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Managing the human component of fire regimes: lessons from Africa

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Human impacts on fire regimes accumulated slowly with the evolution of modern humans able to ignite fires and manipulate landscapes. Today, myriad voices aim to influence fire in grassy ecosystems to different ends, and this is complicated by a colonial past focused on suppressing fire and preventing human ignitions. Here, I review available evidence on the impacts of people on various fire characteristics such as the number and size of fires, fire intensity, fire frequency and seasonality of fire in African grassy ecosystems, with the intention of focusing the debate and identifying areas of uncertainty. Humans alter seasonal patterns of fire in grassy systems but tend to decrease total fire emissions: livestock have replaced fire as the dominant consumer in many parts of Africa, and fragmented landscapes reduce area burned. Humans alter the season and time of day when fires occur, with important implications for fire intensity, tree–grass dynamics and greenhouse gas (GHG) emissions. Late season fires are more common when fire is banned or illegal: these later fires are far more intense but emit fewer GHGs. The types of fires which preserve human livelihoods and biodiversity are not always aligned with the goal of reducing GHG concentrations. Current fire management challenges therefore involve balancing the needs of a large rural population against national and global perspectives on the desirability of different types of fire, but this cannot happen unless the interests of all parties are equally represented. In the future, Africa is expected to urbanize and land use to intensify, which will imply different trajectories for the continent's fire regimes.

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

1. Introduction

Humans impact fire regimes directly by altering the number and timing of ignitions or suppressing fires, and indirectly by altering climate and fuels (figure 1*a*). The relative importance of these impacts globally will vary depending on which factors limit fire, and the type of human activities. In North American boreal forests, the direct impacts of people result in smaller fires due to active fire suppression and increased ignition events [1]. However, indirect human impacts on current climate (increased temperatures and drier fuels) act to increase fire size, fire intensity and total area burned [2].

The impacts of people on fire accumulated slowly over time in Africa, but more recently and abruptly on other continents (figure 1*b*). Determining which human activities drive fire regimes can sometimes be complicated. In Australia, there is evidence for increased biomass burning associated with human colonization 40–50 000 years BP [3], and this has been explained as a direct result of increased ignitions by people [4]. However, humans also exterminated the indigenous mega-fauna of Australia, released herbivory pressure, and thus increased the fuels available for burning [5]. Whether the direct or indirect impacts on fire regimes drove the patterns observed is still under debate.

These issues become important when assessing current impacts of people on fire, and attempting to manage global fire for conservation/safety/geoengineering objectives. It has often been assumed that direct human impacts—through ignition and suppression activities—are what are driving current fire regimes, and these have been the focus of policy and management interventions [6,7].

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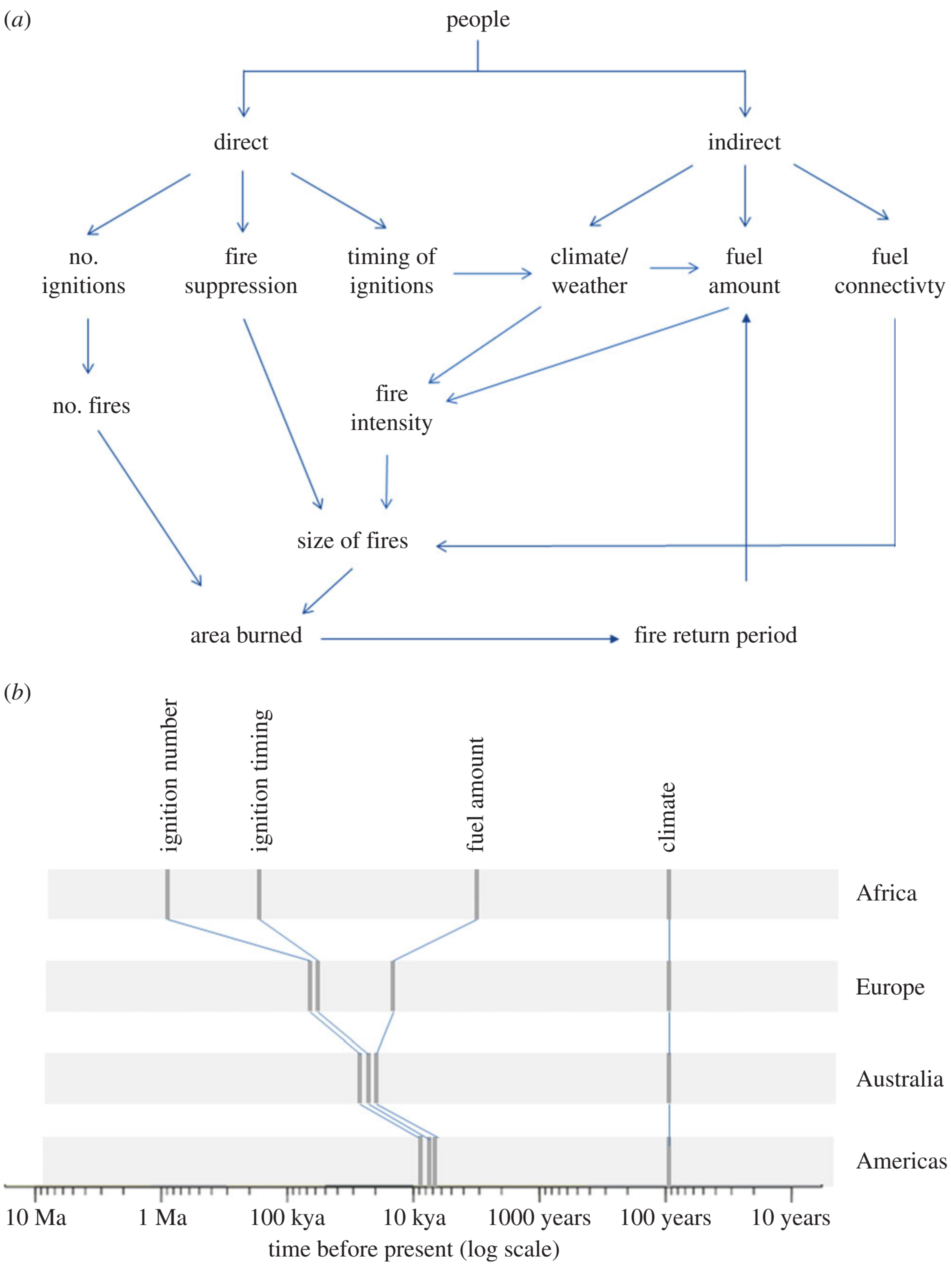

Figure 1. (*a*) The direct and indirect pathways by which humans impact fire and the aspects of fire that are impacted. The relative importance of these pathways depends on the socio-ecological context. In Africa, the impacts on fuels and timing of ignitions currently outweigh the impacts on ignition number or climate. (*b*) The estimated timing of these impacts in four different parts of the globe. Impacts on fire in Africa accumulated slowly over time, but more recently and abruptly in other continents. Impacts on fuels can be positive (extermination of herbivores) or negative (livestock grazing, cultivation, fragmentation). Climatic impacts have occurred the most recently, and uniformly throughout the globe.

Ignoring the numerous indirect impacts of people on fire (figure 1*a*) can lead to ineffective fire management and perverse outcomes [8,9].

A fire regime represents the repeated pattern of burning at a location in space. At global scales, a fire regime is equivalent to a biome/climate region: it represents large-scale syndromes of fire characteristics that emerge due to energetic constraints in relation to fuels and climate [10,11]. Like climate and vegetation, fire regimes can change over time in response to changing drivers, and the dependencies and interactions between climate, fire, people and vegetation are still being unravelled [12–14]. Recent analyses suggest that global fire regimes (pyromes) and global vegetation types (biomes) are closely linked due to feedbacks where fuels determine the type, extent and frequency of fire, and fire controls vegetation structure and biome boundaries [10]. However, the most striking pattern globally is the impact people can have on fire regimes (figure 2)—homogenizing different fire regimes into one 'human-derived' pyrome, which shares similar characteristics (small, cool fires, long fire seasons) across a wide range of climates and fuels. Other research confirms that the overriding impact of people on fire globally is to reduce fire size [15] and increase the length of the fire season [16]—i.e. fires in areas with high human densities are limited by fuel continuity, but are released from ignition limitation, and are less dependent on appropriate weather conditions. Despite their homogenizing influence at global scales, local-scale impacts of people on fire are often perceived as disruptive, and diversifying [17], precisely because they can relieve some constraints, and create others (figure 1).

This paper assesses the relative importance of various human impacts on fire in grassy ecosystems using Africa as a

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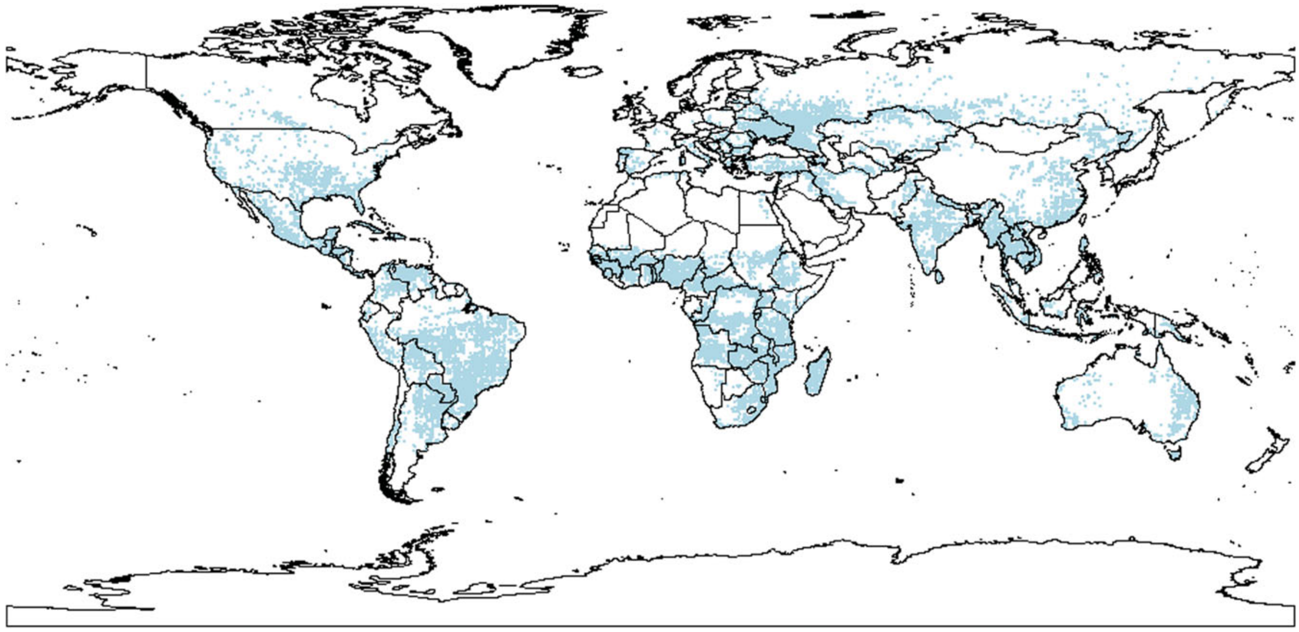

Figure 2. Showing the extent of the human-derived pyrome: areas of the world where fire characteristics are largely controlled by human impacts. Diverse biomes and environments converge on a homogeneous fire regime under high human impacts. Adapted from [10].

case-study. I focus on relationships with population density, although other socio-economic factors are also important in determining how and why people use fire [17–19]. Africa has a long history of human fire, longer than any other continent [20] (figure 1*b*), but current fire management issues on the continent are complicated by (i) a recent colonial past which enforced fire suppression, (ii) a rapidly growing (and rapidly urbanizing) population and (iii) global pressure to initiate climate-mitigation programmes in Africa—often involving changes in how fire is used. Clear information on the past and present impacts of people on various aspects of fire is essential for resolving some of these issues.

The implications are important. Arguments that current fires in Africa are exacerbating industrial greenhouse gas (GHG) emissions [24–26], and reducing precipitation [27] are all based on the assumption that these fires are excessive and unprecedented. This narrative needs to make way for a more nuanced understanding of human–fire interactions in grassy systems: how people act to alter different aspects of a fire regime, and how this varies across productivity/vegetation gradients. Moreover, this understanding should also give us the tools required to intervene in grassy fire regimes to achieve particular objectives.

2. Current area burned in Africa

Remotely sensed information has highlighted both the massive extent of area burned in Africa (2.56 $Mkm^2 yr^{-1}$) and the large number of individual fire events [21]. These data need to be assessed with the knowledge that Africa contains the majority of the world's tropical grassy ecosystems (savannas), and these systems burn far more than any other vegetation type (75% of the total annual burned area occurs in savannas, although they account for only 20% of the global landmass). However, there is still significantly (χ^2-test, $p < 0.001$) more fire in African savannas than would be expected if grassy systems burned equally.

Consequently, it is difficult to believe that the area burned currently in Africa is probably lower than it has been for several thousand years. However, both spatial data and charcoal data confirm this: spatially, there is a strong negative correlation between population density and total area burned [22]—implying that as population numbers increased in Africa in the past few centuries, extent of fire has declined. This is confirmed by palaeo-ecological data which show a downturn in charcoal counts in tropical countries in the past few hundred years [23]. Moreover, the striking contrasts in figure 3 confirm that the areas that burn most extensively in Africa are generally national parks—the least populated parts of the continent.

3. Human impacts on fire in African savannas

As confirmed by data all over the world, human presence in landscapes increases the number of ignition events above the background from lightning strikes. In Africa, *ignition numbers* increase fairly linearly with population density up to a maximum of 10 people km^{-2}, and decrease again as humans start living in closer proximity to each other (figure 4*a*). From data in southern Africa, we estimate that at densities of 2 people km^{-2}, one in every 80 people would need to ignite a fire each year to achieve the observed fire occurrence. This decreases to one in 200 people for 10 people km^{-2}. By contrast, the *size of fires* decreases exponentially with population density [29] and figure 4*b*. It is this impact on fire size that dominates the response of burned area to population density: burned area strongly declines when populations increase above 10 people km^{-2}.

This unintuitive result—that *area burned* in Africa is relatively insensitive to ignition number—is explained by the dynamics of fire spread. Like any percolation process fire exhibits threshold dynamics—where an ignition is either able to spread throughout a landscape, or goes out without burning much area [30,31]. This means that once systems are fragmented below the fire spread threshold then increased ignitions cannot easily compensate for the reduced connectivity (it would take

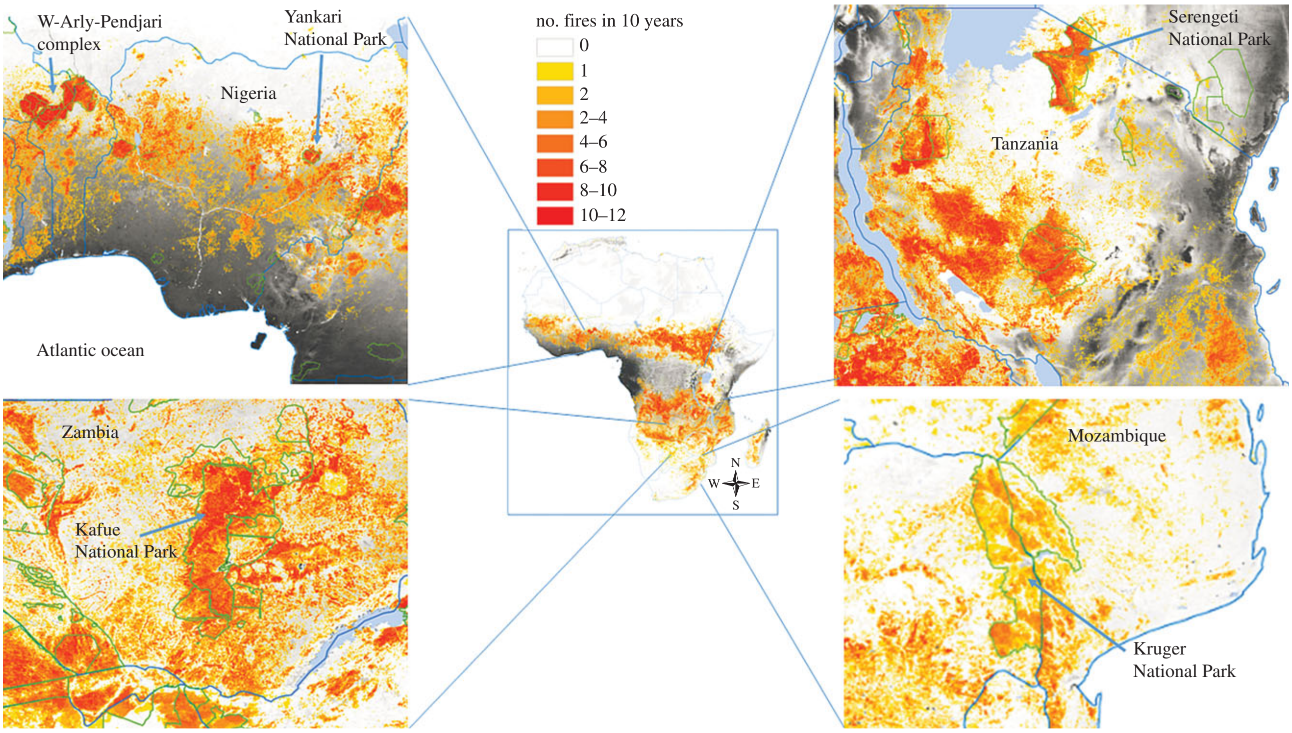

Figure 3. Fire frequency in different parts of Africa (the number of times a fire was recorded in a 500 × 500 m MODIS pixel over 10 years from 2000 to 2010). Clearly National Parks (the least inhabited parts of the continent) burn more extensively, but not more frequently, than non-protected and inhabited regions. This is clear demonstration of the importance of indirect impacts of humans on fuels in grassy systems: by replacing fire with livestock and fragmenting landscapes they have greatly reduced the total area burned in Africa.

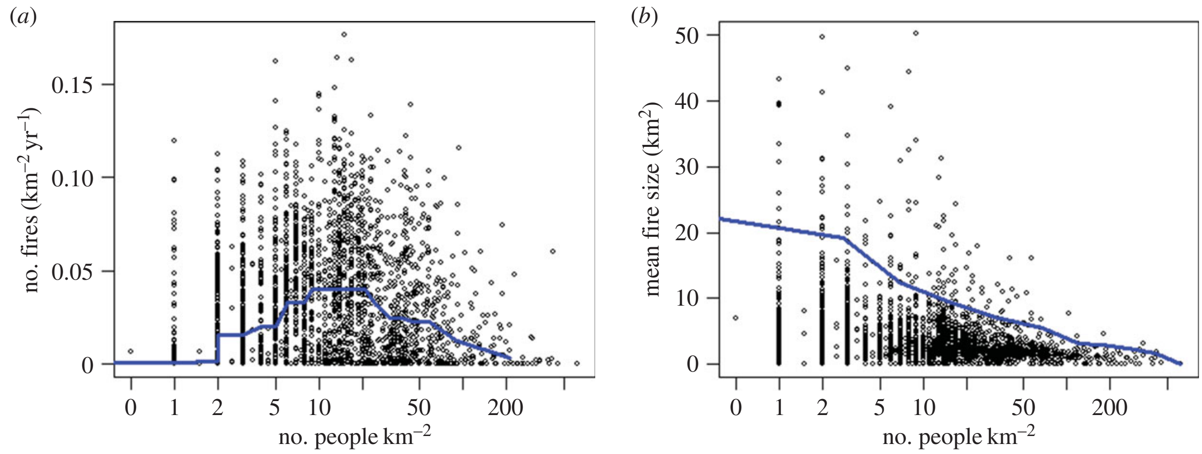

Figure 4. (*a*) Relationship between number of people and the number of fires. (*b*) Relationship between the number of people and the size of fires. Points represent the value per 50 km grid cell. Solid lines represent the median values in (*a*), and the 95th quantiles in (*b*). All data are for Africa south of the Equator and were derived by identifying individual fire events using the methods described by Archibald & Roy [28], i.e. they represent individual ignition events, not active fire hotspots.

many hundreds of fires to burn a substantial area in a disconnected landscape).

The conclusion is that the direct (figure 1*a*) impact of people in increasing ignitions in Africa is swamped currently by their indirect (figure 1*a*) impacts on fuel amount and fuel continuity. These impacts are predominantly associated with high livestock densities consuming fuel that would otherwise burn [32], but the proportion of croplands [33] and the number of roads [22] also act to reduce area burned by fragmenting landscapes. The timing of this impact is fairly recent—livestock and cultivation only spread in Africa in the past 2000–4000 years ([34]; figure 1*b*) and has also not been uniform spatially. In wet, nutrient-poor savannas in Africa, livestock (cattle, goats and sheep) are functionally unable to replace the bulk-feeding herbivores (buffalo, elephant, rhino) that were the dominant herbivores in the past [35], and tsetse flies also constrain livestock production. These areas now have fewer grazers than they did before, and they currently burn extensively.

Another potentially large indirect human impact on fire is through altering woody cover. Poor land management combined with elevated atmospheric CO_2 levels have resulted in widespread thickening of woody species in previously grassy landscapes globally, but especially in Africa [36,37]. Once woody species reach densities sufficient to suppress grassy fuels [38], fire no longer easily spreads in these ecosystems [39]. By contrast, the widespread harvesting of wood biomass for charcoal represents more than a third of all biomass

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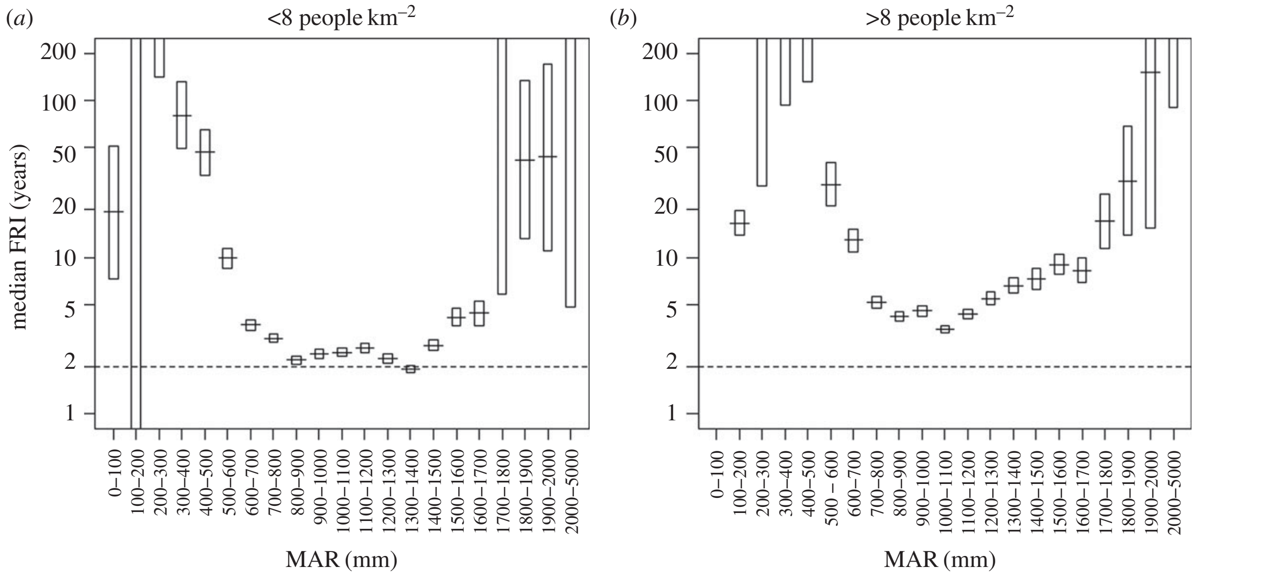

Figure 5. (*a*) Rainfall strongly controls fire return intervals by mediating regrowth rates of the grassy fuels. In Africa, fire return intervals are minimized between 900 and 1700 mm MAR above which the moisture (flammability), rather than biomass of fuel constrains return times [13]. (*b*) High human densities slightly increase the return interval of fire at a location in space despite their frequent ignitions, i.e. the fuels drive the fire regime and humans impact fire via their impacts on fuels. The methods to produce this figure are described by Archibald *et al*. [45].

combustion on the continent (500 Tg yr^{-1} in comparison to 800 Tg yr^{-1} from wildfires [40]) and has resulted in reductions in woody biomass—especially in mesic savannas [41]. Because grassy fuels increase when woody cover is reduced [38], this has possibly increased the area burned and intensity of fires in these systems.

Fire return period is an ecologically important metric reflecting the average return time of fires at a point in space [42–44]. An analysis fitting Weibull distributions to fire interval data extracted from the 15 year MODIS burned area dataset confirms that rainfall strongly controls fire return intervals by mediating regrowth rates of the grassy fuels (figure 5*a*, [46–48]). In Africa, minimum fire return times occur between 900 and 1700 mm MAR (on average every 2 years) above which flammability (fuel moisture), rather than biomass constrains return times [13]. Theoretically, increasing ignitions should increase the likelihood that a location experiences a fire, and should reduce fire return period. Instead high human densities seem to extend the return interval of fire despite their frequent ignitions (figure 5*b*) [46]. Again, the impact on fuels overrides ignitions (see [49] for more discussion on this).

An important direct impact of humans on fire is in changing the *timing of ignition* events. Lightning shows strong seasonality and is the only significant source of ignitions in the absence of people: it usually occurs with rainfall during thunderstorms and is virtually non-existent in the dry season. Thus, the availability of fuels to burn (fuel moisture) and the timing of lightning ignitions are inversely related. Human ignitions are not similarly constrained, and currently in Africa the number of fires peaks when there is no lightning in the middle of the dry season (July in southern Africa [45,48], and December in North Africa [50]; figure 6).

Seasonal changes in ignitions impact *fire intensity* [50–52], with important ecological and biogeochemical consequences. Grass can cure to carry a fire within a few weeks of no rain, but fire intensity tends to increase over the dry season due to changes in weather conditions (decreased relative humidity, increased wind and temperatures), and the continued

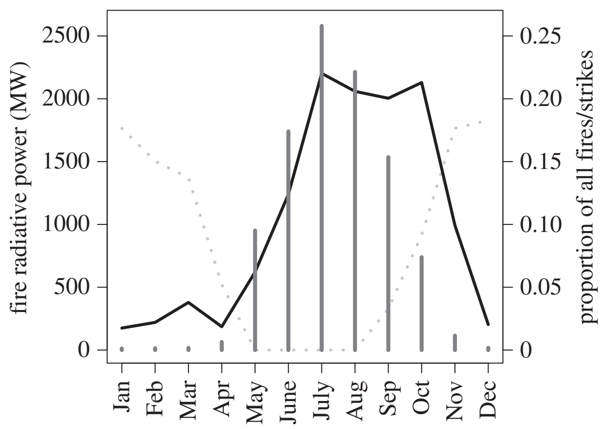

Figure 6. Current seasonal patterns of ignitions in Southern Hemisphere Africa (grey bars) in relation to the maximum fire radiative power values recorded over the season in the region (black lines). Dashed grey lines represent the seasonal pattern of lightning strikes. The late dry season is characterized by the potential for high-energy fires. Currently nearly half (41%) of the fires occur before the late dry season. When lightning was the major ignition source there was still the potential for high-energy fires in the late dry season. Patterns for Northern Hemisphere Africa are similar, but inverted, with peak fires in December [50].

drying of landscapes [29,45,51,53,54]. Consequently, very intense fires only really occur in the late dry season [50,55]. These late dry season fires represent a substantial proportion (about half) of current fire events in southern Africa (figure 6) [45], west Africa [56] and Australia [55], but account for much more than half the total burned area due to their larger size and intensity. Data from figure 6 lead us to believe that fires ignited by lightning would either have been small, wet-season events, or the occasional high-intensity fire event associated with dry lightning at the end of the dry season.

However, we can only speculate about this. A management experiment in the Kruger National Park confirms that trying to recreate a lightning fire regime in these systems is

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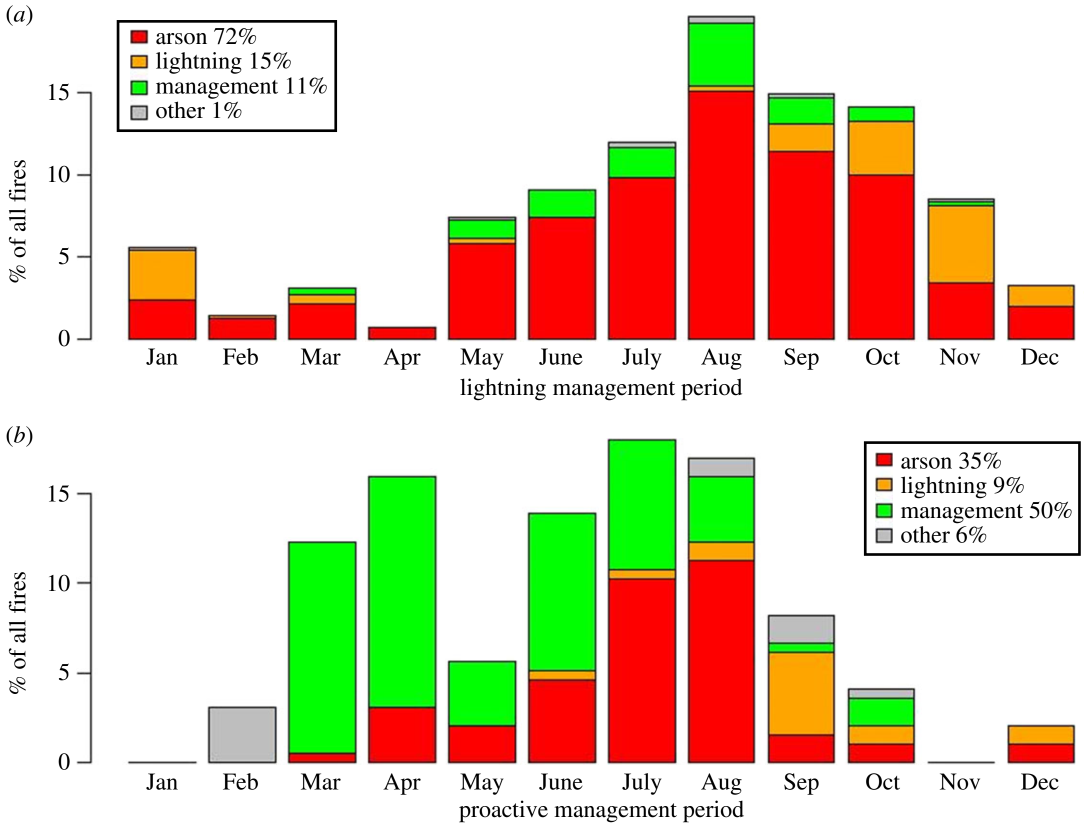

Figure 7. Seasonal patterns of burning in the Kruger National Park when management aimed to exclude all fires except lighting (*a*) and when they proactively burned early season fires (*b*). The total area burned was insensitive to these interventions, but the proactive management period resulted in three times as many fires (171 versus 52 per year), and a higher proportion of early season fires (8% and 22% of the area was burned before July in the lightning and proactive management periods, respectively).

a futile exercise. For 10 years—from 1992 to 2002—the park allowed all lightning fires to burn to extinction, and all fires of non-lightning origin were suppressed [57,58]. In practice, however, the majority of the fires still burned during the dry season, when there was no lightning (figure 7*a*). These were predominantly uncontrolled arson fires lit by tourists, immigrants crossing over the Mozambique border or by accident (72% of all fires). The park did not succeed in increasing the percentage of lightning fires beyond 15%, and most of the area burned during the intense hot late dry season—some of them resulting in fatalities and loss of infrastructure [59].

The control humans can have on the season of burn is demonstrated by what happened after the Kruger National Park stopped its experiment. From 2002, an active prescribed burning programme switched the season of burning to much earlier in the season (figure 7*b*), and the number of arson fires were halved (lightning continued to burn about 9% of the fires). Interestingly, although the number of fires more than tripled during this period (from 52 per year to 171 per year), there was no difference in total area burned which is more controlled by fuel availability (see above). Similar shifts in seasonal timing are described in Mali in West Africa with the institution of burning bans in the 1980s [56]. Unprecedented intense late season fires resulted, with such negative consequences for the local inhabitants that they soon started burning covertly to try to manage and control their landscapes [8]. In Australia, inhabited ecosystems also tend to burn earlier in the season in smaller, less intense fires [60]. Moreover, when people are enabled to ignite fires they can manipulate fire intensity through diurnal timing: planned burning often takes advantage of the drop in relative humidity in the evening to light fires in the late afternoon that are likely to self-extinguish with dewfall [52].

Thus, when given control over their landscapes people appear to prefer igniting early season cool fires as soon as the grass is flammable [52,61]. However, there are instances where particular management goals aim for very intense fires—for example, when preventing forest ingress into threatened savanna habitats [62] or for maintaining high grass ratios in rangelands and conservation areas [63,64]. Here too, this is usually achieved through manipulating the seasonal or diurnal timing of fire [62].

Long-term fire records for several savanna ecosystems, and the Cape fynbos (Mediterranean shrublands), show no trend of increasing fire in response to *changing climates* [48,65], and we would not expect one: in a system where the fuel is predictably dry and flammable for 4–8 months of the year increased temperatures will do little to increase the probability of ignition [66]. However, high temperatures can drive increased evapotranspiration which will reduce grass productivity and fuel loads. If anything, therefore, a negative rather than a positive relationship between high temperatures and total area burned is expected in grassy systems [67]. Moreover, the strong negative impact of people on fuels buffers most parts of Africa from inter-annual variability in climate—with high variations in area burned only possible in sparsely populated landscapes [29,68].

However, weather conditions do appear to constrain the occurrence of extreme fire events in grassy systems (and elsewhere on the globe). The probability of periods of high wind

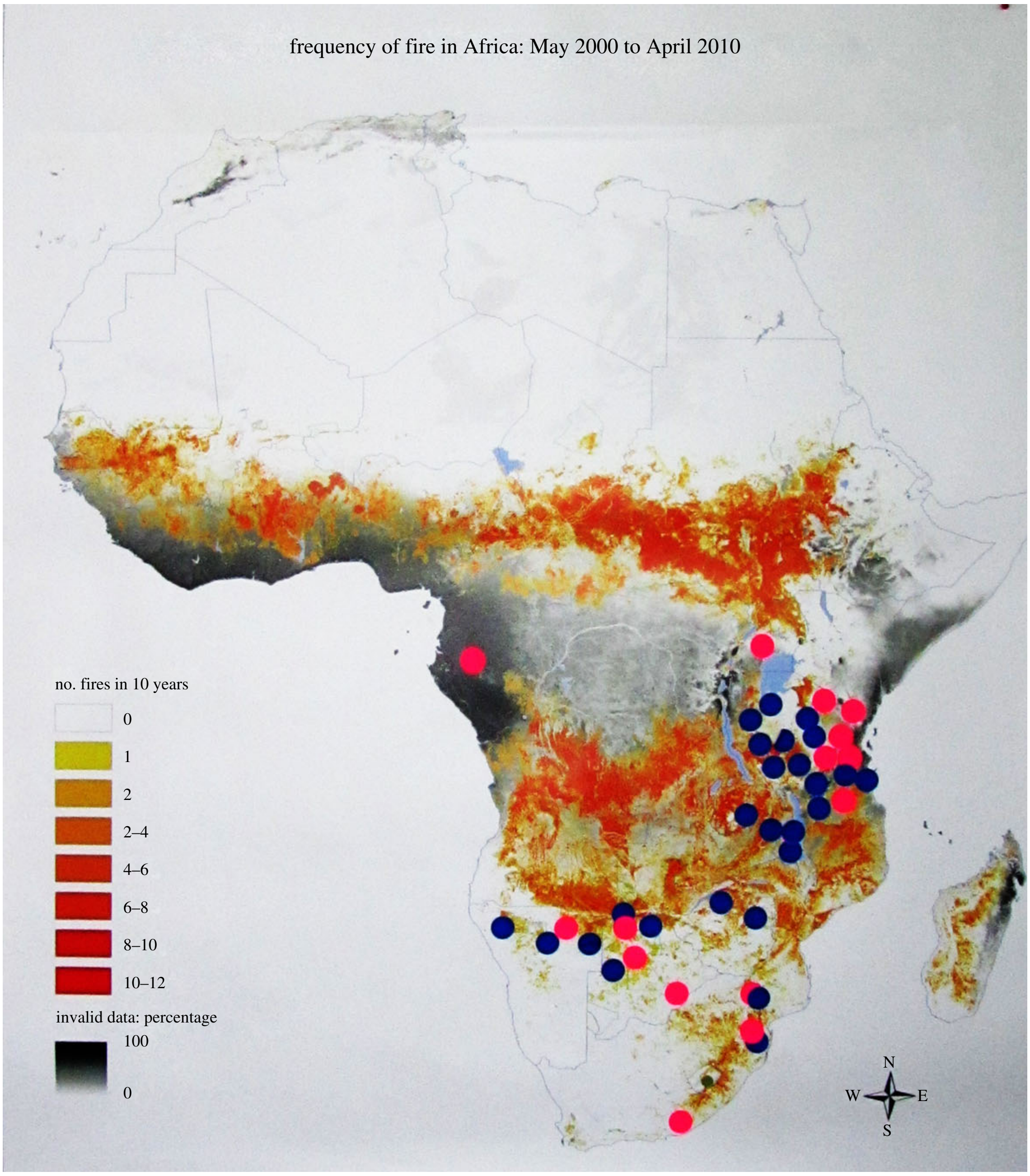

Figure 8. Results of a Southern African Fire Network meeting in Tanzania. Participants were asked to indicate places in Africa where fire should be managed to increase woody cover (dark blue) or to decrease woody cover (light pink). Although the spatial distribution reflects the knowledge of the participants, clearly there are contrasting fire management objectives on the continent.

speeds, high temperatures and low relative humidity are likely to increase in the future [69], and fires burning under these conditions have the potential to massively transform African landscapes by penetrating the impermeable boundary of forested ecosystems [64]. Conversely, rapid tree regrowth rates fertilized by elevated atmospheric CO_2 have demonstrably been increasing woody cover in arid parts of the subcontinent [36]—potentially excluding fire from systems that usually burn. Currently, we have no empirical data on the extent or importance of either of these impacts on fire.

Thus, there are two main pathways in figure 1*a* by which humans impact fire in Africa. Their direct impact on the seasonal and diurnal timing of fires can impact fire intensity with important management implications (see § 4). Their indirect impacts on fuel amount and fuel connectivity reduce the size of fires and the total area burned, meaning that anthropogenic fire regimes in Africa and other grassy systems reduce, rather than increase, fire-related carbon emissions.

4. Managing fire in tropical grassy ecosystems: local, national and global perspectives

Tropical grassy ecosystems are clearly fire-adapted and will burn with or without added human ignitions. However, human intervention in these fire regimes is considered necessary from three main (and unfortunately not necessarily complementary) standpoints—each operating at different socio-political levels.

At a local level, the focus is on sustaining livelihoods—lighting fires to clear/prepare/protect fields, to provide forage, to attract game and to control vegetation structure (tree/grass ratios) [52,68,70,71]. At national levels, conserving biodiversity is the main goal, as well as preventing loss of life/infrastructure, although ensuring the sustainability of people's livelihoods is also an important concern [49,62,70,72]. More recently, global pressure to intervene to manage earth system processes has led to calls to alter fire in tropical systems to reduce GHG emissions and store carbon [73,74]. The impact of tropical burning on climate via aerosols is also gaining attention [27].

Clearly, controlling vegetation structure is a concern from all standpoints. Geoengineering solutions focus on manipulating fire to increase above-ground woody biomass, but a more nuanced perspective emerges from other stakeholders—one which highlights the value of open, grass-dominated systems. In national parks, fire is often used to control woody cover, and maintain open ecosystems [62,75]. Considerable amounts of money are produced by attracting tourists to grassy savannas full of grazing animals [76], and maintaining these is a national priority. Livestock owners also burn actively to maintain the grazing resource for their animals [77]—especially in areas that are threatened by woody encroachment [78].

There are also starkly different perspectives on the desirability of early versus late season fires. Early season fires are less intense [51,54], so have less impact on encroaching woody species and tend to promote higher woody biomass and more large trees [43,44,79]. However, they also burn with far more smouldering combustion—emitting two times the CO concentrations and three times the CH_4 concentrations of late season fires [80,81]. It has been suggested that small early season fires can decrease the total area burned by breaking up the landscape and preventing the spread of later season fires [82,83]. Most conservation areas aim for 'pyrodiversity': having landscapes burning with a range of fire intensities, frequencies and spatial patterns [71,84]. Impacts of changes in fire season and intensity on fauna have not been adequately addressed in Africa (but see [85] for literature from Australian savannas).

Unfortunately, these different perspectives on what fire regimes are desirable are not equally recognized when developing fire governance plans. Erikson [71, p. 244] states: 'In many savanna regions policy makers are using fire suppression policies encouraged by the developed world, rather than developing and adopting fire management strategies suited to regional or local environments'.

At a workshop in Tanzania in 2013, a group of government officials, conservation authorities, scientists and landusers were asked to identify locations in Africa where fire should be used to manipulate woody cover, and to what end. The results were varied (figure 8). There are many parts of the continent where high fire activity, intense fires and reduced woody cover are a concern, but there are equivalent regions where the lack of appropriate fire and the unwelcome dominance of woody species is the problem. Sometimes both of these fire management objectives were identified in the same location, indicating the complexity of fire management in these systems [86]. That the desired fire regimes for large-scale earth manipulation can conflict with the needs of local people and the national mandate to conserve Africa's indigenous biodiversity needs to be recognized at all levels. This is especially important as it is now clear that these suggested geoengineering interventions in no way represent the return to a pre-human more 'natural' state—either in terms of total biomass burned or in the season and intensity of burning.

5. Conclusion and the future

Above I have elaborated on the components of a fire regime that are amenable to direct human manipulation (fire season, location and fire intensity), and those that are controlled by climate and fuels, and therefore only indirectly impacted by people (total burned area, fire return period). I have also discussed examples where this general understanding does not apply. In particular, in fragmented forest–savanna ecotones human ignitions can potentially impact the extent and frequency of fire with important implications for the conservation and management of these systems [87].

Africa's future—and that of other tropical grassy systems—involves increased population densities, but also increased urbanization (the urban population of Africa is predicted to double from 2000 to 2030 [88]). The current high rural densities of people are therefore probably temporary, and likely to reduce within the next 50–100 years. Data presented here, and lessons from Australia and other systems where rural areas have become depopulated [68,89], suggest that the total area burned is likely to increase (figure 3), as will the extent of large, intense, extreme fire events (figure 7) as people remove their influence on fuels and the season of ignition in these grassy fire regimes. However, if this depopulation comes together with the expansion of large-scale agriculture on the continent then both the landscapes and the fire regimes of Africa will be fundamentally transformed, perhaps converging on the 'human pyrome' of figure 2.

Another clear future for grassy ecosystems is hotter climate [69], with higher atmospheric CO_2 levels potentially altering tree–grass dynamics [36]. High temperatures in seasonally dry grassy systems will not increase total area burned, as predicted for boreal and tropical forests [66]. Nonetheless, extreme fire events do have the potential to spread fire into previously fire-proof habitats [64], and increased woody cover threatens to exclude fires and alter system properties.

Fire management objectives of rural people, national government and the global community are sometimes aligned but this is clearly not always the case. Moreover, although we understand the impacts of fire frequency and intensity on these ecosystems [44,90,91], the impacts of fire season—especially the impacts on GHG emissions—are less clear and need to be resolved for effective decision-making. Finally, when it comes to Africa, shifting the focus from discussions of *how much* burns, to *how* it burns [56,92] should enable management plans that are feasible, and create more common ground for decision-making.

Data accessibility. All data presented here have been used in previous research articles, which are referenced in the text, or are freely available (MODIS data products). I am happy to provide more information on data accessibility where required.

Competing interests. I have no competing interests.

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