summer to as low as 10 °C in winter [66]. A wetting and warming trend has been detected since the beginning of the 21st century, with an increment in average annual rainfall of 40–50 mm/10 years, and a temperature rise of 0.15 °C/10 years since the late 1940s [66]. WGC falls within the Gardner botanical district classification [65] and the Mitchell sub-region of the North Kimberley Bioregion [67]. Its vegetation is predominantly biodiverse tropical savannas: *Eucalyptus tetrodonta-E. miniata* savannas are found on the hills and laterite mesas, while *E. tectifica-E. grandifolia* savannas are common on deeper, clay soils on plains. Small patches of monsoon rainforests are interspersed in the savanna, typically found in fire-protected locations [65]. These monsoon rainforests support a high diversity of plant species [22] and are important refugia for savanna-adapted mammals to avoid climatic extremes, predators, and fires [68]. The monsoon forests of the North Kimberley Coast and islands and the Kimberley Plateau have been inscribed on the West Kimberley National Heritage List in recognition of the outstanding national heritage value of its evolutionary refugial role, which has resulted in high invertebrate richness and endemism [69,70].

Some of the reported analyses focused on two specific locations with high rainforest density: the Mitchell Plateau and the Bougainville Peninsula, which share similar climate and geology, but different levels of disturbance. The Mitchell Plateau (754 km^2) has a high fire frequency (average times burnt: 0.5 year^{-1}, data from North Australian Fire Information (NAFI) [71], based on a 15-year time period (2000–2014)), and unmanaged cattle are found throughout the area. By contrast, the Bougainville Peninsula (298 km^2) has a much lower fire frequency (average times burnt: 0.08 year^{-1}), and cattle have never been recorded [35]. These dynamics are likely to have persisted during the last several decades; a study performed in 1985 found that half of the surveyed rainforest patches in the Mitchell Plateau were damaged by fire and/or cyclones, while on the Bougainville Peninsula cyclones were the only visible cause of damage [72].

In the Kimberley, the pastoral industry began in the late 1800s. Cattle stations adjacent to the WGC were consolidated only in the 1950s, after the first roads were surveyed and constructed in the far north. Cattle were first recorded at the Mitchell Plateau in 1976 [48], probably moving in from adjacent pastoral leases established from the 1950s. Mining exploration for bauxite occurred at the Mitchell Plateau and Bougainville Peninsula in the 1980s, and cut lines and crushing sites caused disturbance across the laterite plateaus. Mining companies also established a vehicle track and airstrip at the Mitchell Plateau, which facilitated visitation by tourists and promoted weed incursions along roadsides and campgrounds (weeds include grader grass (*Themeda quadrivalvis*), mintweed (*Hyptis suavolens*), and annual mission grass (*Cenchrus pedicellatus* syn. *Pennisetum pedicellatum*). The tourism industry has expanded in recent decades including an expedition cruise industry operating along the coast [73].

Traditional burning practices undertaken by Wunambal Gaambera people [74] declined when traditional lifestyles were disrupted by European colonisation. By the 1960s, Aboriginal burning was limited to areas around communities where Aboriginal people had now settled [75]. The cessation of Aboriginal burning led to the emergence of large destructive late dry season wildfires, set by both anthropogenic ignitions and lightning, that became a dominant feature of the fire regime of the region until recent times [76].

2.2. Mapping Distribution and Local Environmental Factors

An ex novo map of rainforest patches in the WGC was developed to investigate the relationship between rainforest distribution and local environmental factors. The map was generated and ground-truthed as described in Ondei et al. [62], overlaying a 30 m × 30 m lattice on orthophotos

of the area taken in 2005 (most recent available), and manually classifying each cell as 'rainforest' or 'other' based on the dominant vegetation type in the cell. Adjacent cells classified as 'rainforest' were merged to form a rainforest patch. Rainforest density was then calculated as rainforest area/km^2, and associated with local factors, such as geology, topography, and distance from the coastline using thematic layers and ArcMap (v. 10.3, Environmental Systems Research Institute Inc., Redlands, CA, USA). A comparison was then made between mainland rainforests exposed to frequent ambient wildfires and those on islands and peninsulas that have lower fire frequency being naturally fire protected.

Based on the outcomes of the mapping process, we identified the most isolated patches by calculating, for each rainforest patch, the average edge-to-edge distance of the nearest five neighbours, using the 'average nearest neighbour' tool in ArcMap. A simple connectivity index was then calculated as follows:

$$Patch\ connectivity = \frac{A}{Dist}$$

where *A* is the area of the focal patch (ha), and *Dist* is the average distance to the nearest five patches (km) [77]. Patch isolation increases with the decrease of this index. Further analysis was then undertaken to identify risk factors associated with isolation (see 'Vulnerability Index' below).

2.3. Vegetation Transects

Rainforest patches were sampled at two locations to investigate the influence of patch distribution, environmental factors and potential threatening processes on rainforest plants. To do so, vegetation transects, running across the rainforest–savanna boundary, were established in the Mitchell Plateau and Bougainville Peninsula, and the data analysed [61]. Each transect included five 10 m × 20 m plots, and for each plot data on canopy cover, grass cover, rock cover, floristic, stand basal area, and number of adult trees were collected.

Vertebrate species occupancy was also sampled by positioning 40 camera traps (RECONYX, Holmen, WI, USA, HyperFire^{TM} PC800 Professional) along the vegetation transects for 8–9 months (from July/August 2014 to May/June 2015). For each transect, two cameras were positioned, one on the rainforest edge and the other in the savanna, at a minimum distance of 500 m. Initial cattle results are reported in this paper, while other species results are to be published elsewhere.

2.4. Determining Rainforest Change

The next step was to investigate the effects of disturbance on historical rainforest boundary change and vegetation structure [61]. To do so, a landscape-scale natural experiment was performed, mapping rainforest patches (adopting the same 30 m × 30 m lattice applied above) in the fire- and cattle-prone Mitchell Plateau and the low-disturbance Bougainville Peninsula, using available historical aerial photographs from 1949 to 1969, and comparing the results with the map of current rainforest distribution. To associate rainforest dynamics with current vegetation characteristics, each plot in the transects described above was associated to the corresponding vegetation trends, classified as 'stable rainforest', 'rainforest expanded in 1969', 'rainforest expanded in 2005', or 'stable savanna'. This approach is explained in more detail by Ondei et al. [61].

2.5. Examining Threats to Rainforest Health

A controlled burning experiment was conducted to investigate the capacity of rainforest species to survive a low-intensity fire. Rainforest and savanna saplings, located across the rainforest–savanna boundary, were exposed to either a natural low-intensity fire (for savanna species) or a controlled experimental burning, calibrated to reproduce the effects of a natural mild savanna fire (for rainforest species) [47]. Differences in fire-protection (bark thickness), survival rates, and resprouting strategies (basal or aerial) were recorded and compared.

The recent fire history of rainforest patches was examined using 'firescar' data created at a pixel resolution of 250 m based on MODIS satellite imagery, accessed from the North Australian Fire Information website [71,78]. A 250 m buffer was created around each individual rainforest patch and the fire scar data for each year from 2000 to 2015 was analysed using the 'spatial join' function in ArcGIS. Each rainforest patch was considered to have experienced fire if one or more fire scars occurred within its area. This was intended to be an index of fire regime rather than an absolute measure of fire impact on rainforest patches and their boundaries given the low resolution of MODIS relative to rainforest mapping and other limitations with the firescar method [79–81]. Total fire frequency, frequency of early dry season fires (EDS, January to July), and frequency of late dry season (LDS) fires (August to December) were calculated [82]. As described earlier, the period from the 1950s to 2000s had little or no effective fire management, whilst prescribed burning (a combination of ground-lit fires and aerial burning) had been initiated in 2010 through the Wunambal Gaambera Healthy Country Plan. Fire scar years were organised into unmanaged 'baseline' years (2000–2009) and managed 'project' years (2012–2015), aligning with the Wunambal Gaambera Uunguu Fire Project and the Savanna Burning Methodology [82]. The years 2010 and 2011 were excluded from the analysis, as they were 'transition' years where WGAC was reaching management capacity. Differences in the frequency of EDS fires, LDS fires, and total fire frequency were then analysed with a paired t-test. The frequency of fires was calculated using the baseline period (2000–2009, for which fire scar data were accessible) as a sample of the pre-management period (1950s–2000s). Pearson product moment correlation coefficient (*r*) was employed to examine correlations between fire frequency and distance from the coastline as well as slope. Fire frequency was also assessed in relation to geology types using the Kruskal–Wallis test, and the average fire frequency was calculated for each geology type.

In order to identify which patches were most at risk of being completely destroyed by fire, with lower chance of being recolonised, we calculated a vulnerability index, taking into account patch size, distance from neighbouring patches, and fire frequency. The 'Vulnerability index' was calculated for each rainforest patch as follows:

$$\frac{Patch\ connectivity}{Total\ Fire\ Freq_{bas}}$$

where *Patch connectivity* includes information on patch size and distance from the nearest five patches, and total *Fire Freq*$_{bas}$ is the total fire frequency in proximity of the patch recorded during the baseline years. We used total fire frequency because under unmanaged fire regimes even EDS fires can be extensive and intense due to fuel load accumulation. Note that lower index values indicate higher fire risk.

Based on the fire risk index values, we tested for the presence of clusters of patches potentially at risk, by using the Moran's I test in ArcMap on (i) all patches and (ii) the 5% most vulnerable patches. We then evaluated the effectiveness of planned burning in protecting particularly vulnerable patches by comparing using a paired t-test, changes in LDS fire frequency for the 5% most vulnerable patches.

3. Results

3.1. Rainforest Distribution and Local Environmental Factors

A total of 6460 rainforest patches were mapped in the WGC, ranging from 0.1 to 220 ha in size (average 1.6 ha ± 0.1 (SE)), although most (75%) were smaller than 1 ha (Figure 2) [62]. This was a substantial improvement from the previous assessment of rainforest occurrence, which detected 1500+ rainforest patches over an area of 170,000 km^2 of the entire Kimberley region [35]. The disparity was most likely due to the lower resolution (80 m pixel size) of the earlier study, so that smaller patches were not detected.
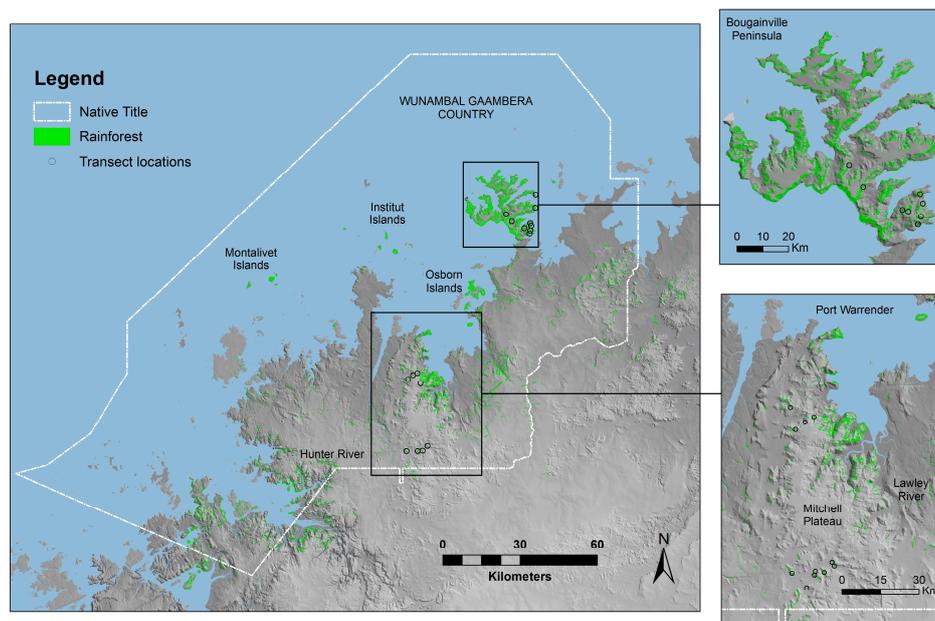
Figure 2. A map of rainforest patches in WGC. Insets show areas of high patch size and density at the Bougainville Peninsula and Mitchell Plateau, including transect locations. Note that patch size has been enhanced to better illustrate patch distribution at map scale.

Rainforest density is strongly dependent on rainfall, as shown by the correlations between rainforest density and mean annual rainfall in the Australian monsoon tropics and distance from coastline [62]. Rainforests were also preferentially located on relatively nutrient-rich substrates, such as basalt, and on fire-protected topographic settings (slopes and valleys). These results confirm the importance of nutrient and water availability, as well as protection from disturbance, as pivotal factors affecting the dynamics occurring between rainforests and savannas [83,84].

The average distance from a rainforest to the five nearest patches ranged from 0.015 to 10.879 km (average 0.659 km $\pm$ 0.011 km), and the patch connectivity index ranged from 0.008 to 7327.150 (average 8.887 $\pm$ 1.774) (Figure 3). The frequency of baseline fires was correlated with distance from the coastline ($r = 0.65$), but not with slope ($r = -0.15$). It also differed significantly between geology types ($p < 0.001$).
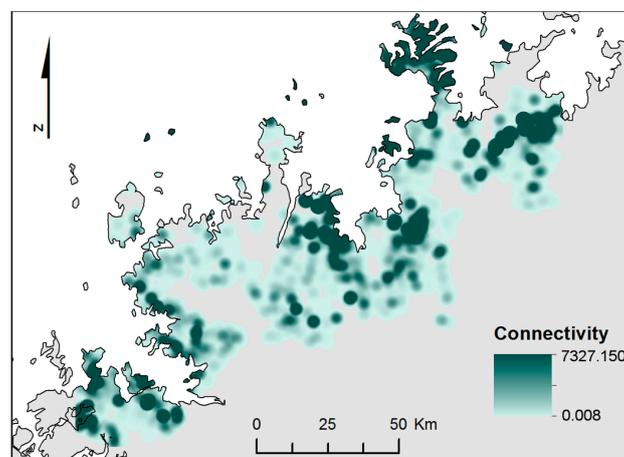

Figure 3. Patch connectivity of rain forests in WGC. Patches with high connectivity (dark shade, up to 7327.150) are larger and/or closer together than patches with low connectivity (light shade, down to 0.008).

3.2. Vegetation and Cattle Patterns

Although not designed to describe the totality of floristic diversity of the area, the rainforest study captured a representative portion of it: we recorded 82 rainforest and 29 savanna tree species on the Bougainville Peninsula, 71 rainforest and 31 savanna tree species on the Mitchell Plateau. Fifteen of the rainforest tree species and 13 of the savanna tree species identified were listed as culturally significant by Karadada et al., 2011 [21]. The Bougainville Peninsula contained regionally interesting floristic elements in both rainforests and savannas. *Eucalyptus oligantha* Schauer and *Xanthostemon psidioides* (Lindl.) Peter G. Wilson & J.T. Waterh, found in the Bougainville Peninsula's savannas, are uncommon in Western Australia, and the latter is considered near threatened in the State (Western Australian Herbarium, 2016). Other species, such as *Acacia drepanocarpa* subsp. *latifolia* Pedley and *Vachellia ditricha* (Pedley) Kodela, were thought not to grow in North Kimberley [85].

Rainforests did not present substantial structural differences between the Mitchell Plateau and Bougainville Peninsula, being characterised by high canopy cover, and absence of grasses and savanna tree species in both locations. Abrupt changes in vegetation were detected across the rainforest–savanna boundary in the Mitchell Plateau, including differences in canopy cover, grass cover, species richness, and the proportion of rainforest trees. Conversely, on the Bougainville Peninsula, these changes were more gradual, and savannas included a high proportion of adult rainforest trees, despite the high grass cover. Rainforest species were also recorded in the understorey of each plot located on the Bougainville Peninsula, signalling ongoing expansion [61]. Our vegetation assessment provided similar results to those of the vegetation survey performed in 1987 [60].

Stinking passionflower was present at only 10% of the vegetation transect plots on the Mitchell Plateau. All of them were close to the rainforest edge; none was inside the rainforest. In contrast, more than half of the plots on the Bougainville Peninsula included stinking passionflower, which was common in savannas and on rainforest edges, but never inside rainforest patches. Where present, stinking passionflower coverage was extensive.

Cattle were not detected on the Bougainville Peninsula, but at the Mitchell Plateau they were detected in camera-traps and their impacts were evident in transects. Cattle were detected twice as often in rainforest as savannas and behaviours included foraging, travelling, and resting (Reid, unpublished), providing the first photographic evidence of the extensive use of rainforests by cattle in North Kimberley, thereby corroborating the conclusion of earlier observers [35]. Rainforests were used but cattle not only for grazing, but also as shelter from the heat and sun. Decreased seedling density was associated with elevated cattle density in both rainforests and savannas, negatively affecting tree species recruitment [61]. Elevated cattle density was not correlated with decreased grass cover in adjacent savanna.

3.3. Rainforest Change

The historical analysis of rainforest patches showed that rainforests had expanded in all locations since 1949, probably in response to the wetting trend detected in the area [66]. However, there were substantial differences in expansion rates associated with varying levels of disturbance. On the fire-protected and cattle-free Bougainville Peninsula, rainforest expanded by 69% (for the 1949–2005 time interval), compared with 9% recorded in the Mitchell Plateau. In areas with low disturbance, rainforests also expanded in topographic settings that do not provide fire protection, such as flat areas, while this phenomenon was not observed in the disturbance-prone plateau. Rainforest expansion was more likely to occur close to the edge of already existing big patches, suggesting that small rainforest patches may be particularly sensitive to local disturbance. These results suggest that fire activity and grazing are important factors affecting rainforest distribution and, at a landscape scale, they modulate the effects of climate-driven vegetation changes.

Aerial photographs from 1949 showed two fire scars that are likely to have been lit by Aboriginal people in the dry season. One fire scar was on the Bougainville Peninsula, in the vicinity of Seaflower Bay, and corresponds to an area of savanna with a cycad (*Cycas basaltica*) population that is known

to have been accessed as a food source (Louis Karadada pers. comm.; [26]) (Figure 4). Another fire scar was located at the Mitchell Plateau in an area that is known to have been an important kangaroo hunting ground (Wilfred Goonack, pers. comm.). In 1949, some indigenous people were still living Traditional lifestyles and many had returned to the bush following wartime bombing raids on Kalumburu in 1943.
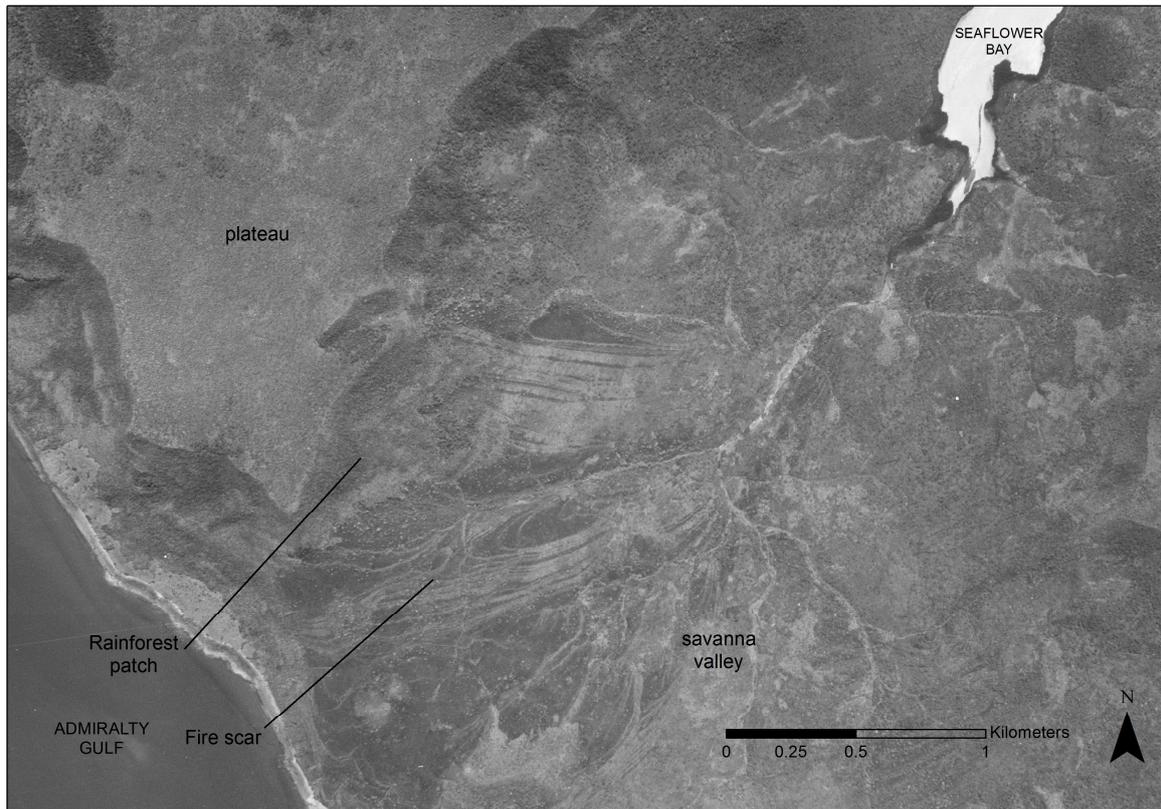

Figure 4. Aerial image of Seaflower Bay, the Bougainville Peninsula, June 1949 with a recent fire scar in a savanna valley in close proximity to a rainforest patch. The savanna valley contains cycad populations that were harvested as a food source by Aboriginal people.

3.4. Fire Ecology

Rainforest saplings displayed capacity to survive a single mild fire during the experimental burning. When exposed to low-intensity experimental fire, most rainforest saplings survived the treatment (81%), although stem survival was lower (63%), probably due to their thin bark. By comparison, savanna saplings experienced higher whole plant and stem survival (98% and 88% respectively). These differences were reflected in their recovery strategies; while savanna saplings expressed both aerial and basal resprouting, rainforest plants were predominantly characterised by basal resprouting. This negatively affected growth rates: rainforest trees were, on the average, 43% shorter after one year, while savanna saplings had regained their pre-fire height [47].

The fire history estimated for the baseline years (2000–2009) showed that total fire frequency around rainforest patches ranged from 0.000 to 0.900 times burnt·year^{-1} (average 0.295 ± 0.003; Figure 5a), while during the project years total fire frequency ranged from 0.000 to 1.000 times burnt·year^{-1} (average 0.333 ± 0.004; Figure 5b) (Table S1). Total fire frequency under unmanaged conditions (baseline years) was correlated with distance from the coastline ($r = 0.65$), but not with topographic slope ($r = -0.15$). It also differed significantly between geology types ($p < 0.001$), with alluvium and colluvium experiencing the highest average frequency (0.36 ± 0.03 times burnt·year^{-1})

and coastal deposits the lowest (0.16 ± 0.02 times burnt·year^{-1}), reflecting contrasting productivity of these substrate types.
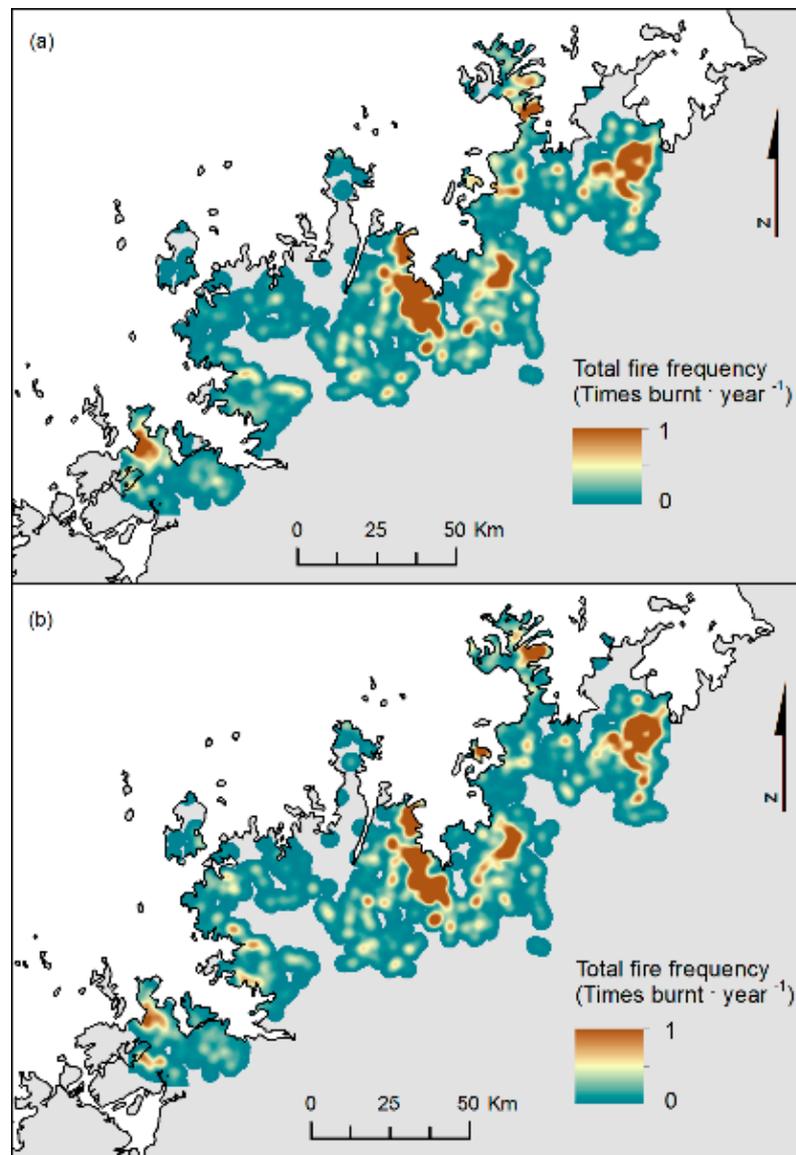

Figure 5. Heat maps showing total fire frequency in proximity of rainforests during (**a**) the unmanaged baseline years and (**b**) the project years.

Prescribed burning, initiated under the Wunambal Gaambera Healthy Country Plan [13] in 2012, resulted in a significant reduction in LDS fires between the baseline years and the project years ($p < 0.001$), and a significant increase of EDS and total fire frequency ($p < 0.001$ for both; Figure 6). Average frequency of EDS fires, LDS fires, and total frequency for the baseline years and the project years are reported in Table 1.

Based on our vulnerability index, which considers patch size, distance from neighbouring patches, and fire frequency, no clustering was detected when considering all rainforest patches. However, when only the 5% most vulnerable patches were considered, we detected significant clustering ($p < 0.001$; Figure 7). The most vulnerable patches experienced a significant reduction in LDS fires, with an average reduction of 0.32 times burnt·year^{-1} during the LDS ($p < 0.001$), while total fire frequency did not significantly change.
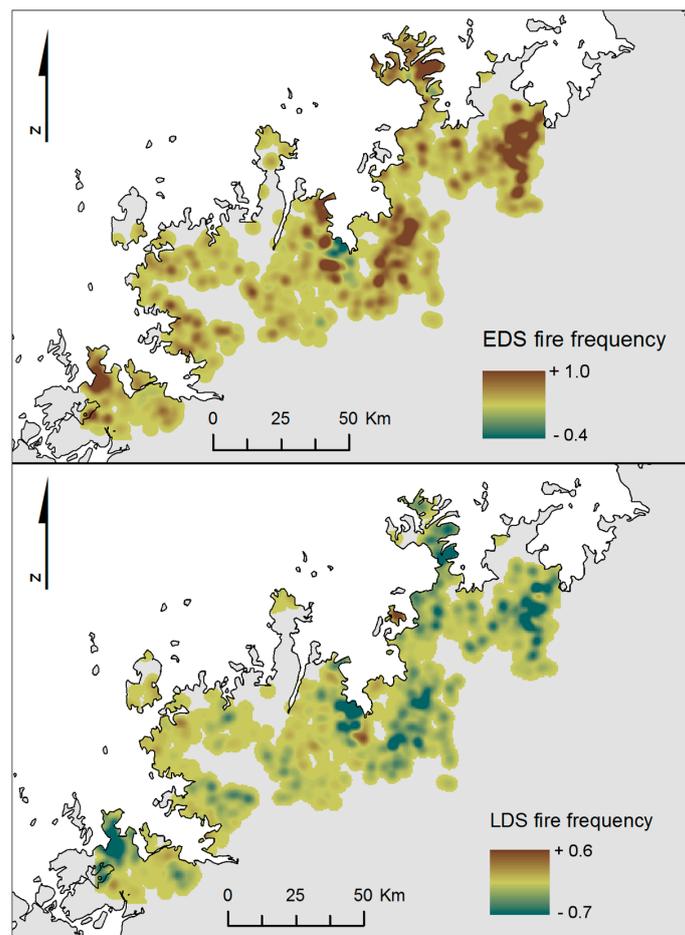
Figure 6. Heat maps displaying variations in the frequency of early dry season (EDS) fires and late dry season (LDS) fires in proximity of rainforests between the baseline years and (2000–2009) and the project years (2012–2015). Note the heat maps reflect change in fire frequency not actual fire frequency as per Figure 5.
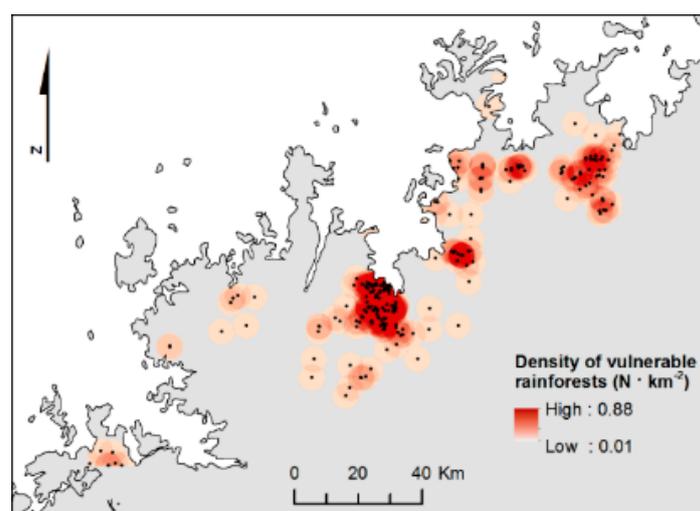

Figure 7. Location and density of the 5% most vulnerable rainforest patches, based on their size, distance from neighbouring patches, and fire frequency. The density map (red gradient) shows some clear clusters of vulnerable patches. Black dots represent single patches.

4. Discussion

This collaborative research project between indigenous land managers and a research institution has been able to fill key ecological knowledge gaps and develop resources and methods for the long-term management and monitoring of 'Wulo' or monsoon vine thickets in WGC.

Rainforest patches have now been effectively mapped and quantified, providing a comprehensive picture of their distribution. Mapping has confirmed that, while rainforest occur in a wide range of geologic and topographic settings, they are concentrated in higher rainfall areas and on richer geographic substrates such as basalt. Patches are typically small (75% are less than 1 ha) and embedded in a flammable savanna matrix with some exceptions. The Bougainville Peninsula holds the largest single rainforest patch, 220 ha in size, as well as 6 other patches over 100 ha in size. Its patches also have a high level of connectivity. Large patches ranging between 10 and 100 ha were also located at key locations including Lawley River National Park, Crystal Head, Hunter River, the Osborn Island group, the Institute Island group, and a few inland sites.

Rainforests occur in clusters of higher density in some locations, such as the Bougainville Peninsula and the Lawley River National Park, while other patches are significantly isolated (such as in inland areas). The fragmentary distribution of rainforests (including those on offshore islands) has facilitated speciation of low-dispersal taxa such as landsnails (a value which has been recognized on the National Heritage Listing of the West Kimberley) [69,86]. Conversely, volant taxa like fruit-eating birds and bats are dependent on the network of rainforest patches (patches are typically small and embedded in a flammable savanna matrix) [87–89]. In this context, there is a need to manage the entire network of rainforest patches to prevent individual patches from contracting below the minimum size needed to support the animal species that currently inhabit them [90], with particular attention to small, isolated rainforests. This is now possible given our detailed mapping of all the rainforests >0.1 ha in extent.

This study found a 10–60% expansion in rainforest boundaries in the last 50 years despite the rise of severe wildfire events during that time. The expansion matches similar trends in Northern Australia attributed to regional wetting trends and perhaps atmospheric CO_2 enrichment over the same period. Climate models predict significant potential for ecological change in Australia's northern savannas [91] including a high turnover of plant species by 2050 [92]. Long-term monitoring can help to determine any change in the number and extent of rainforest patches in response to climate change.

Stinking passionflower was the only weed species recorded in the patches, but other weed species in the region have the potential to change fire regimes and damage both rainforests and savannas [52]. Of concern are large grass species already present in the region that can substantially increase fire severity, with associated savanna and rainforest tree mortality that potentially cause rainforest to retreat. Exotic vines, such as stinking passionflower, which is now naturalized in North Kimberley, have the potential to smother and kill rainforest species [93]. The continuation and evaluation of existing weed management programs is essential to the long-term management of healthy rainforest. In particular, it is important that grass weeds are contained on roadsides and campgrounds and do not establish in the wider landscape.

Large, long unburnt areas can contain relatively high and continuous fuel loads of grass, litter and woody debris, which presents a risk of extensive and potentially destructive fires late dry season wildfire ignited by lightning, as occurred on Bigge Island in 2012 and Middle Osborn Island in 2015 [71]. Nonetheless, in some areas, rainforests have expanded over the past 50 years, and this was most pronounced in areas with low fire frequency such as the Bougainville Peninsula and offshore islands, despite the abundance of grasses found in the adjacent savannas [61]. Small patches were less likely to expand compared with bigger patches, possibly due to their higher sensitivity to intense fires due to higher perimeter to core ratio [52]. By contrast, patches exposed to frequent fire activity, such as at the Mitchell Plateau, were found to have stable boundaries, probably because they are restricted to topographic settings such as slopes and valleys, which, compared with flat locations, provide a higher abundance of nutrients and water as well as fire protection [61,94].

No rainforest patches had contracted or disappeared since 1949, despite having experienced a prolonged period without fire management during which wildfire events were more likely to be severe and large in extent. This suggests that rainforest patches are relatively resilient to fire, somewhat in contrast to other rainforest types such as the Anbinik (*Allosyncarpia ternata*) rainforests on sandstone-derived substrates in Arnhem Land, which are sensitive to wildfire events [95–97]. Edwards and Russell-Smith, in 2009 [37], identified a critical ecological threshold when >10% of patch boundaries are affected by one or more LDS fires. Accordingly, Warddeken rangers undertake an annual program of protecting 50 'at risk' sites with mineral earth breaks and fire breaks [98]. Evidence presented here suggests that most Wulo rainforests do not appear to have the same sensitivity to fire and do not require such intensive management of individual patches as Anbinik but could rather be managed through establishing and maintaining healthy fire regimes in the adjacent savanna matrix in areas characterized by high fire frequency. However, there may be some benefit in applying more direct management to isolated inland patches and vulnerable patches such as those in the Lawley River NP, which are exposed to frequent wildfire.

Rainforest boundaries can be impacted by single severe wildfire events (through inadequate fire management) as well as recurrent frequent management fires. Using a combination of aerial and ground-based ignitions Uunguu Rangers have caused a shift from LDS fires to EDS fires in the savanna matrix adjacent to rainforest patches. This approach is consistent with traditional Aboriginal fire management [20] that limited wildfires that could cause damage to rainforests. Prior to colonization, Traditional Owners burned some savanna areas on the peninsula to facilitate walking, hunting and gathering. In particular, they burnt the open woodland on the laterite plateau and some of the larger savanna areas in the valleys and slopes, including the areas with cycads (*Cycas basaltica*), a traditional food resource and important endemic species (Figure 8). Unburnt areas may disadvantage some plant species such as the cycad population on the Bougainville Peninsula. Traditional Owners, and Aboriginal Rangers involved in fieldwork during this study, suggest that savanna areas that become overgrown with vine thicket elements such as 'arndarn' or thorny vine species (including *Capparis* spp., *Protasparagus racemosa*, and *Smilax australis*) should be burned occasionally to ensure that they do not become unhealthy and impenetrable to people. Clearly, there is a need to carefully balance the health of the substantial rainforest patches and the health of the adjacent savanna matrix.

(**a**)	(**b**)

Figure 8. (**a**) A rainforest patch in a fire protected gully surrounded by open savanna on the plateau of the Bougainville Peninsula, and (**b**) a cycad growing amidst senescent long unburnt grass and invasive Stinking Passionflower vines on the Bougainville Peninsula.

Although cattle have not yet caused rainforest to retreat they may represent a threat for the long-term persistence of some rainforests in the WGC, as found for other locations in the Australian tropics [52]. The local impact of feral cattle on rainforest patches is not easily detectable by remote

sensing, but evidence suggests that cattle are damaging the understorey of rainforest patches. The high number of cattle detections in rainforests, combined with the reduced number of seedlings associated with their presence, is consistent with the observations during early surveys [35], that cattle degraded patches in the Kimberley through trampling and browsing by cattle. Cattle are currently an important source of food for Aboriginal People in the WGC [21], as in other Aboriginal communities in Northern Australia [99]. Traditional Owners are currently developing programs that balance their food needs with conservation objectives, and have undertaken some aerial culling with partner agencies. A fence is also maintained on the narrow neck of the Bougainville Peninsula to keep the area free of cattle and smaller cultural sites have also been fenced off from cattle. Management will likely focus on ensuring that some areas remain cattle-free and that numbers are kept at sustainable levels in high conservation areas such as where there are important rainforest patches. Ongoing monitoring of the structure and floristics of rainforest patches in areas used by cattle is needed to determine the ecological thresholds associated with cattle numbers.

A large proportion of rainforest patches are associated with bauxite reserves that have been the focus of mining exploration in the past. Bauxite is typically extracted by strip mining and requires the clearing of vegetation. Recent legislation permanently removed mining interests from the Mitchell Plateau, but the Bougainville Peninsula has an extant mining lease and remains at risk from mining. Under state legislation, national park tenure provides a degree of protection from mining but requires negotiation between industry, government, and Traditional Owners to achieve.

The monsoon vine thickets of the Dampier Peninsula in Southwest Kimberley were recently recognized as a threatened ecological community under the Environmental Protection and Biodiversity Conservation Act 1999. Given the threats of weeds, cattle, wildfire, and mining, a similar listing of the monsoon vine thickets of North Kimberley may also be justified.

5. Conclusions

We report the findings of a study that sought to provide baseline data on the distribution and health of monsoon rainforests, or Wulo, on the WGC. Using historical and contemporary remote sensing imagery combined with fieldwork, and collaborating with Aboriginal rangers and Traditional Owners, we were able to significantly improve our understanding of the value, health, and threats to this regionally restrictive and biogeographically significant community. Of prime importance is the ongoing management of fire, feral cattle, invasive weeds, and potential mining across the WGC lands. Particular attention, both in terms of land management and legislation, needs to be paid to the Bougainville Peninsula as it has the dual distinction of being one of the largest areas of rainforest in the Australian monsoon tropics but also free from the threat of feral cattle and prevailing wildfires. This study also provides further proof that collaborative research partnerships can provide substantial benefits to Traditional Owners responsible for managing remote high conservation lands and seas.

Author Contributions: The research was conceived, designed and implemented as a collaborative project between WGAC and UTAS. Tom Vigilante and Stefania Ondei drafted this paper with supervision from David M. J. S. Bowman and GIS advice from Paul Young. The paper utilized work undertaken by Stefania Ondei as part of a doctoral thesis as well as additional analyses. Catherine Goonack and Desmond Williams advised and collaborated on field work and Traditional Ecological Knowledge.

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