Fire in Highland Grasslands: Uses, Ecology, and History

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Introduction

Each year fires burn across around one-half of the grasslands that cover most of Madagascar's Central Highlands, particularly in open, less densely settled areas. Before humans arrived on the island (see Wright and Rakotoarisoa, p. xx), lightning fires helped shape the temporal and spatial mosaic of highland vegetation. Since settlement, the Malagasy have harnessed fire for diverse resource management goals while altering vegetation communities and biogeochemical processes (Figure 1). Due to the environmental consequences of fire, administrators sought to suppress fires throughout the 20th and 21st centuries. Government policies were contentious with rural communities and have seen little success in these inherently flammable landscapes (Kull 2004).

Here, we provide an overview of current understanding on fire in the Central Highlands, motivations for human use of fire, and the consequences of fire for the vegetation and broader ecological dynamics of the region, alongside how fire management has changed over time. The research presented is based on a synthesis of several sources: an ethnographic, archival, and socio-ecological research project conducted in the late 1990s (Kull 2004) updated via continued field visits and personal communication, and combined with more recent ecological and remote sensing research that brings expertise in African and Australian fire ecology to Madagascar (e.g., Lehmann et al. 2011, 2014; Lehmann and Parr 2016). We restrict our attention to fire in grass-dominated ecosystems, which include pure grasslands as well as "savanna woodlands" with their grassy ground layer, such as those dominated by *Uapaca bojeri* (Solofondranohatra et al. 2018).

For the purposes of this contribution, the Central Highlands were defined as the zone west of the moist evergreen forest escarpment consistently above 800 m. This zone forms a rough triangle from Andringitra in the south, to the Bongolava chain in the northwest, and across the Tampoketsa d'Ankazobe to the Anjafy Plateau northeast of the capital.

Uses: Types and Patterns of Fire

The vast majority of today's fires are lit by humans for specific resource management goals, as in tropical grasslands worldwide (Laris 2002; Archibald 2016; Fowler and Welch 2018). However, not all fires are anthropogenic. Lightning, which is prevalent across the Central Highlands, doubtlessly caused fires before human arrival (Burney 1987; Bovalo et al. 2012). Today, lightning fires are a small fraction of burned area and ignitions, largely due to preemptive anthropogenic burning (Bloesch 1999; Archibald et al. 2013).

Malagasy farmers and herders use fire for a wide variety of goals (Table 1). The dominant use of fire in highland Madagascar is pasture management to provide fresh green nutritious forage for cattle as grasses rapidly regrow post-fire and to control tree and shrub encroachment in grasslands used for pasture (Andrianampionona 1992; Kull 2004; Klein et al. 2007). While near-village sites with concentrated heavy grazing and sufficient moisture support 'grazing lawns' of high quality forage that rarely burn, over the much wider grasslands fire produces green pick for the cattle (Hempson et al. 2019; Solofondranohatra et al. 2020). Pasture and grassland fires comprise between 95 and 99% of all fires in terms of surface area burned in the Central Highlands (Kull 2004). These fires begin in western zones of the highlands in May, peak in August, and continue into November (Randriambelo et al. 1998; Alvarado et al. 2018). In extensive range management, with low stocking rates, large area, and low capital and labor inputs, fire is the most efficient way to sustainably manage pasture quality and availability, as is the case across the tropics.

Grassland fires serve two roles for pasture management (see Table 2 for a summary of main grass species; also see Lehmann et al., p. xx for a description of key grassland types across Madagascar). First, repeated fires maintain grass dominance, retarding woody plant encroachment. Without periodic burning, highland pastures are rapidly invaded by shrub species such as *Sarcobotrya strigosa*, *Erica* spp., *Helichrysum* spp., or introduced *Acacia dealbata* (Cori and Trama 1979; Koechlin 1993; Bloesch et al. 2002) that do not provide forage to obligate grazers, namely cattle. In eastern and southeastern Africa, woody plant encroachment is recognized as a serious form of land degradation (Archer et al. 2017) reducing and altering ecosystem services (Lehmann and Parr 2016).

Second, fire renews grassland vegetation by removing the previous year's growth thereby alleviating growth constraints due to self-shading (Linder et al. 2018). Flammable grasses senesce during the dry season and with high carbon to nitrogen ratios in leaf material they are poor in nutrition for cattle. At this time, the grasslands are inherently flammable landscapes with contiguous low-density fuel layers. Pasture renewal is critical to cattle health, for the protein-rich resprouts – even of poor forage quality native grass species such as *Aristida rufescens* – can carry the cattle through the end of the dry season when they no longer have access to crop stubble or rice straw as farmers prepare fields for planting and irrigation.

The Malagasy burn grasslands opportunistically in a spatial and temporal rotation (Kull 2004). Fires burn different areas in succession, filling in gaps as time goes on, covering 0.5 to over 100 ha per fire, and much larger in unpopulated areas over the course of a year. The resulting patchy grassland includes unburned zones (also used for the collection of roofing thatch) and multiple zones with grasses in various stages of development. This patchiness serves to ensure resprouts over successive months and as a built-in protection against larger and uncontrolled running wildfires (Kull 2004; Laris 2002; Price et al. 2012). Essentially, people act to pre-empt the late season fires that, in a lightning-based fire regime, would be associated with heavier fuels (more vegetation build-up), thus elongating the fire season forward in time. Increasing population densities in landscapes reduces the average fire size, though there can be more, yet smaller and less intense fires (Archibald et al. 2013).

Beyond the larger grassland fires, farmers set numerous small-scale fires for crop field preparation, burning the standing vegetation in the grassland or fallow plots they intend to cultivate, including encroached woody plants. Such burns can take place throughout the season and range from 0.01 to 0.2 ha in size. In some cases, farmers collect additional fuel to burn, such as rice stalks or cut grasses, particularly in fields destined to be flooded as rice nurseries. Other types of agricultural fires include, first, burning the catchment basin above rice paddies to encourage the erosion of important nutrients or soil particles into the paddies. Second, farmers burn to clean irrigation canals and field edges (Kull 2004).

Fires control a wide variety of pests harmful to crops, livestock, and humans. Small cleaning fires around crop fields and residences help reduce rat populations (see Ramasindrazana et al., p. xx) and destroy the brush in which rice-thieving birds such as the *Foudia madagascariensis* (see Craig, p. xx) perch between raids. Fires help control cattle ticks, mosquitoes, and other insects. Vast areas are burnt during locust invasions, when fires serve both to ward off locust swarms in flight and to facilitate the collection of resting locusts (Kull 2004). Of interest also, despite being outside the Central Highlands, is the fact that villagers burn wetland marshes of the Lake Alaotra region in the dry season in order to dig up the introduced fish *Channa maculata* (Copsey et al. 2009).

Another use of fire is to fight uncontrolled fire. Some fires are accidentally ignited, resulting from dropped cigarettes, campfires, or charcoal ovens, or were intentionally lit but burn more than expected. To avoid associated damages, easily controlled, low intensity fires can reduce fuel loads later in the season. Controlled fires around houses and private woodlots serve as firebreaks. The rotation of burns through the dry season establishes patchy, informal firebreaks that facilitates landscape-level control of more dangerous late dry season fires. Finally, villagers ignite backfires to fight active wildfires (Kull 2004).

In highland *tapia* “savanna woodlands”, villagers promote the dominance of pyrophytic *Uapaca bojeri* (see Kull and Birkinshaw, p. xx), a fruit- and silkworm-bearing tree, through use of fire (Figure 1D). Although, individual fires affect fruit production (Alvarado et al. 2014, 2015), regular fire may also reduce populations of silkworm parasites (Kull 2004).

In highland pine and eucalyptus plantations, some tree growers burn to provoke regeneration and in a precocious manner to clear out undergrowth that could lead to more serious wildfires. *Pinus patula*, from Mexico and *P. khasya*, from southeast Asia, both benefit from fire, which opens seeds and can facilitate regeneration (Schwilk and Ackerly 2001). Given the invasive nature of pines in many grassland areas, frequent fires can be a tool to control such invasions as young pine trees are vulnerable to fire, which is not the case for larger trees.

Finally, due to its self-propagation and easily anonymous ignition, fire can also be used for destructive or criminal purposes, or for self-gratification. Criminal burning of houses, crop fields, or woodlots occurs for purposes of revenge, protest, jealousy, tenure conflict, or personal gain. Destructive fires in woodlots and forests may benefit non-owners if people may freely collect resulting dead wood for household fuel. Some fires are associated with cattle-thieving bandits, who purportedly use fire to hide traces of cattle rustling, to draw able-bodied men away from their homes, or to create green shoots to attract free-ranging cattle for theft (Kull 2004; Klein et al. 2007).

The size, extent, and intensity of fires varies in the highlands by region, by month, and from year to year. Kull (2004) estimated that roughly one-half of grassland zones burnt annually at the turn of the century, equaling about one-third of the island. Advances in remote sensing allow for easier assessment of burnt area and active fire points, the latter notably with the MODIS satellite (Musinsky et al. 2018). Remote sensing evidence shows that, viewed at regional scale, levels of burning in Madagascar's highland grasslands correspond to similar climate zones in upland southern Africa (Archibald et al. 2010). The limited investigation that has taken place has found fire return intervals in highlands are one to three years, similar to the previously mentioned parts of Africa (Alvarado et al. 2018). Alvarado et al. (2018) used remote sensing to document fires over a 27-year period at Ibity and Itremo, which have been named as protected areas since 2015, showing that following fire suppression interventions at each site, the number of ignitions decreased but total burnt area was stable with bigger and later fires.

Ecology: The Effects of Vegetation Burning

Despite their utility, fires can have negative impacts for human assets and air quality. Each year, fires incinerate some houses, crop fields, fruit trees, or pine and eucalyptus plantations (Figure 1E). However, the vast majority of grassland fires burn uneventfully (Figure 1C), stopping at the edge of crop fields due to sparse fuel or riparian forests due to humidity and fuel moisture. Annually, smoke from fires envelopes many highland areas. Fires negatively affect air quality, contributing particulates, carbon monoxide, carbon dioxide, hydrocarbons, and tropospheric ozone (Randriambelo et al. 2000; Johnston et al. 2012).

The effects of fire in highland Madagascar on vegetation dynamics, nutrient cycling, erosion processes, atmospheric chemistry, and other processes are not well documented. In particular, research on fire, grasslands, and grazing in this portion of the island is limited, partly out of a long-standing bias that considers grassland ecosystems to be of lesser (or no) interest compared to forest ecosystems (Solofondranohatra et al. 2020). Here we summarize existing knowledge, drawing in part on parallels with grass-dominated ecosystem research elsewhere.

Fire is an integral part of tropical grassland and savanna ecosystems (Bond 2008; Parr et al. 2014). Increasing evidence suggests that several fire-adapted highland C_4 grassland communities, as well as associated fires linked to lightning or volcanism, long predate human arrival in this portion of the island (Bond et al. 2008; Vorontsova et al. 2016; Nanjarisoa et al. 2017; Hackel et al. 2018; Goel et al. 2020; Solofondranohatra et al. 2020). Different types of evidence suggest that the Central Highlands in the late Pleistocene were dry with widespread grassland-savanna vegetation, and that during the Holocene the highlands were a spatially and temporally varying mosaic of riparian and closed-canopy forest, "savanna woodlands", heath, and grassland shaped by fire and grazing megafauna (Burney 1997; Burney et al. 2003, 2004; Bond et al. 2008; Willis et al. 2008; Solofondranohatra et al. 2018).

Analysis of pollen and charcoal in sediment cores suggest that post-human arrival was associated with an increase in fire frequency and an expansion of flammable grasslands at the expense of woody communities (Burney 1997; Burney et al. 2004). The first influence of people on the regional fire ecology could have been indirect, for example, via the hunting of the herbivore megafauna. Herbivores "compete" with fire for vegetation, reducing herbivore populations would have rapidly transformed grassland ecosystems enabling taller grass vegetation and therefore more fuel and hence more frequent fires (Hempson et al. 2019). That is, fire and herbivory support dichotomous communities of grasses (Solofondranohatra et al. 2020), and with human hunting and reduction of megafauna populations, herbivore dominated grasslands may have been relatively rapidly replaced by fire grass communities. The consequent introduction of cattle by people, estimated to have been in the 9th to 12th centuries (Burney et al. 2004) could have functionally replaced the role of the herbivore megafauna (Solofondranohatra et al. 2020). Direct influence by people on fire would have come via fire ignitions. Compared to natural lightning strikes, fires ignited by people notably occur much earlier in the season and are less concentrated on points of higher relief, like mountains.

Fires are frequently implicated in the degradation of the ecotone between grasslands and moist evergreen highland forests. However, elsewhere in the world tropical grassland-forest boundaries are typically structured by positive feedbacks (Hoffmann et al. 2012). Edges of intact Malagasy highland forests can remain stable in the face of fire in adjacent grasslands (Figure 1B), except where tree cutting, cultivation, or charcoal production activities provide entry-points for more flammable grassy vegetation that would carry fire. Tapia woodlands, a savanna formation, are in contrast fire adapted (Kull 2004; Solofondranohatra et al. 2018; see Birkinshaw and Kull, p. xx).

The interactions of fire with highland grassland vegetation communities vary with frequency, season, species composition, plant maturity and density, flowering stage, air temperature and moisture, soil moisture, litter amount and quality, grazing intensity, wind, topography, time of day, direction of burn, nutrient legacy, and historical land use. These factors determine the spatial extent and intensity of fires, their effects on standing vegetation and soil microfauna. Influential mid-20th century understandings of the effects of repeated fire saw vegetation communities follow a reverse successional model (retrogression), in which increasing fire frequency replaced forest, first with large tall albeit palatable grasses such as *Hyparrhenia* *rufa* and *Heteropogon contortus*, and later with a degraded system of low-value *Aristida* spp. characteristic of over-grazing (Perrier de la Bâthie 1921; Granier and Serres 1966; Bosser 1969). More recent research supports a different perspective in rangeland ecology in highland Madagascar, whereby actual transformations in grassland communities probably follow multiple transitions between different states, based on fire regime, grazing pressures, land use, climate, and initial plant community (Jacquin et al. 2010; Parr et al. 2014; Briske 2017).

Indications on fire-grazing-grassland interactions in the highlands can be gleaned from the limited research on the topic. Grass research at Itremo identified a "fire grass" group in grassland and tapia woodland areas that is tolerant of or dependent on frequent burning (Nanjarisoa et al. 2017). Such a finding is corroborated by a more recent analysis of grass functional traits and community composition across the Central Highlands, which shows the existence of an ancient fire-maintained assemblage grassland community (Solofondranohatra et al. 2020). Investigating the impacts of a 2003 fire at Ibity, Rasoafaranaivo (2005) found that fire had little negative impact on 10 endemic species characteristic of montane environments, while Randriatsivery (2005) found that grassland areas were comparatively more species rich and had higher vegetation cover after the passage of fire. A variety of species do co-occur with grasses, including herbs, tuberous geophytes, aloes, orchids, and pachypodiums, and exhibit fire adaptations (Lamont and Downes 2011; see Lehmann et al., p. xx). Alvarado et al. (2018) demonstrate that fire exclusion is not attainable in highland grasslands, nor necessarily needed for conservation of this formation. Indeed, it is likely that fire exclusion in certain cases could decrease biodiversity, as found by Rakotoarimanana and Grouzis (2006) in the grasslands of the southwest, ecologically different from the Central Highlands, where the thesis of Rakotoarimanana (2002) remains one of the only detailed analyses of grazing, fire, and grassland interactions. Much future work is warranted, particularly in a context where policy-makers not only seek to limit fires but also rush to plant trees in grassland areas to meet carbon sequestration targets but not considering the alterations to fire regimes caused by such interventions (Veldman et al. 2015; Bond et al. 2019).

Knowledge on the relationship of grassland burning to soil erosion and pedogenesis in the Central Highlands is essentially limited to mid-20th century studies at several sites which demonstrated higher erosion rates in burned areas, at least in the first post-burn rainy season, and which paid little attention to types of fire and vegetation (Kull 2004). Fires can cause soil compaction (Randriatsivery 2005) but also influence vegetation cover. In a general manner, impacts on erosion depend on timing with respect to rain or wind events, type of fire, and type of vegetation (Scott et al. 2014). The consequences of erosion can be locally severe, including siltation, flooding, and gullying, yet may be exaggerated due to a failure to put erosion figures from test plots in context, or by ignoring the positive inputs that erosion can provide downhill (Kull 2000).

History: Fire Management and the Economic and Political Context

Following the 1896 conquest, French colonial administrators sought to limit vegetation burning (Kull 2004; cf. Moura et al. 2019). While some district officers argued in favor of burning for pasture maintenance, colonial scientists argued that these practices resulted in the destruction of valuable forests and impoverished the soils (Perrier de la Bâthie 1921; Humbert 1949). Viewed from a European perspective that favored intensive cattle husbandry, the extensive fire-based system appeared wasteful and destructive. Confusion was (and continues to be) frequent between fires in different vegetation types, like grassland versus forest, and between potentially useful fires and fires that threaten assets.

Legislation in 1907 banned all fires except for locust control and pasture renewal, with the idea that the development of "modern" intensive cattle husbandry would make pasture fires obsolete. New laws in 1930 tightened the screws but still allowed for pasture fires upon written authorization. At independence in 1960, Malagasy legislation echoed colonial laws, and the government organized periodic anti-fire awareness campaigns. In the 1970s, penalties for illegal wildfires were severely stiffened, yet enforcement fell far behind. Anti-fire propaganda and enforcement again intensified around 1990 as money associated with environmental conservation began to pour into the country; at this time the Forest Service also stopped issuing pasture-burning authorizations in many regions (Kull 2004).

Similar patterns continue into the 21st century (Rarivomanana 2017). During his 2001 to 2009 tenure as President, Marc Ravalomanana called bushfires a primary threat to development, and decreed an incentive system across the country to reward municipalities (*communes rurales*) who took action against bushfires. In 2003, the Ministry of the Environment and Forests established a satellite-based fire monitoring system in partnership with USAID and Conservation International, which was frequently used to identify hotspots and compare communal and regional performance (Ralaimihoatra 2008). Firefighting committees were widely established (Figure 1E), and moments of zealous enforcement sometimes led to heavy prison sentences. Despite political upheavals, no important changes characterized bushfire policy and action in the most recent decade (2010-2020). Local authorities (mayors, gendarmes, and forest officers) continued to seek to mobilize local communities to control burning, while some protected areas sought to protect forests using fire breaks and watch-towers. However, despite these different programs and efforts, fire policies and associated actions are frequently not implemented, and when applied are characterized by inconsistencies and arbitrariness. Dramatic fires continue to periodically capture media attention, such as a 2019 blaze in the grasslands around and forests within Ankarafantsika National Park (C. Kull, unpublished data).

Despite 120 years of anti-fire policies and activities, fires continue to burn widely in the Central Highlands, which is characterized by flammable fire-dependent grasses and a wet-dry climate. Alvarado et al. (2018) show that exclusion efforts lead to reduced ignitions but subsequently more prominent fires later in the season. As Kull (2004) argued, this is aided by the easy anonymity of fire ignition and fire's self-propagation, which allows people to start fires surreptitiously in order to accomplish their agro-pastoral tasks. Villagers protect each other from enforcement and some lower-level officials are reluctant to enforce unpopular or lower-priority rules. Farmers light fires opportunistically (Figure 1F), following an unwritten management plan, in response to both bioclimatic factors (rainfall and vegetation growth) and political factors (moments of reduced enforcement of anti-fire laws, elections, or locust invasions).

Over the decades, some officials have sought alternative solutions to fire exclusion and bans (Kull 2004). All fire legislation reluctantly made some room for people to obtain authorization to burn pasture areas; this system worked in some historical locations and time periods, not in others. Specialists occasionally promoted burning outside the dry season, when fires would remain easier to control and burn less severely. However, such fires are less useful in providing the "green bite" for cattle. Despite policy failures and frequent claims that fires are increasing, fire use has decreased this century in highland areas where population density and/or intensive land use increased (Andela et al. 2017; cf. Archibald 2016 for the rest of Africa). In some areas, the expansion of crop fields due to population growth squeezed out fire use; in other areas, the spread of important cash crops, such as eucalyptus woodlots or fruit orchards, led to a limitation of burning (Kull 2004).

Community-based natural resource management policies in the 1990s allowed for the decentralization of the management of different habitats to local communities, but were mainly applied to forest protection and usually took anti-fire approaches. These methods could have led to a new era of community fire management but did not (Kull 2004), though they may have contributed towards a lower fire frequency (Andrianandrasana 2016). In or around some protected areas, such as Ibity or Ankazobe (associated with Ambohitantely), efforts at involving communities in planned burning and the construction and maintenance of firebreaks have advanced, but these remain the exception.

Conclusion

In conclusion, what is clear is that, in the wet-dry climate of the Central Highlands, fires are an inevitable part of the landscape, a feature of these landscapes well before human settlement with a different level of periodicity, and likely to be around for a long time into the future. Research into fire in Madagascar, alongside research into grassland ecology, will be critical to dispelling myths about fire as well as help develop approaches to burning that aid sustainable land management issues like invasive species (Figure 1A), such as *Pinus* and *Eucalyptus* at the forest edge. Fire can be used productively as a tool to manage landscapes just as it is across the wider wet-dry tropics. Policies of suppression serve only to create out of control fires with then little expertise to manage fire and lead to disharmony between government administrators and local communities who are aware of the value of fire for creating green pick for cattle in hungry months.

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References

Alvarado, S. T., Buisson, E., Rabarison, E., Rajeriarison, C., Birkinshaw, C., Lowry, P. P., and Morellato, L. P. C. 2014. Fire and the reproductive phenology of endangered Madagascar sclerophyllous tapia woodlands. *South African Journal of Botany* 94: 79-87.

Alvarado, S. T., Buisson, E., Carriere, S. M., Rabarison, H., Rajeriarison, C., Andrianjafy, M., . . . Birkinshaw, C. 2015. Achieving sustainable conservation in Madagascar: the case of the newly established Ibity Mountain Protected Area. *Tropical Conservation Science,* 8: 367-395.

Alvarado, S. T., Silva, T. S. F., and Archibald, S. 2018. Management impacts on fire occurrence: A comparison of fire regimes of African and South American tropical savannas in different protected areas. *Journal of Environmental Management* 218: 79-87.

Andela, N., Morton, D. C., Giglio, L., Chen, Y., van der Werf, G. R., et al. 2017. A human-driven decline in global burned area. *Science* 356 (6345): 1356.

Andriamampionona, A. 1992. Les feux de brousse dans la région de l'Itasy. Antananarivo: FAO/PNUD/MAG/88.032.

Andrianandrasana, H. 2016. Testing the effectiveness of community-based conservation in conserving biodiversity, protecting ecosystem services, and improving human well-being in Madagascar. Ph.D. thesis, University of Oxford.

Archer, S. R., Andersen, E. M., Predick, K. I., Schwinning, S., Steidl, R. J., and Woods, S. R. 2017. Woody plant encroachment: Causes and consequences. In *Rangeland systems: Processes, management and challenges*, ed. D. D. Briske, pp. 25-84. Cham, Switzerland: Springer Open.

Archibald, S. 2016. Managing the human component of fire regimes: Lessons from Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371: 20150346.

Archibald, S., Scholes, R. J., Roy, D. P., Roberts, G., and Boschetti, L. 2010. Southern African fire regimes as revealed by remote sensing. *International Journal of Wildland Fire* 19: 861-878.

Archibald, S., Lehmann, C. E. R., Gómez-Dans, J. L., and Bradstock, R. A. 2013. Defining pyromes and global syndromes of fire regimes. *Proceedings of the National Academy of Sciences of the USA* 110: 6442.

Bloesch, U. 1997. La problématique des feux sur le plateau de l'Andohariana (RNI 5) et sa zone périphérique. Consultants report. Antananarivo: WWF.

Bloesch, U. 1999. Fire as a tool in the management of a savanna/dry forest reserve in Madagascar. *Applied Vegetation Science* 2: 117-124.

Bloesch, U., Bosshard, A., Schachenmann, P., Rabetaliana, H. S., and Klötzli, F. 2002. Biodiversity of the subalpine forest-grassland ecotone of the Andringitra Massif, Madagascar. In *Mountain biodiversity: A global assessment*, eds. C. Korner and E. M. Spehn, pp. 165-176. New York: Routledge.

Bond, W. J., Silander Jr., J. A., Ranaivonasy, J., and Ratsirarson, J. 2008. The antiquity of Madagascar's grasslands and the rise of C4 grassy biomes. *Journal of Biogeography* 35: 1743-1758.

Bond, W. J., Stevens, N., Midgley, G. F., & Lehmann, C. E. R. 2019. The trouble with trees: afforestation plans for Africa. *Trends in Ecology & Evolution,* 34: 963-965.

Bosser, J. 1969. *Graminées des Pâturages et des Cultures à Madagascar*. *Mémoire ORSTOM No. 35*. Paris: ORSTOM.

Bovalo, C., Barthe, C., and Bègue N. 2012. A lightning climatology of the South-west Indian Ocean. *Natural Hazards and Earth System Sciences.* 12: 2659-2670.

Briske, D. D. (ed.) 2017. *Rangeland systems: Processes, management and challenges*. Cham, Switzerland: Springer Open.

Burney, D. A. 1987. Late Quaternary stratigraphic charcoal records from Madagascar. *Quaternary Research* 28: 274-280.

Burney, D. A. 1997. Theories and facts regarding Holocene environmental change before and after human colonization. In *Natural and human-induced change in Madagascar*, eds. S.

M. Goodman and B. P. Patterson, pp. 75-89. Washington, D.C.: Smithsonian Institution Press.

Burney, D. A., Robinson, G. S., and Burney, L. P. 2003. *Sporormiella* and the late Holocene extinctions in Madagascar. *Proceedings of the National Academy of Sciences of the USA* 100: 10800-10805.

Burney, D. A., Burney, L. P., Godfrey, L. R., Jungers, W. L., Goodman, S. M., Wright, H. T., and Jull, A. J. T. 2004. A chronology for late prehistoric Madagascar. *Journal of Human Evolution* 47: 25-63.

Copsey, J. A., Jones, J. P. G., Herizo, A., Rajaonarison, L. H., and Fa, J. E. 2009. Burning to fish: Local explanations for wetland burning in Lac Alaotra, Madagascar. *Oryx* 43: 403-406.

Cori, G., and Trama, P. 1979. *Types d'élevage et de vie rurale à Madagascar*, *Travaux et Documents de Géographie Tropical No. 37*. Bordeaux: Centre d'Etudes de Géographie Tropicale, Centre National de la Recherche Scientifique.

Fowler, C. T., and Welch, J. R. (eds.) 2018. *Fire otherwise: Ethnobiology of burning for a changing world*. Salt Lake City: University of Utah Press.

Gade, D. W. 1996. Deforestation and its effects in highland Madagascar. *Mountain Research and Development,* 16: 101-116.

Goel, N., Van Vleck, E., Aleman, J. C., and Staver, A. C. 2020. Dispersal limitation and fire feedbacks maintain mesic savannas in Madagascar. *bioRxiv*: 2020.01.14.905208.

Granier, P., and Serres, H. 1966. A propos de l'incidence des feux de brousse sur l'évolution des pâturages. *Bulletin de Madagascar* 16: 789-791.

Hackel, J., Vorontsova, M. S., Nanjarisoa, O. P., Hall, R. C., Razanatsoa, J., Malakasi, P., and Besnard, G. 2018. Grass diversification in Madagascar: In situ radiation of two large C3 shade clades and support for a Miocene to Pliocene origin of C4 grassy biomes. *Journal of Biogeography* 45: 750-761.

Hempson, G. P., Archibald, S., Donaldson, J. E., and Lehmann, C. E. R. 2019. Alternate grassy ecosystem states are determined by palatability–flammability trade-offs. *Trends in Ecology and Evolution* 34(4): 286-290.

Hoffmann, W. A., Geiger, E. L., Gotsch, S. G., Rossatto, D. R., Silva, L. C. R., Lau, O. L., Haridasan, M., and Franco, A. C. 2012. Ecological thresholds at the savanna-forest boundary: How plant traits, resources and fire govern the distribution of tropical biomes. *Ecology Letters* 15: 759-768.

Humbert, H. 1949. La dégradation des sols à Madagascar. *Mémoires de l'Institut de Recherche Scientifique de Madagascar* D1(1): 33-52.

Jacquin, A, Chéret, V., Sheeren, D., and Goulard, M. 2010. Impact of fire on savanna vegetation trends in Madagascar assessed using a remote-sensing based statistical analysis, ed. R. Reuter, pp. 409-422. Paris: EARSeL Conference Proceedings.

Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., Kinney, P., Bowman, D. M. J. S., and Brauer, M. 2012. Estimated global mortality attributable to smoke from landscape fires. *Environmental Health Perspectives* 120(5): 695-701.

Klein, J., Réau, B., Kalland, I., and Edwards, M. 2007. Conservation, development, and a heterogenous community: The case of Ambohitantely Special Reserve, Madagascar. *Society and Natural Resources* 20: 451-467.

Koechlin, J. 1993. Grasslands of Madagascar. In *Natural grasslands: Eastern Hemisphere and résumé*, ed. R. T. Coupland, pp. 291-301. Amsterdam: Elsevier.

Kull, C. A. 2000. Deforestation, erosion, and fire: Degradation myths in the environmental history of Madagascar. *Environment and History* 6: 423-450.

Kull, C. A. 2004 *Isle of fire: The political ecology of landscape burning in Madagascar*. Chicago: The University of Chicago Press.

Lamont, B. B., and Downes, K. S. 2011. Fire-stimulated flowering among resprouters and geophytes in Australia and South Africa. *Plant Ecology* 212: 2111-2125.

Laris, P. 2002. Burning the seasonal mosaic: Preventative burning strategies in the wooded savanna of southern Mali. *Human Ecology* 30: 155-186.

Lehmann, C. E. R., Archibald, S. A., Hoffmann, W. A., & Bond, W. J. (2011). Deciphering the distribution of the savanna biome. *New Phytologist,* 191: 197-209.

Lehmann, C. E. R., Anderson, T. M., Sankaran, M., Higgins, S. I., Archibald, S., Hoffmann, W. A., Hanan, N. P., Williams, R. J., Fensham, R. J., Felfili, J., Hutley, L. B., Ratnam, J., San Jose, J., Montes, R., Franklin, D., Russell-Smith, J., Ryan, C. M., Durigan, G., Hiernaux, P., Haidar, R., Bowman, D. M. J. S., and Bond, W. J. 2014. Savanna vegetation-fire-climate relationships differ among continents. *Science* 343: 548-552.

Lehmann, C. E. R., and Parr, C. L. 2016. Tropical grassy biomes: Linking ecology, human use and conservation. *Philosophical Transactions of the Royal Society B: Biological Sciences* 371: 20160329.

Linder, H. P., Lehmann, C. E. R., Archibald, S., Osborne, C. P., and Richardson, D. M. 2018. Global grass (Poaceae) success underpinned by traits facilitating colonization, persistence and habitat transformation. *Biological Reviews* 93(2): 1125-1144.

Moura, L. C., Scariot, A. O., Schmidt, I. B., Beatty, R., and Russell-Smith, J. 2019. The legacy of colonial fire management policies on traditional livelihoods and ecological sustainability in savannas: Impacts, consequences, new directions. *Journal of Environmental Management* 232: 600-606.

Musinsky, J., Tabor, K., Cano, C. A., Ledezma, J. C., Mendoza, E., Rasolohery, A., and Sajudin, E. R. 2018. Conservation impacts of a near real-time forest monitoring and alert system for the tropics. *Remote Sensing in Ecology and Conservation* 4(3): 189-196.

Nanjarisoa, O. P., Besnard, G., Ralimanana, H., Jeannoda, V. H., and Vorontsova, M. S. 2017. Grass survey of the Itremo Massif records endemic central highland grasses. *Madagascar Conservation and Development* 12(1): 34-40.

Parr, C. L., Lehmann, C. E. R., Bond, W. J., Hoffmann, W. A., and Andersen, A. N. 2014. Tropical grassy biomes: Misunderstood, neglected, and under threat. *Trends in Ecology and Evolution* 29(4): 205-213.

Perrier de la Bâthie, H. 1921. La végétation Malgache. *Annales du Musée Colonial de Marseille*, série 3, 9: 1-266.

Price, O. F., Russell-Smith, J., and Watt, F. 2012. The influence of prescribed fire on the extent of wildfire in savanna landscapes of western Arnhem Land, Australia. *International Journal of Wildland Fire* 21(3): 297-305.

Rakotoarimanana, V. 2002. Feu, pâturage et dynamique des savanes à *Heteropogon contortus* (L) P. Beauv. Ex Roem and Shult. dans le sud ouest de Madagascar (région de Sakaraha). Ph.D. thesis, Université d'Antananarivo.

Rakotoarimanana, V., and Grouzis, M. 2006. Influence du feu et du pâturage sur la richesse et la diversité floristiques d'une savane à *Heteropogon contortus* du sud-ouest de Madagascar (région de Sakaraha). *Candollea* 61(1): 167-188.

Ralaimihoatra, S. N. 2008. Le système de suivi satellitaire des feux, un outil de gestion des Madagascar. In Les XIèmes Journées Scientifiques du Réseau ressources naturelles à

Télédétection de l'AUF, 03 au 07 novembre 2008, pp. 279-281. Antananarivo: Agence Universitaire de la Francophonie.

Randriambelo, T., Baldy, S., Bessafi, M., Petit, M., and Despinoy, M. 1998. An improved detection and characterization of active fires and smoke plumes in south-eastern Africa and Madagascar. *International Journal of Remote Sensing* 19(14): 2623-2638.

Randriambelo, T., Baray, J.-L., and Baldy, S. 2000. Effect of biomass burning, convective venting, and transport on tropospheric ozone over the Indian Ocean: Reunion Island field observations. *Journal of Geophysical Research* 105 (D9): 11813-11832.

Ranriatsivery, F. M. 2005. Evaluation des impacts du feu sur la végétation des savanes du massif d'Ibity. Mémoire du DEA en Ecologie Végétale, Université d'Antananarivo.

Rarivomanana, H. T. 2017. Analyse de la mise en œuvre des stratégies de lutte contre les feux a Madagascar : Cas de la région Sofia. Mémoire de Master, Département des Sciences et Gestion de l'Environnement, Université de Liège.

Rasoafaranaivo, M. H. 2005. Evaluation des impacts du feu sur la biologie de quelques espèces végétales du massif d'Ibity (Antsirabe). Mémoire DEA en Ecologie Végétale, Université d'Antananarivo.

Ratsimamanga, A. R. 1968. *Dictionnaire des Noms Malgaches des Végétaux*. Antananarivo: Institut Malgache de Recherches Appliquées.

Schwilk, D. W., and Ackerly, D. D. 2001. Flammability and serotiny as strategies: Correlated evolution in pines. *Oikos* 94: 326-336.

Scott, A. C., Bowman, D. M. J. S., Bond, W. J., Pyne, S. J., and Alexander, M. E. 2014. *Fire on Earth: An introduction*. Hoboken, New Jersey: Wiley Blackwell.

Solofondranohatra, C. L., Vorontsova, M. S., Hackel, J., Besnard, G., Cable, S., Williams, J., Jeannoda, V., and Lehmann, C. E. R. 2018. Grass functional traits differentiate forest and savanna in the Madagascar Central Highlands. *Frontiers in Ecology and Evolution* 6: 184.

Solofondranohatra, C. L., Vorontsova, M. S., Hempson, G. P., Hackel, J., Cable, S., Vololoniainana, H. J., and Lehmann, C. E. R. 2020. Fire and grazing determined grasslands of central Madagascar represent ancient assemblages. *Proceedings of the Royal Society B (Biological Sciences)*. 287: 20200598.

Veldman, J. W., Overbeck, G. E., Negreiros, D., Mahy, G., Le Stradic, S., Fernandes, G. W., Durigan, G., Buisson, E., Putz, F. E., and Bond, W. J. 2015. Tyranny of trees in grassy biomes. *Science* 347(6621): 484-485.

Vorontsova, M. S., Besnard, G., Forest, F., Malakasi, P., Moat, J., et al. 2016. Madagascar's grasses and grasslands: Anthropogenic or natural? *Proceedings of the Royal Society of London B: Biological Sciences* 283: 20152262.

Willis, K. J., Gillson, L., and Virah-Sawmy, M. 2008. Nature or nurture: The ambiguity of C4 grasslands in Madagascar. *Journal of Biogeography* 35: 1741-1742.

Figure 1. Different facets of fire in the Central Highlands. **A**) Peri-urban fire in a grazing pasture dense with invasive *Acacia dealbata*, *Lantana camara*, and other bushes in Central Highlands, near Ambositra, October 2018; **B**) fire scar mosaic in grassland near riparian forest in western Central Highlands in Bongolava range, west of Tsiroanomandidy, July 1996; **C**) active grassland fire close to eucalyptus woodlots near Ambositra, June 1999; **D**) monitoring nighttime fire at village outskirts in western Central Highland near Tsiroanomandidy, July 1994; **E**) fighting fire to protect homes and fields near Antsirabe, September 1998; and **F**) early season grass fire in tapia woodlands near Antsirabe, April 1998. Photos by C. Kull.

Table 1. The purposeful uses of vegetation fire in Central Highland Madagascar. Note that often one fire accomplishes several purposes.

Sector	Purpose	Specific task or use
Cattle raising	Maintain pasture	- fight bush encroachment - pasture renewal (green shoots)
	Pest control	- control tick populations
	Cattle control	- facilitate observation and mobility - collect free-ranging cattle
Agriculture	Field preparation	- clear brush for plowing/spade work - fertilize fields
	Downhill transfers	- encourage erosion to fertilize downstream fields - encourage runoff to speed up irrigation
	Cleaning	- clean out irrigation canals - remove pest habitat around fields (rats, birds)
Other	Wildfire prevention and control	- early burns for fuel management - burning fire breaks - back fires against wildfires
	Pests	- ward off and/or collect locusts - control rats, ticks, mosquitoes
	Tapia woodland management	- maintain dominance of *Uapaca bojeri* - control silkworm parasites
	Woodlots and woodfuel	- encourage pine regeneration - create dead branches for woodfuel collection
	Travel	- to clear trails and roadsides - to light the way in the dark
	Ground clearance	- to see mineral outcrops - to see wild tuber crops
	Grass species management	- encourage *Aristida rufescens*, used for brooms and roofing
	Celebration/spectacle	- natural firecrackers and entertainment
	Protest/revenge	- symbolic protest, arson

Table 2. Important Central Highland grass species (family Poaceae). Based on Ratsimamanga (1968), Bosser (1969), Gade (1996), Bloesch (1997), and Kull (2004); see Lehmann et al. (p. xx). Pan-tropical species are noted with an asterisk (*). Regional variations on local names indicated as follows: SV = southern Vakinankaratra, i.e. Antsirabe; NV = northern Vakinankaratra, i.e. Ambatolampy; T = Tsiroanomandidy; A = Ambositra; and N = Ambalavao-Andringitra.

Genus and species	**Local names**	**Comments**
Aristida rufescens	*Horona* (SV, NV), *horombohitra* (T) *kofafa vavy* (A, N), *horombavy, pepeka*	Widespread, extremely fire tolerant perennial; used to make grass roofs and brooms, little nutritious value when mature.
A. similis	*Horombavy, kofafavavy, ahitsorohitra madinika* (SV)	Extremely fire tolerant, perennial, hygrophile, poor forage quality when mature but palatable as regrowth.
**A. congesta*	*Kofafalahy* (N)	Smaller plant found in cooler, higher areas that is not palatable.
**Ctenium concinum*	*Ahitsorohitra* (SV)	Perennial, mediocre forage found in repeat-burned short-grass savannas >900 m, associated with *Aristida* and *Loudetia.*
**Cynodon dactylon*	*Kindresy* (N), *fandrotrarana* (SV), Bermuda grass	Good forage; found near villages and on cool high pastures in grazing lawns and is not tolerant to fire.
**Heteropogon contortus*	*Danga* (SV, T), *ahidambo* (N), *lefondambo, ahimoso*	Perennial, common <1300 m in association with *H. rufa*, moderately tolerant of both fire and grazing, good forage when young.
**Hyparrhenia rufa*	*Vero, verofotsy, veromena, fataka*	Perennial, good forage (especially in association with *Heteropogon contortus*), less tolerant of fire and commonly found along waterways.
**H. cymbaria*	*Verobe, verotsanjy, vero, verovato*	Large perennial, intolerant of fire, found on good deep soils, at forest edges.
**Imperata cylindrica*	*Tenina* (SV), *manevika, fehena, antsoro* (NV)	Perennial, rhizomous, <2000 m; in dry, well-drained spots, not on eroded soils and can be associate with tree cover at forest edges.
Lasiorrhachis vigueri	*Haravola* (SV, NV)	Used to make straw mats, baskets; cattle eat new shoots only. In higher locations remains green through winter.
**Loudetia simplex* (var. *stipoides*)	*Horona* (A), *horo* (N), *berambo, kilailay, kirodrotra, felika* (SV)	Perennial, widespread, poor pastoral value, quite fire resistant, found on leached, poorly drained soils. Widespread across Africa and Madagascar.
**Panicum maximum = Urochloa maxima*	*Verotsanga* (T)	Large perennial bunch grass, decent forage. Known as "guinea grass".
**Paspalum* spp.	*Gebona, gebo* (N)	High pastoral value especially from March to May.
Pennisetum pseudotriticoides	*Horompotsy* (NV), *tohiambazaha*	Endemic, 1000-2000 m, found on humid, cool, silty or sandy alluvions.