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People, El Niño southern oscillation and fire in Australia: fire regimes and climate controls in hummock grasslands

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While evidence mounts that indigenous burning has a significant role in shaping pyrodiversity, the processes explaining its variation across local and external biophysical systems remain limited. This is especially the case with studies of climate–fire interactions, which only recognize an effect of humans on the fire regime when they act independently of climate. In this paper, we test the hypothesis that an anthropogenic fire regime (fire incidence, size and extent) does not covary with climate. In the lightning regime, positive El Niño southern oscillation (ENSO) values increase lightning fire incidence, whereas La Niña (and associated increases in prior rainfall) increase fire size. ENSO has the opposite effect in the Martu regime, decreasing ignitions in El Niño conditions without affecting fire size. Anthropogenic ignition rates covary positively with high antecedent rainfall, whereas fire size varies only with high temperatures and unpredictable winds, which may reduce control over fire spread. However, total area burned is similarly predicted by antecedent rainfall in both regimes, but is driven by increases in fire size in the lightning regime, and fire number in the anthropogenic regime. We conclude that anthropogenic regimes covary with climatic variation, but detecting the human–climate–fire interaction requires multiple measures of both fire regime and climate.

This article is part of the themed issue 'The interaction of fire and mankind'.

1. Introduction

Despite calls for a greater understanding of the biophysical and socioeconomic drivers and processes linking fire regimes to human decision-making [1], there is currently little consensus on the historic and/or contemporary role of people relative to climate in shaping the temporal and spatial patterning of fire on the landscape. Some suggest that climate and vegetation dynamics are the primary drivers of fire regimes, and that indigenous burning is and was ecologically insignificant at the landscape scale [2–5]. Much of this work rests on the assumption that the existence of a correlation between climate and fire or vegetation dynamics necessarily precludes human influence. For example, Daniau *et al.* [3] assume that a tight correlation between climatic variation and biomass burning in Africa means that humans played little role in shaping African fire regimes across the vast history of their tenure on the continent. Williams *et al.* [2,6] draw the same conclusion for Australia, proceeding on the assumption that to find human influence, we need to see fire/vegetation anomalies, dynamics that are independent of climate. This argument is based on an analysis showing no significant relationships in cross-correlations of archaeological radiocarbon dates over the last 20 000 years and a synthesis of charcoal records at continental and regional scales. They suggest the lack of correlation contradicts the suggestion of continent-wide land management and habitat modification. Others propose that even in strongly climate-driven fire regimes, indigenous burning shapes plant and animal community structure [7–10], increases pyrodiversity [11–14] and reduces the incidence and or size of large climate-driven lightning fires [15–18] and thus may produce fire regimes which are buffered from climatic variation. While this buffering

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effect could come about because people burn independently of climatic conditions, it might be more likely a result of people burning under *different* climate cues than those that drive lightning fires. Very little research has explored the possibility of interactive effects of humans, climate, vegetation and fire; that is, how climate might influence how and why people use fire at a landscape scale. Understanding how people interact with climate in affecting fire regimes has important implications for understanding the history of fire in shaping ecosystem structure, especially in fire-prone habitats, and for dealing with the effects of future climate change influencing the global distribution and patterning of fire on the landscape. In this paper, we present contemporary evidence for fire regime–human–climate interactions at the landscape scale in an ecosystem with strong fire–climate coupling: the semi-arid grasslands of interior Australia. We ask whether an anthropogenic fire regime is independent of climate, or whether it interacts with climate in ways that might differ from 'natural' regimes.

(a) Fire ecology and climate in Australian grasslands

Grasses dominate much of the interior of the Australian continent. Twenty-six per cent of the total continental land area covered by vegetation (pre-1750 assessment) is grasslands, whereas an additional 56% of open woodlands and forests maintain herbaceous understories dominated by grasses [19]. Perennial xerophytic hummock grasslands comprise the largest single vegetation group on the continent (18%). Hummock grasses grow slowly and are spaced widely, thus their ability to carry fire is dependent upon their size. The growth rates of hummock grasses are highly variable and linked closely to precipitation, thus fire regimes across much of the interior are driven by high seasonal and interannual variation in rainfall [20–24]. As hummock size increases and spacing reduces, greater fuel loads improve the probability of fire spread at lower wind speeds [25]. Because hummock grasses are perennial, and are composed of primarily non-photosynthetic vegetation during dry periods, drought increases their flammability. The high variability of the Australian climate regularly produces several years of high rainfall alternating with several years of drought, which drives episodic pulses of fire that extend across vast expanses of the north and arid interior. This climatic variability is driven by interactions between El Niño southern oscillation (ENSO), the interdecadal Pacific oscillation, the Indian ocean dipole and fluctuations in the strength of the Asian–Australian monsoon [24,26].

However, where these grasslands are subject to aboriginal land use, there is evidence that fire regimes are substantially different, especially in relation to their links with climatic variability. Fires on aboriginal lands throughout northern and central Australia tend to exhibit a higher incidence but lower fire intensity, with the density of fires increasing close to communities and vehicle tracks [11,12,17]. While regions lacking aboriginal ignitions tend to be dominated by infrequent, large, late dry season or early wet season lightning fires, aboriginal-dominated landscapes tend to exhibit fire throughout the year, albeit concentrated in the dry season [13,27]. Previous work on aboriginal fire–climate interactions has shown that cumulative antecedent rainfall causes temporal and seasonal peaks in fire size under a lightning-driven fire regime, but not in landscapes buffered by indigenous hunting fires [17].

Aboriginal ignitions in northern Australian grasslands tend to be focused around facilitating hunting, particularly hunting for small, burrowed animals such as monitor lizards and skinks [8,28,29] but in wetter locations, burning also improves hunting for macropods [30]. In the Western Desert, fires are set targeting large tracts of hummock grass in sandplain habitats. Most of these fires occur during the winter (dry season) months of April–September, when lizards and other herpetofauna are burrowed against the cold. Fire exposes a large area for search, increasing search efficiency by reducing the time to locate occupied burrows. Burning increases foraging returns for burrowed prey during the dry season, and fire incidence tends to increase as monitor lizard hunting improves and more people spend more time hunting [14]. Monitor lizard hunting is increased under conditions of economic scarcity [31] and when dependency ratios are high [32] and like all hunting activities, is more frequent in more remote communities [33]. In many of these communities, burning is organized by indigenous Ranger programmes as part of a variety of different 'caring for country' initiatives [34], but in many others, it also remains part of a hybrid economy in which customary hunting is entangled in market and state sectors but remains vital for subsistence and social purposes [35].

The patterning of hunting fires across the landscape has strongly significant effects on pyrodiversity and the distribution of plants and animals. The climate-buffering effect of indigenous ignitions protects more mature grassland from burning, and creates greater patchiness at the landscape scale [14,17]. More diverse patches of regenerating vegetation in turn support higher populations of animals that form the basis of the subsistence economy: hill kangaroo (*Macropus robustus*) and sand monitor lizards (*Varanus gouldii*) [8,9]. Anthropogenic burning thus supports more sustainable hunting economies and stabilizes plant and animal communities in an ecosystem subject to strong climatic variation. These results would seem to support the hypothesis that anthropogenic fire is decoupled from climate, and acts independently to shape fire regimes. However, if the goal of burning is to increase hunting returns, and hunting returns are affected by climatic conditions, then anthropogenic fire might not be simply decoupled from climate, as is often supposed, but rather it may be linked to the aspects of climate that influence variation in hunting returns.

Towards that end, we focus on teasing out the climatic effects on temporal variation in aboriginal-dominated and lightning-dominated fire regimes over a 10 year period across a 47 000 km^2 region of hummock grassland in Western Australia. Our analysis examines the effects of seasonal and interannual variation in fuels growth, rainfall, temperature, wind speed and wind directional shifts, ENSO and aboriginal foraging decisions on the number of fires, mean fire size and total area burned at roughly six month intervals between April 1999 and March 2010.

(b) Study region

The study region (47 000 km^2) includes a large portion of the Martu Aboriginal Native Title and Karlamilyi (Rudall River) National Park in which two Martu communities (Parnngurr, population 60–80, and Punmu, population 90–120) are located (figure 1). The Martu are a linguistically affiliated group of Western Desert Aboriginal people who were among the last people to live as full-time hunter–gatherers in Australia in the 1950s and 1960s. Punmu was established in 1982 by a group of Martu from Strelley outstation, and

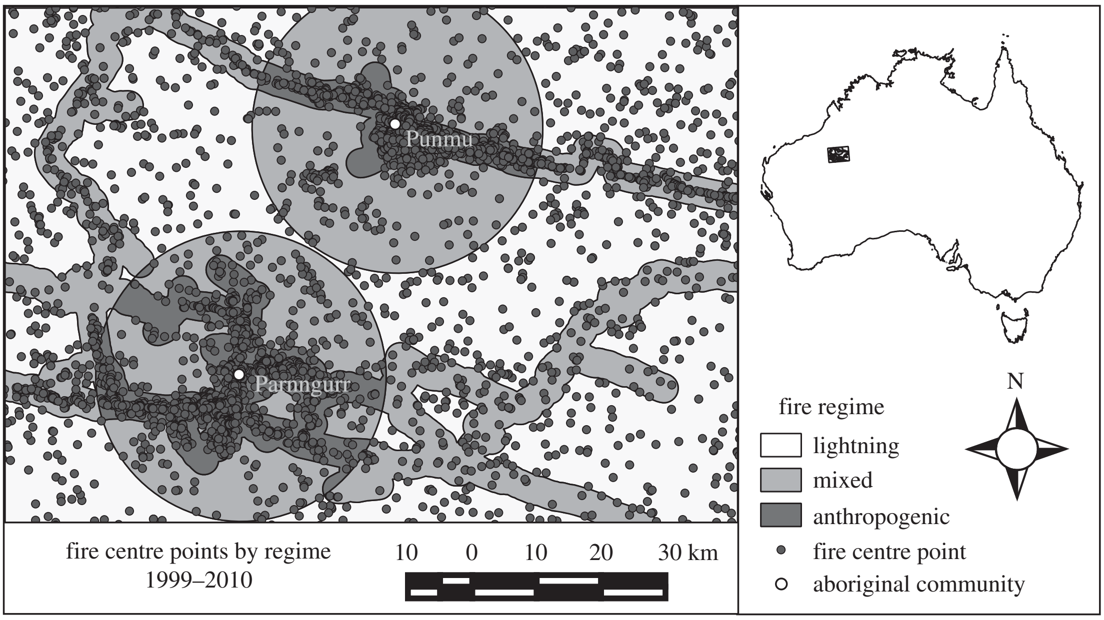

Figure 1. Map of the study region.

Parnngurr in 1984 by a group from Jigalong attempting to halt uranium mining in the area, and have been continuously inhabited since. Many of the families returning to the communities include among their older members those who were living nomadically in this region in the 1950s and 1960s.

The climate of the study region is strongly seasonal and generally hot and dry. Average 30 year rainfall is 384 mm, but with substantial variation, ranging from 113 mm at the lowest in 1977, to 817 mm in 2000, a coefficient of variation of 49% (Telfer Aero, 013030, 21.71° S, 122.23° E, accessed at www.bom.gov.au). Eighty-three per cent of the annual rainfall falls from November–January, the summer wet season. Rainfall has been increasing over the last 100 years by about 10 mm per decade, and also experiences alternating cycles of prolonged drought and excessive rain with an approximately 10 year periodicity. The region is strongly affected by the southeasterly tradewinds during the winter months (May–September), when conditions tend to be cool, dry and sunny; and by the Indo-Australian monsoon and associated convective thunderstorms and tropical storms during the summer months, typically active from December to April. Relative humidity is highest during the summer (30–40%) and lowest in the winter (10–20%). Temperatures are high during the summer, with a daily average of 40°C in January and December, dropping to 25°C in June and July. Minimum temperatures in the winter months are typically mild (14–15°C), with occasional frosty nights in July.

The study area is dominated by extensive red sand dune fields that form long, parallel ridges in the direction of the prevailing tradewinds, interspersed with low rocky breakaways, mesas and ranges. Washes and drainages tend to be uncoordinated, channelling rainfall into localized soaks, clay pans and salt lakes. The sandy, nutrient-poor soil supports four primary ecological communities: (i) spinifex (*Triodia schinzii* and *T. basedowii*) and *Acacia* (*A. pachycarpa* and *A. ligulata*, among others) dominated sandplains and dunes covering 85.6% (40 232 km^2) of the total land area, (ii) lateritic uplands and clay-dominated soils with mulga (*Acacia aneura*) woodland (2.4% or 1128 km^2) and *Senna* shrubland (1.1% or 517 km^2), (iii) *Triodia*-dominated but poorly vegetated rocky ranges (7.3% or 3431 km^2) and (iv) *Eucalyptus* (mainly *E. victrix* and *E. camadulensis*) dominated watercourse margins and floodplains (3.2% or 1504 km^2). Spinifex-dominated arid grassland fire regimes are strongly fuel- and climate-limited. A fuel-limited regime has frequent sources of ignition (mainly via lightning ground strikes) but fire spread is limited by vegetation growth, which is dependent upon soil fertility and rainfall. Here, sources of 'natural' ignition are frequent during summer monsoons, and fuel accumulation is rapid during years of good rainfall [10]. Between fires, there is generally a period of time when fuel loads are too low to support the spread of fire, a period depending upon the rate of growth of the dominant ground-cover fuels. Spinifex is a perennial hummock grass, which grows slowly and with wide spacing, taking at least 5 years of good rainfall to become dense enough to carry a fire.

2. Methods

To construct the fire history of the study region, we used a time series of 21 30 m resolution Landsat 7 TM+ (1999–2002) and Landsat 5 TM (2003–2010) two-image mosaics taken at roughly six month intervals (barring cloud-free days) from November 1999 to April 2010. Fire scars were classified by hand on each image using a ratio of bands 7 and 4, which increased the reflectivity of recent burns. Each fire footprint was hand-digitized in ENVI by comparing the current image with the previous timestep, with November 1999 serving as the base image. The minimum size of detectable fires was 0.1 hectares (two pixels). Ground-truthing of the classified map was completed in May 2011, in which we randomly selected 50 map pixels for ground-based burn age classification, with the constraint that pixels must have burned within the last 3 years and were within 500 m of a road or track (for logistical reasons). Ninety per cent of those map pixels selected for truthing were classified correctly relative to their estimated burn age.

The second classification layer constructed was a fire regime map (figure 1 and [17]), which breaks up our area of interest into two landscapes (anthropogenic and lightning) stratified by which ignition source is dominant. The anthropogenic regime was defined by the density of Martu foraging camps present in our database, which covers 347 sample days and 4461 person-hours of search and pursuit in hunting and collecting (all seasons, June 2000–September 2010) sampled during 12 of the

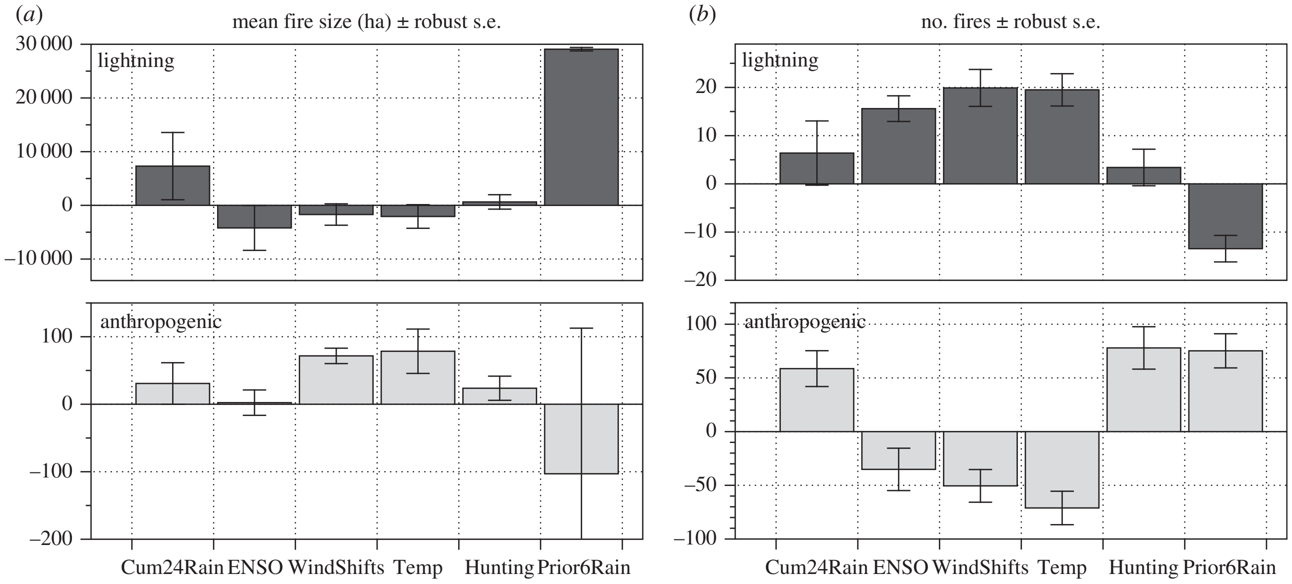

Figure 2. (*a*,*b*) Relative effects of climate variables on anthropogenic versus lightning fire regimes. The standardized coefficients (and associated robust standard errors) predicting number of fires and mean fire size, which can be used to compare the relative effect size across predictors and between fire regimes. The coefficients can be interpreted as showing the change in the mean number of fires with a 1 s.d. change in the predictor variable.

22 timesteps covered by the satellite imagery. On each sample day, we accompanied a foraging group from the community (Parnngurr or Punmu), usually in a vehicle, and recorded the location of the 'dinner camp', a centrally located cooking hearth that served as the temporary home base for the foraging group, and followed at least one hunter as they walked on foot from the dinner camp, which marked the beginning and end of each individual foraging bout. Each foraging bout ($n = 1811$ bouts, 104 different foragers) includes the number, type and weight of all resources acquired by each participant in the foraging party, total time each spent in search, pursuit and processing of each resource type, as well as time spent in burning and the location of ignition points. Vehicle tracks used during foraging trips were mapped using a hand-held GPS and overlaid on the fire map to construct the buffer zones. A buffer zone of 5 km to either side of roads and tracks up to 50 km from an aboriginal community is the anthropogenic regime, characterized by mainly Martu ignition sources (484 230 ha, or 10% of the total area of interest). The lightning regime (2 315 552 ha or 50% of the total area of interest) includes regions greater than 50 km from communities and 5 km from tracks. The remainder of the landscape is a mixed regime with neither influence predominating. To analyse fire size distribution, we plotted the spatial location of each fire centroid on the regime map. Fires were attributed to regimes based on the location of this centroid (figure 1).

Climate variables that influence fire size, incidence and extent were obtained from the only recording station within the area of interest (Telfer Aero, 013030, 21.71° S, 122.23° E, accessed at www.bom.gov.au). We selected climate variables that are well-known correlates of fire spread and ignition rates: rainfall, which affects fuel moisture in the short term and fuel growth and continuity in the long term [21]; ENSO index, which affects rainfall, lightning frequency and the strength and penetration of the Indo-Australian monsoon, with a positive ENSO increasing lighting frequency [36]; and daily variation in wind direction and mean temperature, which affects evapotranspiration and fuel flammability, both influences on fire spread [37]. Climate variables used in this analysis include: *fuel load*, measured as cumulative 24 month antecedent rainfall (mm); *Prior6*, the prior six month rainfall (mm); *rain*, the rainfall during the time period over which fires were counted; *wind shifts*, the average daily difference in wind direction (the difference in degrees between the wind direction at 09.00 and at 15.00) and *temp.*, the mean afternoon temperature. Each variable was averaged over each six-month timestep. The *ENSO* index used in this analysis is the bivariate ENSO time series (BEST index; [38]), calculated as the mean index for a six month period prior to the image date. For comparison, we also use the observed percentage of foraging time spent in hunting activities that depend on fire (monitor lizard hunting), which is available for 10 of the 22 timesteps. The dependent variable mean fire size was log-normally distributed and was analysed using a maximum-likelihood generalized linear model with a Gaussian distribution and a log link; total area burned used a gamma distribution and a log link, anthropogenic number of fires was normally distributed and used a Gaussian distribution and an identity link, and lightning/mixed fire number used a gamma distribution and identity link. Model fit was assessed by examining the deviance residuals. All analyses were conducted in STATA v. 13.1 [39]. All research involving human decision-making was approved by the Stanford Institutional Review Board and the Martu Prescribed Body Corporate. Data used in this paper are available by request to the primary author.

3. Results

We find disparate effects of climate across two of our three measures of fire regime (figure 2, tables 1 and 2). The number of fires and mean fire size respond to very different climate influences in anthropogenic compared with non-anthropogenic regimes. In the anthropogenic regime, a strong El Niño six months prior (an ENSO index above 1, which tends to correlate with dryer conditions in the study area) reduces the number of fires, but it significantly increases fires in a lightning-dominated regime. Positive ENSO also reduces lightning fire mean size, and negative values increase it, while having no effect on mean size in the anthropogenic regime. Fuel load increases the number of anthropogenic fires, and the size of lightning fires, but not the number of lightning fires. Rain in the prior six months strongly increases the number of anthropogenic fires but strongly decreases the number of lightning fires while simultaneously increasing their size. In the anthropogenic regime, shifting winds and high temperatures decrease the number of fires, whereas

Table 1. Results from generalized linear modelling of climate predictors on the number of fires, size of fires and total landscape area burned ($n = 22$ six-month timesteps between April 1999 and March 2010) for three types of fire regimes distinguished by their primary ignition source: anthropogenic (Martu), lightning and a mixed regime where neither predominates. Climate variables used in this analysis include: cumulative 24 month antecedent rainfall (mm) (fuel load), prior six month rainfall (mm), average daily difference in wind direction (the difference in degrees between the wind direction at 9.00 and at 15.00 pm), and mean afternoon temperature. The human variable used in this analysis is the proportion of total foraging time observed hunting parties spent on monitor lizard hunting during the period covered by the satellite image timestep. Because mean and sum area burned use log links, we report both the exponentiated regression coefficients, and (in brackets) the marginal change (*dy*/*dx*) in the dependent variable with a one unit change in the independent variable; for the number of fires, the coefficient is the unit increase in the mean value of the dependent variable with one unit increase in the independent variable. D^2 reports the percentage of the model deviance explained by the covariate (as Cameron and Windmeijer's pseudo-R^2 [40]).

		no. fires			mean fire size (ha)			total area burned (ha)		
predictor		Martu	light	mix	Martu	light	mix	Martu	light	mix
ENSO	β	−41.67	18.51	8.88	1.02 [2.76]	0.41 [−4984]	0.76 [−315]	0.62 [−8798]	0.75 [−34420]	1.3 [16 863]
	95% CI	−87.5, 4.1	12.3, 24.7	−4.6, 22.3	0.70, 1.5	0.19, 0.90	0.34, 1.7	0.35, 1.1	0.35, 1.6	0.57, 2.8
	p	0.075	0.001	0.197	0.902	0.027	0.501	0.092	0.444	0.551
	D^2	10.60%	40.00%	6.20%	0.04%	14.30%	2.90%	10.70%	1.70%	1.40%
fuel load 24 months rain (mm)	β	0.18	0.02	0.03	1.00 [0.09]	1.00 [22.6]	1.0 [2.5]	1.0 [31.8]	1.0 [259]	1.0 [223]
	95% CI	0.08, 0.28	−0.02, 0.06	0, 0.06	0.99, 1.0	1.0, −1.0	1.0, 1.0	1.0, 1.0	1.0, 1.0	0.99, 1.0
	p	0.001	0.337	0.049	0.364	0.011	0.019	0.003	0.001	0.051
	D^2	32.70%	2.30%	11.90%	4.90%	22.40%	7.10%	31.20%	14.50%	13.40%
prior six months rain (mm)	β	0.33	−0.06	−0.05	0.99 [−0.45]	1.03 [128]	1.0 [1.7]	1.0 [12.7]	1.0 [117]	0.99 [−70.8]
	95% CI	0.19, 0.47	−0.08, −0.03	−0.10, 0.01	0.98, 1.01	1.03, 1.04	0.99, 1.01	0.99, 1.0	0.99, 1.0	0.99, 1.0
	p	0.001	0.001	0.091	0.675	0.001	0.781	0.448	0.368	0.434
	D^2	48.60%	25.40%	9.80%	13.40%	97.40%	2.50%	2.30%	2.00%	2.60%
wind shifts (degrees)	β	−4.92	1.94	0.43	1.06 [6.97]	0.97 [−166]	1.04 [74.5]	1.02 [411]	1.02 [2739]	1.1 [9345]
	95% CI	−7.8, −2.0	1.2, 2.7	−0.97, 1.84	1.03, 1.09	0.93, 1.01	1.0, 1.1	0.98, 1.1	0.96, 1.1	1.0, 1.2
	p	0.001	0.001	0.551	0.001	0.144	0.002	0.317	0.478	0.037
	D^2	22.40%	33.20%	1.40%	42.70%	1.60%	7.30%	3.20%	1.20%	18.00%
temp. (°C)	β	−16.87	4.63	1.92	1.16 [18.6]	0.91 [−491]	1.0 [12.3]	1.01 [253]	1.04 [5254]	1.1 [12407]
	95% CI	−24.1, −9.6	3.1, 6.2	−1.1, 4.9	1.0, 1.3	0.83, 1.0	0.91, 1.1	0.89, 1.1	0.89, 1.2	0.95, 1.4
	p	0.001	0.001	0.215	0.016	0.056	0.892	0.834	0.61	0.163
	D^2	45.40%	46.50%	7.10%	30.60%	2.60%	0.03%	0.10%	0.70%	7.60%
hunting time (per cent)	β	3.13	0.13	0.49	0.05 [0.95]	0.01 [25]	1	0.25 [568]	0.42 [5666]	0.06 [833]
	95%CI	1.6, 4.7	−0.16, 0.44	0.11, 0.87	0.22, 114	0.33, 5.5	0.29, 3.7	0.07, 0.9	0.05, 35.1	0.001, 554
	p	0.001	0.371	0.011	0.309	0.673	0.967	0.001	0.098	0.401
	D^2	57.60%	3.10%	31.90%	9.50%	0.20%	0%	31.60%	5.60%	2.90%

Table 2. Summary of climate effects on fire regimes. Plus or minus signs show positive/negative effects on the dependent variable, whereas the number of signs indicates the strength of the effect.

	no. fires			mean fire size			total ha burned		
	Martu	lightning	mix	Martu	lightning	mix	Martu	lightning	mix
ENSO	−	+++			−−		−		
24 months rain	+++		+		++		+++	++	+
prior six months rain	+++	−−−			+++				
wind shifts	−−−	+++		+++					+
temperature	−−−	+++		+++	−				
hunting time	+++		++				+++		

these conditions increase the number of lightning fires. Overall, the strongest effects on fire incidence in the lightning regime are ENSO and temperature, whereas fire incidence in the anthropogenic regime is best predicted by prior six month rainfall and the proportion of time people devote to hunting burrowed lizards. Fire size is best predicted by prior rainfall in the lightning regime, and by wind and temperature in the anthropogenic regime.

However, while fire incidence and size in anthropogenic versus lightning regimes respond to very different climate conditions in different ways, the total area burned in all regimes covaries only with antecedent cumulative rainfall. The total area burned in the anthropogenic regime also covaries strongly with foraging time.

4. Discussion

Our results do not support the hypothesis that anthropogenic fire regimes in the Western Desert of Australia are uninfluenced by climate. Here, anthropogenic fire regimes are significantly different than lightning regimes, but neither are uncoupled from climate. That human fire responds to climate shifts suggests that climate shifts play an important role in structuring hunting decisions, particularly in affecting the likelihood of people using fire to increase economic gains. In pursuit of burrowed prey, Martu maintain a regime that responds differently to climate than does a lightning-dominated regime. The lightning regime varies primarily in the mean size of fires, whereas the anthropogenic regime varies primarily in fire incidence. Aboriginal hunters light more fires when temperatures are low, winds are consistent, and fire size and direction can be more easily controlled. Lightning causes more fires when conditions are better for fire spread. From year to year, increases in vegetation caused by extensive rainfall fuel very large fires in the lightning regime, but the human response to fuel build-up is to light more, smaller fires. Fire size in the anthropogenic fire regime covaries most with shifting winds and temperatures, whereas fire size in the lightning regime responds most strongly to prior rainfall. Aboriginal hunters thus seem to respond to climate variation in ways that buffer its effects on the fire regime, creating stability in the face of chaotic non-equilibrium dynamics.

These kinds of fire–human–climate dynamics are increasingly recognized as playing an important role in shaping community structure in in ecosystems characterized by high interannual and interseasonal variability in precipitation [41]. ENSO cycling plays an important role in Australian fire regimes in the absence of people. Shifts from a human- to lightning-dominated fire regime in the face of strong ENSO cycling are suspected to be the major cause of recent population extinctions of native mammals in Australia [42,43]. Between 1920 and 1970, a diachronic shift in the density of fires in the Western Desert occurred, with 100-fold fewer fires 1000 times greater in size [16], coincident with the regional loss of aboriginal population through introduced disease, economic shifts and forced dispossession. Similar shifts in the regime occurred in our study region, but with the aboriginal re-occupation here in the mid-1980s, a regime identical to the historical one re-established close to roads and communities [44]. Coincident with these fire regime shifts, 21 species of native marsupial went extinct, and 43 more are currently in decline [19,45,46]. Most of the species losses were concentrated in the hummock grassland ecosystems, which lost proportionately more species than any other bioregion in Australia. In these ecosystems, absence of fire allows hummock grasses to out-compete and crowd out a variety of other shrubs, forbs and grasses, many of which are important food sources for many species [25]. However, mature patches of hummock grass are also superb refuge for smaller, ground-dwelling native species, and access to such patches tends to improve survivorship, especially in regions that have recently been burnt [42]. A patchier fire mosaic with smaller fires is thus suspected to support higher populations of fire-sensitive native mammals by increasing access to refuge from predation, and reducing the costs of foraging [47–49]. With the onset of strengthening ENSO climatic variability during the mid-Holocene [50–52], it seems likely that aboriginal fire ignitions in hummock grass ecosystems would have played a significant role in maintaining some form of stable equilibrium for fire-sensitive species, an equilibrium that has since been lost over much of the region, because of colonization and forced dispossession of aboriginal lands.

Given the continuing debate over the economic viability of remote aboriginal communities such as these, there is a strong threat of losing even these local influences over the fire regime [53]. This could be devastating in the face of climate change: over the past 50 years, there has been an increase in seasonality in northern Australia, stemming from increases in the amount of rainfall, the duration of rain events, and greater interannual variability [54]. As climate change accelerates, variability in precipitation is predicted to become more extreme across Australia, resulting in an increased frequency and duration of droughts interspersed with periods of heavy rainfall driven by a strengthening monsoon [55]. This increased climatic variability is suspected to drive increases in fire activity, especially in the size and severity of fires, which, in turn, would create conditions for high levels of predation and habitat loss and cause severe population declines in many small, ground-dwelling native species. Because people respond to fuel build-ups by lighting more small fires, the effects of increasing variability would be mitigated in an anthropogenic-dominated fire regime.

Similar climate-buffering arguments have been made for other fuel-limited fire regimes, such as savanna grasslands in Africa, where anthropogenic burning may stabilize lightning-driven fire regimes in ways that permit long-term coexistence of grass and trees, preventing one or the other from achieving dominance [56,57]. Likewise, savanna mosaics in Brazil may have been maintained through indigenous burning [18]. However, in ignition-limited fire regimes (ecosystems where lightning is rare and rainfall is high and fires rarely ignite or spread), humans may interact with climate in ways that intensify its effects and cause rapid shifts from forest to grassland ecosystems as may have occurred following the Maori colonization of New Zealand [58,59]. Likewise, the loss of aboriginal burning from ecosystems adapted to it may cause state shifts favouring the dominance of trees and woody shrubs relative to grasses [60,61]. Whether anthropogenic burning buffers climate–fire interactions or intensifies them may depend critically on the existence of self-reinforcing positive feedbacks along gradients of ecosystem productivity and rainfall [62].

More broadly, this analysis suggests that debates over the relative importance of humans versus climate in shaping vegetation and fire dynamics are misplaced. Attempts to tease out their relative impacts are based on the assumption that human decisions about burning are essentially random with respect to climatic conditions, and that finding correlations between climate and fire/vegetation dynamics precludes any human influence. However, the data presented in our analysis clearly show that we cannot disentangle human versus climatic drivers of fire-regime change in the way that Williams *et al.* [2] assume. Across a vast region of Australia's Western Desert relatively few foragers can generate radical landscape-level changes in fire regimes. Those anthropogenic regimes emerge from the way that people differentially respond to climate variability, which in the Martu case, results in dramatically smaller but more numerous fires in dry cool conditions. This feeds back to buffer against the effects of ENSO cyclicity which, in the absence of human burning, significantly increases both fire ignitions and fire size. Anthropogenic fire regimes thus emerge from dynamic interactions between people and climate and are clearly detectable at landscape-level scales, but would not be predicted in an analysis that decouples climate and human drivers of fire regime dynamics. Rather, as some are beginning to point out [63,64], climate affects not only plants and animals, but human populations, mobility and land/resource use decisions as well, which in turn have significant effects on fire and vegetation at landscape scales.

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