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Viability and desirability of financing conservation in Africa through fire management

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Adopting early dry season fires in African conservation areas has been proposed as ecologically desired and a means of generating sufficient carbon revenues for their management. We interrogate available peer-reviewed information on the ecology and biogeochemistry of fire in Africa to offer an informed perspective on the full implications of the proposal. We conclude that there is insufficient evidence that a shift to early dry season fires will reduce greenhouse gas emissions, that resultant biodiversity and ecosystem service outcomes may not be desired, and that adopting a single burning regime limits the use of fire to achieve a diverse range of goals.

Commitments to mitigating climate change increased rapidly following the establishment of the Paris Agreement. As achieving targets through reducing fossil fuel use is difficult, there is growing interest in flexible mechanisms, particularly climate change mitigation projects that are aimed at enhancing carbon stocks and reducing greenhouse gas (GHG) emissions within the terrestrial domain. As many land-use-based projects either restore ecosystems or halt further degradation, they have the potential to achieve several sustainability goals simultaneously, including enhancing the resilience of ecosystems and downstream economies and communities to climate change, as well as the long-term conservation of biodiversity.

Yet, enthusiasm in quickly implementing 'nature-based solutions' may not always lead to desired outcomes and may not be supported by current science and data. One such example is a proposal to generate carbon revenues through changing fire regimes in African conservation areas[1], particularly the implementation of early dry season (EDS) fires (Box 1).

Early carbon offset projects based on the adoption of EDS fire regimes in the Northern Territory, Australia[2], spawned interest in the degree to which this approach could be applied in other global fire-prone grassy ecosystems[3]. This led to several global assessments of the potential to reduce GHG emissions and sequester carbon through EDS fire regimes[4], which led to considerable debate on the complexities of transferring the Northern Territory EDS fire regime into other socio-ecological contexts[5–7]. Nonetheless, the concept developed in Australia is still being used as the basis for new climate change mitigation projects in other parts of the world that have different fire dynamics[1]. A recent prominent paper[1] even suggested that implementing EDS fire regimes could generate enough revenue to fully fund the management of African conservative areas.

Funding for conservation is urgently needed in Africa, and logistical support for improved fire management is also desirable in many contexts. Here we summarize the large and growing literature on fire impacts and emissions in Africa to assess whether applying EDS fires will achieve their desired goals. It should be emphasized that the intention of this Perspective is not to question the EDS programme located in the Northern Territory of Australia, but rather to review

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BOX 1

Characterizing seasonal changes in fire behaviour and moving beyond EDS and LDS distinctions

In seasonally arid tropical ecosystems, fire characteristics change throughout the year as the fuel and weather conditions vary. While the main driver of fire conditions is the gradual decline in fuel moisture content as grasses senesce in the dry season, numerous other factors influence fire behaviour at the landscape scale. In Australian tropical savannahs, researchers tend to distinguish EDS burning, which occurs when weather conditions and fuel are less prone to combustion, and LDS burning, which happens during more extreme fire weather (see, for example, refs. 75,76). However, the exact date when EDS shifts to LDS is unclear, and there is no recognized standard to determine a threshold (but see ref. 77). Some researchers use May, others June and still others July as the cut off. However, burning at different times of day can have as much effect on fire behaviour as burning in different seasons because humidity, fuel moisture and wind velocity all change during the day. Consequently, time of day can be used effectively to achieve particular fire intensities and behaviours in most fire seasons. Moreover, the direction of fire (head or back) is a critical determinant of fire intensity, combustion completeness and emissions, but it is rarely considered in savannah fire research.

African researchers sometimes distinguish 'early', 'middle' and 'late' season fires[78], and have shown that CH_4 emissions, for example, have nonlinear responses and can peak in the mid-dry season[6]. Still, others focus on the unique characteristics of fires that happen in summer (when the trees and grasses are physiologically active), autumn (when grasses are curing but some green leafy material remains, and shrubs and trees still have leaves), winter (where frost or very low humidity will have cured the fuel loads and increased fire spread rates) and spring (after the first rains, when the vegetation is starting to flush)[49,79]. Many Indigenous fire users take advantage of these changes by progressively burning off dry vegetation to create a 'patch-mosaic'[80], which is thought to reduce large, more intense fires later in the season (that is, fire abatement as envisaged for climate mitigation is already part of many indigenous burning practices in Africa). Once fuels become uniformly cured across an unburned landscape, and relative humidity has decreased, fires tend to burn throughout the night, and this represents an important threshold in terms of fire behaviour (fires become larger and less easy to control).

As climate, topography and vegetation characteristics vary spatially (for example, the amount of tree cover and types of herbaceous cover), the changes in fire behaviour throughout a season are not predictable or transferable from one place to another, and characterizing fires by their intensity (rather than the season that they are burning) and their fuel characteristics, as well as weather conditions, all of which determine intensity and severity, will enable better generalization for the purposes of emissions assessment.

the application of the concept in the ecological and socio-economic context of African savannahs.

We critically assess the relationship between fire and its impact on GHG emissions and above- and below-ground carbon stocks in African savannahs based on available data. We provide a much-needed perspective on the ecology of fire in Africa and the different ways fire is used by land managers to achieve a range of outcomes. We assess the viability of generating carbon revenues by altering fire regimes across different African landscapes, and we propose guidelines for how to develop appropriate interventions in the context of fire management in Africa.

Climate mitigation potential

GHG emissions from fire

Terrestrial carbon pools are in a constant state of turnover[8]. Most of the atmospheric carbon absorbed through photosynthesis is released again through heterotrophic respiration, autotrophic respiration, herbivore consumption and fire[8]. Most burned biomass regrows again, and the carbon dioxide (CO_2) released through fire is a net neutral flux unless changes in fire regimes result in a long-term change in terrestrial carbon stocks. However, fire events also release other climatically important gases, particularly nitrous oxide (N_2O) and methane (CH_4), which are not climate-neutral, and have global warming potentials ~27 times (CH_4) and ~273 times (N_2O) larger than CO_2 (ref. 9).

Importantly, smouldering combustion that has limited access to oxygen produces higher CH_4 emissions, while flaming combustion of dry, well-aerated fuels produce lower CH_4 emissions[10]. This is quantified using an emissions factor (EF), which indicates the proportion of each GHG emitted per unit of biomass burned[11]. The net GHG emissions of fire therefore depend on the amount, type and structure of biomass burned as well as the type of fire and the associated EF, that is, the amount of CH_4 and N_2O released.

Data from African savannahs show that fire EFs vary substantially through the year, depending on the moisture content of the perennial grass species, and the phenology of trees. For example, green leaves on standing vegetation burn very differently compared with leaf litter (the former having high moisture content and the latter, low aeration). Woody fuels also have higher CH_4 EFs than grassy fuels. Early season fires in Africa are burning grasses that are not fully cured, and are characterized by smouldering combustion with very high CH_4 EFs—up to 4 times higher than late dry season (LDS) fires in wet grasslands and 2–3 times higher in savannahs[12]. There is also a substantial reduction in nitrogen (N) emissions when drier fuels with low N contents are combusted later in the season[10]. A recent study[6] noted that small woody trees[13,14] in the flame zone in African savannah fires also increased EFs in the early and mid-dry seasons, because they still retained green leaves and burned with smouldering combustion. It concluded that although EDS fires burn less area with lower combustion completeness in African savannahs, the total amount of CH_4 released could be greater than that of larger fires that burn once the fuel is fully cured[6,12].

African savannahs are often home to large numbers of herbivores that consume potential grass fuel loads throughout the year, resulting in more patchy fires with lower combustion completeness[15,16] but considerably larger EFs when dung is combusted[17]. Finally, litter fuels have higher EFs for CH_4 and N_2O than grasses, so when tree cover is high EFs can increase again later in the dry season when trees drop their leaves[10]. Temporal changes in fire-derived GHG emissions are therefore too complex to summarize with simple distinctions between early and late-season burning, and will vary depending on the savannah type (Box 1). Therefore, it is currently not clear what the GHG emission impact of changing fire season would be, although the processes are well understood, and more data are becoming available to parameterize better predictive models.

The woody biomass carbon pool

The woody biomass in savannahs can be substantially altered by fire. Frequent or intense fires will inhibit tree growth and reduce the amount of above-ground carbon, whereas reducing fire or applying cooler, less intense fires will increase above-ground woody biomass[14,18,19] to the point that grasses are greatly reduced and the ecosystem becomes resistant to fire[20]. Therefore, changing fire regimes to cooler, smaller fires would result in an increase in above-ground woody carbon stocks across most savannahs, and might even act eventually to prevent fire in high-rainfall savannahs. This increase in above-ground carbon stocks is often the focus of fire-abatement carbon-credit programmes[1].

Below-ground biomass stocks have often been assumed to follow similar patterns to above-ground stocks[21]. However, woody species in fire-prone African savannahs and woodlands require underground resources to coppice rapidly following disturbance[19,22] and can have large root systems below-ground[23,24], even when fires are intense and remove most above-ground woody biomass. A recent study[25] found a much more limited increase in below-ground biomass than above-ground biomass when fires were reduced in a semi-arid savannah. The impacts of fire on below-ground carbon stores cannot, therefore, be assumed to follow a similar trajectory to above-ground stores[26], adding uncertainty to fire-related climate change mitigation interventions.

The soil organic carbon pool

Fire can affect soil organic carbon (SOC) by altering (1) the rate of litter input into the soil (that is, burning it before it is incorporated into soil); (2) the growth and turnover of fine roots; (3) the pH and nutrient ratios in soil and therefore decomposition rates; and (4) the form of carbon in soil into more or less labile forms: black carbon (or ash) represents a particularly resistant and permanent soil carbon stock[27].

Although these drivers are conceptually understood, the net impact of different fire regimes on SOC in African savannahs is unclear. Field data from West Africa show temporary (<4 year) reductions in SOC following LDS fires[28], but long-term field trials in southern African grassland and savannahs[27,29,30] illustrate that differing fire regimes have little impact on soil carbon stocks directly, although they can have indirect effects through altering tree cover and litter inputs[31]. Indirect effects via tree cover depend on soil texture and rainfall[32]. In mesic areas, with the capacity for the most above-ground biomass accumulation from changed fire regimes, data show that soil carbon decreases when woody plants increase in a system[33]—that is, opposite trends to above-ground stocks. The lack of evidence demonstrating that fires directly impact SOC in African systems is supported by recent global analyses, which concluded that the impact of fire on SOC cannot be generalized[34] as reported impacts ranged from −66% to +95% in tropical savannahs and grasslands. There is therefore little evidence that less frequent, cooler fires will consistently increase SOC in African savannahs and grasslands.

In summary, empirical data from African savannahs provide little evidence that an EDS fire regime will mitigate global climate change. The only mechanism for which there is clear data and understanding is through increasing above-ground woody biomass, which has large ecological and socio-economic consequences (described further below) and might also reduce SOC, as well as increasing the CH_4 and N_2O emissions due to the higher litter content in understory fuels.

Desired ecological states and co-benefits

When considering the appropriateness of implementing an EDS burning regime, it is important to ask how it will impact ecological structure and function and associated ecosystem co-benefits. Open savannah systems are iconic landscapes in Africa, supporting high biodiversity and human livelihoods[35]. Fire dynamics are driven by climatic conditions and fuel load characteristics that depend on the amount and seasonality of rainfall, vegetation structure and composition, herbivory and further land use. The role and impact of fire is, therefore, highly variable in heterogenous contemporary African landscapes, and management often entails maintaining a mosaic of differing fire sizes and intensities to maintain heterogeneity, promote biodiversity and meet local needs.

Soil properties

For many years EDS fires were considered poor land management practice in southern Africa as they left the soil exposed throughout the dry season, and were thought to increase erosion[36–38]. Further studies, however, showed no impact of fire season on either the basal cover or the dry matter production of grasslands[37,39,40]. Likewise, impacts of fire seasonality on soil properties in African savannahs are small and ephemeral[41], with no clear evidence that either EDS or LDS fires lead to long-term reduction in water infiltration.

Direct effects on biodiversity

Research on insect, reptile and small mammal responses to fire is scarce in Africa, but available evidence shows that invertebrates are affected by fire season, with mid-season fires having the least impact[42] and fires after the first rains lowering the abundance of some groups[43]. The timing of fire is less important than size and extent for small mammals[44–46], while mammalian herbivores benefit from fresh forage resources from fires in any season[45,46]. Long-term burning experiments show that herbaceous communities are resilient to a range of fire seasons and intensities[47–50], while shifts in dominance can occur in the woody layer, as fire-sensitive species are reduced (but not excluded) in late-season fire treatments (see, for example, refs. 51,52).

Indirect effects on biodiversity

The indirect impacts of fire via woody cover are substantial[44] and will shift the functional composition of ungulate, arthropod and bird communities[44,53,54], and cause turnover in ground-layer species richness[55]. Owing to the substantial impacts of fire on vegetation structure, there is evidence that a diverse fire regime, with variation in fire size, intensity and frequency, results in the highest bird and mammal diversity in wetter savannah regions (>700 mm of mean annual rainfall)[56]. Observing such diversity in open grassland and savannah landscapes is the basis of tourism in the region and the principal source of income for many conservation areas.

In summary, there is evidence that fire season affects woody structure and biomass across a wide range of savannah environments, and that this will have indirect effects on herbaceous flora and invertebrates, as well as small and large fauna. There is no evidence, however, that the higher woody biomass and dense canopy conditions promoted by EDS fires are always more ecologically desirable, nor that the application of LDS or MDS fire causes degradation of soil properties or biodiversity. In fact, bush encroachment (the transformation of indigenous savannahs into a dense woody state) is formally recognized as a form of land degradation by the United Nations Convention to Combat Desertification due to its negative impact on ecosystem services to local residents and downstream economies[57]. Rather, the ecological literature supports the application of a wide variety of fire regimes, and the most appropriate approach appears to depend on the ecological needs and particular management priorities[58].

Learning from the past

Decades of research on the continent show that no single fire regime will achieve all management goals (Table 1). Instead, a range of fire regimes are required to achieve specific management objectives in different landscapes and desired social-ecological outcomes.

Fire management for particular objectives already occurs across most of Africa's fire-prone landscapes and in some of Africa's

Table 1 | Summary of motivations for applying fires, the types of fire necessary to achieve these various goals, and spatial and temporal scales of impact

Goal	Ideal burn seasons	Spatial scale of impact	Temporal scale of impact	Type of impact
Increase visibility/improve movement	Early–middle	Local	Annual	Livelihoods
Prevent later damaging fires	Early–middle	Regional	Subannual	Livelihoods
Protect croplands/houses	Early season	Local	Annual	Livelihoods
Prepare croplands[70]	End of fire season	Local	Annual	Livelihoods
Attract grazers/modify grazer movements[71]	Varied	Local	Subannual	Livelihoods/conservation
Alter tree–grass dynamics: reduce tree cover[72]	Late season/summer	Local/regional	Decadal	Livelihoods/conservation
Increase biodiversity[56]	Varied	Regional	Decadal to millennial	Conservation
Alter tree–grass dynamics: increase tree cover[73]	Early season	Local/regional	Decadal	Conservation/geoengineering
Reduce fire-GHG emissions	Not clear	Regional/global	Decadal	Geoengineering
Alter aerosol load (decrease radiative forcing)[74]	Late season	Global	Subannual	Geoengineering

Importantly, the benefits accrue to different communities for different purposes. Nature-based solutions require alignment between climate mitigation, biodiversity conservation and human livelihoods, but this table indicates that when it comes to fire management there will usually be trade-offs between these different needs, and that a dynamic, flexible approach is necessary.

protected areas. Fire use differs for reasons that are tightly coupled to people's culture, needs and management roles, and is adapted to the environmental conditions. Residents in certain areas of Africa already implement fires relatively early in the season—once the grass layer has sufficiently dried and cured[6]. This is often done in an adaptive manner that depends on rainfall in the past year, past and current grazing pressures, prevailing weather conditions, and other practices (for example, clearing undesirable grass biomass). LDS fires are also frequently applied for preparing fields and inducing new green shoots for grazing (often after the first rains), resulting in a heterogeneous mosaic pattern of burnt patches.

Active fire management has occurred in several protected areas for decades—for example, Lopé National Park[59], Kruger National Park[60], Serengeti National Park[61], Bwabwata National Park[62]—while in others, a non-intervention approach has been preferred (for example, Limpopo National Park[63]). A key lesson has been that a flexible approach to fire management is required based on contemporary needs and knowledge (Box 2). The Kruger National Park, for example, has changed its fire management plans almost every decade for the past half a century, due to new insights and changing conservation challenges[64].

Viability of implementing EDS fires

In addition to consideration of desired ecological states is the practicality and economics of implementing fire regimes, especially at scale. Where EDS fires are chosen by management, they are not easy to implement in large national parks with few staff. Because EDS fires are patchier, cooler, smaller and often fail to spread, disproportionately more time and human resources are required to implement them. For example, efforts in the relatively well-resourced Kruger National Park to increase EDS fires were thwarted by lack of capacity[64]. Problems introducing EDS burning could be overcome to a certain extent through alternative implementation models: for example, in Kasanka National Park (Zambia), managers bring in local community members to help burn extensive areas in cool fires. In Tanzania, the rangers are allowed to set fires in the late afternoon without being required to monitor and control the fire spread, yet this approach does allow the possibility of accidental runaway fires, which may not be socially, politically or legally acceptable in other countries. In most of West Africa, thousands of people are voluntarily involved in an annual effort to burn patches of annual grasses in the EDS to fragment the landscape and prevent the spread of later fires[65,66]. Park managers need flexibility to achieve a broad range of goals and outcomes[67], and if management becomes dependent on certain fire regimes for their financing they might be expected by authorities to 'burn for money' rather than 'burn for social-ecological resilience'. The practical feasibility of applying EDS burning, as well as the socio-political feasibility of avoiding perverse outcomes, should not be underestimated.

A way forward

Opinions on African fires have varied widely over the past century. For decades, EDS fires were considered an irresponsible land management practice as they were perceived to promote erosion and reduce available forage, particularly in environments with frequent droughts[68]. The conventional approved approach was to burn after the first rains at the end of the dry season (that is, LDS[38]), and this was applied strictly in many countries in southern Africa, to the detriment of ecological processes[69]. It has taken many decades of learning from Indigenous people in Africa, and of research into the impacts of varied fire regimes in different African ecosystems, to develop a coherent understanding of how fire interacts with ecosystem processes in fire-prone ecosystems, and that a dynamic, heterogeneous and site-specific approach to fire management is required. We now have the tools and understanding at our disposal to be creative in our use of fire to achieve a range of conservation and landscape management objectives. It would be a tragic mistake to reproduce the errors of the past, by again adopting a single approach to fire management across Africa's diverse landscapes.

We therefore propose, first, that potential carbon revenues should not drive fire management decisions to the detriment of livelihoods, biodiversity and ecosystem service outcomes. Carbon offset programmes in Africa should be assessed according to the African position statement, which prioritizes climate change adaptation and biodiversity conservation. Climate change mitigation activities should only be supported when aligned with these other priorities. Second, we suggest that distinguishing early versus late dry season fires, while simple, is insufficient for effective policy guidelines, and cannot be used to predict GHG emissions or carbon cycling. Process-based models that incorporate factors such as fuel load, structure, composition, greenness and prevailing weather conditions are required to meet diverse management objectives. Finally, we argue that local data and evidence should not be ignored in regional assessments of climate change mitigation and restoration opportunities. This is especially important when these local data contradict the findings of the global models.

There is a vibrant and growing community of researchers on the African continent with knowledge, data, skills and willingness to resolve some of the current uncertainty and help produce the required science to fill gaps in knowledge. This potential should be utilized to provide the guidance to empower land users and managers to make appropriate context-specific decisions.

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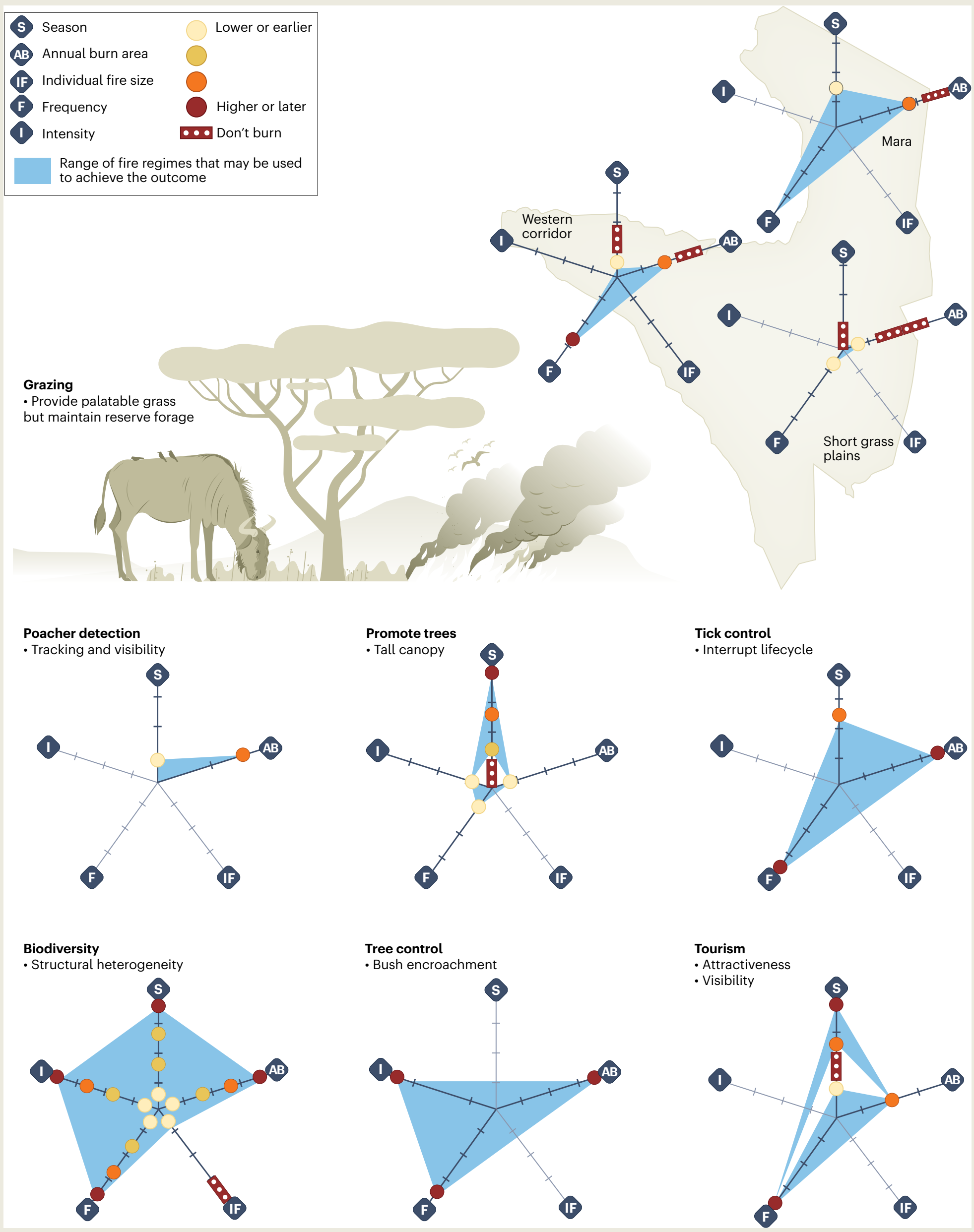
BOX 2

Prescribed burning in conservation areas

Managers in conservation areas balance a range of desired outcomes when deciding when and how to burn. In the Serengeti, for example, the best time of year to burn to control ticks is undesirable from a tourism perspective, and biodiversity conservation requires a varied fire regime. Adding carbon storage as an additional consideration might increase income, but it would complicate the decision-making process and need to be evaluated against the importance and value of other outcomes. Simple messages that a shift to a single fire regime is good and that carbon-related income should be priortized, belies the complexity of managing an ecological process for multiple competing outcomes.



Summary of the range of outcomes considered by managers in the Serengeti when deciding when and how to apply prescribed fires. The schematics highlight five different components of a fire regime that managers can manipulate (season, intensity, frequency, size and total area burned), and a range of outcomes they consider when deciding when and how to burn (biodiversity, poacher detection, tree structure, tick control and tourism). The angles represent different aspects of a fire regime and the colours represent what is desirable for the particular management outcome. The size of the area shaded in blue represents the range of fire regimes that may be used to achieve the outcome. Some outcomes (for example, biodiversity) require a varied fire regime with a range of characteristics, and others (for example, poacher detection) require particular components to be set. Clearly there is no one fire regime that will achieve all desired outcomes. Credit: Joon Mason.

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Competing interests

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