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The early/late fire dichotomy: Time for a reassessment of Aubréville's savanna fire experiments

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Abstract

A fundamental principal of savanna fire ecology is that the fire regime determines vegetation cover, especially as it pertains to trees. A corollary is that late fires are more damaging to trees than early fires. Much evidence in support of this principle has been derived from a series of long-term burning experiments based on the pioneering work of André Aubréville. Eighty years ago, Aubréville devised an experiment to study the impacts of fire on savanna trees in Africa. The design conventions of this study remain highly influential. It is now clear, however, that the dates chosen by Aubréville and his followers do not reflect the burning practices of West African people. Dates that were chosen for "early" and "late" are not representative of actual fire timing; they represent extremes. This study has four goals: (i) to critically review the results of the burning experiments; (ii) to examine them in the context of results from recent savanna fire studies; (iii) to evaluate their limitations based on data for actual burning practices and fires from West Africa; and (iv) to critically evaluate the use of the early/late terminology in contemporary fire research. We find the majority of West African fires occur during the "middle" of the fire season. Our field studies find that fire temperature and burn completeness are highest in the middle-season. We conclude that the early/late fire dichotomy is not sufficient for understanding the impacts of anthropogenic fires in the region and we make suggestions for rethinking its use more broadly.

Keywords

Savanna, fire, burning experiments, Africa, fire timing, critical physical geography

I. Introduction

Eighty years ago, renowned French scientist and forester André Aubréville devised a field experiment to test his assumption that cutting

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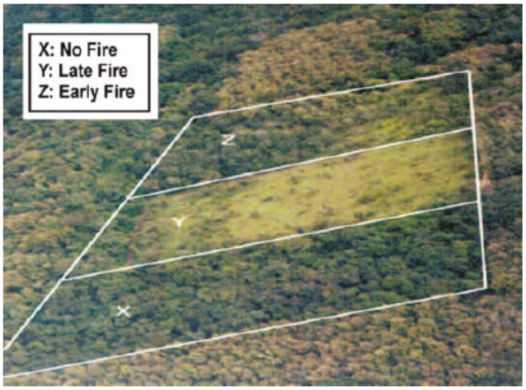

Figure 1. Layout for Aubréville's burning experiment showing the impact of different burning regimes (no fire, late fire, early fire) on vegetation cover over the long term (Photograph by Marc Ducousso).

and burning of dry forest caused savannization. He established experimental plots at a research station in Ivory Coast, West Africa. Plots were isolated from any agro-pastoral or burning practices of local inhabitants and annually subjected to three treatments: early fire, late fire and no fire. The experimental work persisted for over 60 years and has become one of the longest running field experiments of any kind (Aubréville, 1953; Louppe et al., 1995). Aubréville's burning experiment was not the first of its kind, but it was very influential and many scientists went on to establish similar ones in different savannas across Africa and around the world (e.g. Andersen et al., 2003; Furley et al., 2008; Laris and Wardell, 2006; Menaut et al., 1995; Swaine, 1992). The combined results of these experiments have been influential in the development of savanna fire ecology.

The results of the experiments clearly showed that intense fires can prevent reforestation on previously cleared land and that the seasonality or *timing* of fire is a critical determinant of tree cover. As can be seen in Figure 1, the early-burned plot of Aubréville's experiment is far more wooded than the late-burned plot, although less wooded than the unburned plot. That is, while late fires can prevent tree establishment and growth, early fires do not necessarily have this effect, although they do tend to modify tree species and reduce cover.

To date, countless studies have adopted the early/late fire convention in the design of savanna fire experiments. The practice of dividing the savanna fire season into two periods has become deeply engrained in savanna science in all of the world's major savanna regions (e.g. Andersen et al., 2003; Furley et al., 2008; Govender et al., 2006; Mistry and Berardi, 2005; Prior et al., 2010; Ramsay and Rose-Innes, 1963; Russell-Smith et al., 2003a, 2003b, 2013).

Contemporary savanna fire ecological models and theories have incorporated the findings from these burning experiments in the form of a general principal: *the fire regime is a key determinant of vegetation cover in a savanna* with the corollary that *late dry season fires burn more intensively and are more damaging to trees (especially juveniles) than early fires*. This basic principal has been widely cited in the savanna and ecology literature (e.g. Cole, 1986; Menaut et al., 1995; Sankaran et al., 2004; Scholes and Walker, 1993; Staver et al., 2011; Swaine, 1992), has influenced models for savanna fire emissions (Russell-Smith et al., 2009, 2014) and it remains the basis for fire codes in many countries (Kull and Laris, 2009; Laris and Wardell, 2006; Mistry and Berardi, 2005).

It is important to note that Aubréville's intent in establishing the experiments was explicitly political and anti-fire. His goal was to provide supporting evidence for his theoretical argument that savanna fires caused degradation in the form of savannization (a reduction in tree cover and forest species) and to refute the argument that savannas were climatically or edaphically determined (Laris and Wardell, 2006). As Aubréville stressed in his original article, which summed-up the preliminary results of his experiments, the findings

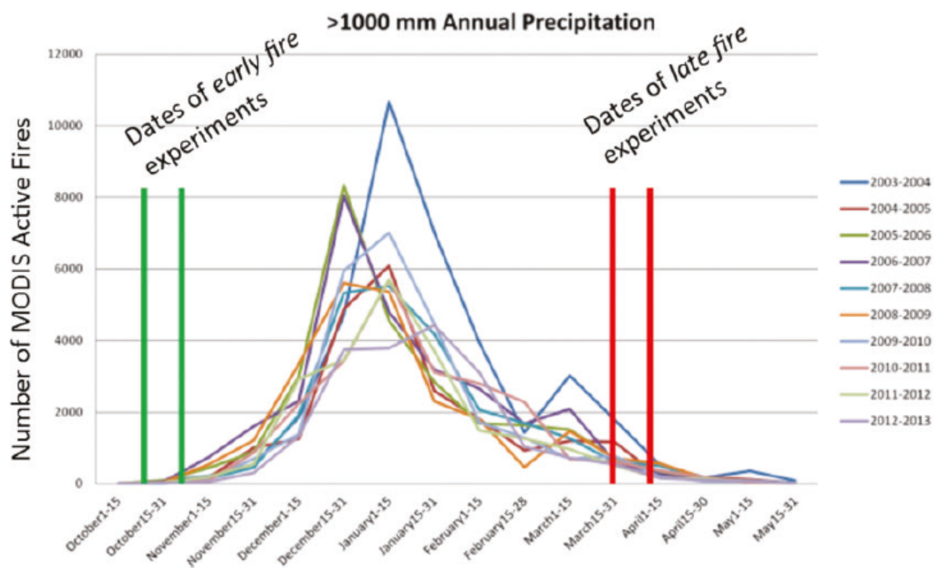

Figure 2. The fire regime for southern Soudan and Guinea savanna and the dates of commonly cited burning experiments for which burn dates are known (Aubréville, 1953; Brookman-Amissah et al., 1980; Ramsay and Rose-Innes, 1963).

should be widely dispersed so as to influence policy:

> We must remember that these experiments are meant not only to support our own conception of forestry policy but also to convince others of our conclusions, especially administrative and political authorities. *They must be like propaganda and not remain secret* ... I remind the reader that the principle of these demonstrations, being conducted to *prove the effects of brush fires and conversely the effects of their suppression*, is to delimit several plots in the woody savannah, of which one is the control plot, completely protected from brushfires while, in the others, various types of treatments are experimented with: early fires, late fires, extreme cutting following the passage of fire or protection from fire altogether, etc. (Aubréville, 1953: 5) (emphasis added)

It is also quite clear from their own writings that Aubréville, and others studying fire at the time, held a very negative view of traditional burning practices, which they viewed as haphazard and environmentally degrading (Aubréville, 1949, 1953; Fairhead and Leach, 1996; Krebs et al., 2010; Laris, 2004) which likely influenced the experimental design as well.

To provide evidence for his theory of savannization, Aubréville selected burn dates for his experiments corresponding to the beginning and end of the fire season, what he referred to as *early* and *late* fire, presumably to capture the least and most extreme fire conditions. It is now abundantly clear, however, that the dates chosen by Aubréville did (and do) not reflect the burning practices of West Africans. Our findings, based on analysis of two long-term data sets, indicate that the majority of fires occur during the mid-dry season (Laris, 2011; Laris et al., 2015, 2016) and thus at a time of year that does not conform to the dates chosen by Aubréville and others that followed (Figure 2; see below). The dates of the experiments represent the extreme ends of the fire season—we refer to these dates as *very early* and *very late*. As such, we argue that the results of the experiments tell us very little about the actual impacts of fires in the region because the vast majority of the fires are neither *early* nor *late* but rather occur in the "mid-" fire season.

Today, the Sudanian and Guinean savanna of West Africa remain among the most frequently and widely burned savanna (e.g. Giglio et al., 2010; Randerson et al., 2012) and the fires have a major influence on woody vegetation cover (Bond et al., 2005; Staver et al., 2011), greenhouse gas (GHG) emissions and the carbon cycle of the savanna (e.g. Bowman et al., 2009). Given their continued influence and recognized limitations, it is time for a critical assessment of the West African burning experiments.

This paper takes a critical physical geography approach to examine the original experiments, and the studies that followed, in that it aims "to produce critical biophysical and social explanations while also reflecting on the conditions under which those explanations are produced" (Lave et al., 2014: 4). The goal of this paper is thus to scrutinize not only the findings, but also the concepts and categories used in savanna fire ecology, following Sayre (2015):

> Scientific categories have histories; they should not be taken for granted as given or natural, but understood as the result of actions taken by particular people (scientists and non-scientists) in particular contexts. This is especially important in cases where repeated use over time has cemented concepts into the literature and occluded the decisions and assumptions that attended them at the outset. Such decisions necessarily reflected, in some measure, the social conditions in which they were made, and they very likely rested on assumptions that may have been faulty from the start, or that may have become faulty as conditions subsequently changed. (Sayre, 2015: 577)

We argue that the early/late fire convention is deeply embedded in contemporary savanna fire science and policy. The specific purpose of this paper is thus to critically analyze the origins and continued use of this convention in savanna fire research, and to question its dominance in shaping savanna fire science and research, while bringing attention to other explanations.

The objective of this article is, firstly, to review the West African burning experiments, their origins, the key conventions these studies produced and their current use in the savanna literature; and, secondly, to reassess the appropriateness of the experimental design based on three sources: (i) an examination of experimental results from recent savanna fire studies from a variety of locales; (ii) data about actual burning practices of West Africans; and (iii) fire temperature and burn completeness data from experimental fires in a variety of savanna types gathered from a field site in the Ivory Coast. Finally, based on this review and data presented, we consider the importance of alternative factors, including time of day, fire direction and grass species, for determining impacts of savanna fires on trees.

II. Fire ecology research in savannas

1. Aubréville and the long-term fire experiments

Aubréville believed that vast tracks of savanna in West Africa were of anthropogenic origin, derived from tropical dry forests that he had theorized were the natural vegetation climax for the region. He was convinced the principle drivers of savannization were slash and burn agriculture combined with frequent and widespread burning of the savanna and he was determined to prove that people, not climate, caused particular savannas (Aubréville, 1947, 1949, 1953). Aubréville established his experiments at a time of global debate over the role of traditional burning practices and their impact on woodlands in tropical areas (Krebs et al., 2010; Pyne, 1990). His views were influential in defining the perceived fire problem in West Africa in terms of fire's negative impacts, which demanded action to prevent widespread degradation (Fairhead and Leach, 1996; Laris, 2004).

To test his theory, Aubréville selected a study site for his pioneering experiment in the savanna of Ivory Coast. Care was taken to create a laboratory-like setting by clearing surrounding vegetation so that the vegetation on the plots could be subjected to specific fire treatments. Every year three different treatments were applied, one to each plot: plot one was totally protected from fire; plot two was burned "early" at the beginning of the dry season on 15 December; and plot three was burned "late" at the end of the dry season in May. The treatments were repeated annually for decades (Aubréville, 1953; Louppe et al., 1995).

As noted, Aubréville's fire experiment proved to be extremely influential; during subsequent decades, experiments using a similar design were established in numerous African savannas (e.g. Charter and Keay, 1960; Furley et al., 2008; Jouvanceau, 1962; Onochie, 1964; Ramsay and Rose-Innes, 1963; Rose-Innes, 1971). Indeed, Aubréville's burning experiments held such influence that authors of many similar studies that followed did not include the actual dates of burning, rather they simply listed "early" and "late" fire (see Table 1).

The results of Aubréville's experiment generally agree with the published findings of numerous other studies that have come to define savanna fire ecology (see Furley et al., 2008, for a global review). Following decades of fire treatment there were marked differences in the vegetation cover on the three plots as follows.

- Trees cover the protected site and in some cases the canopy is completely closed, making fire impossible.
- Grasses dominate the vegetation on the late burning site.
- The early burned site is somewhere in-between the other two. It is similar to the protected site but with fewer trees and more grass cover. The trees are proportionately different in size [lower density but higher girth] from the protected site.
- Fire intolerant tree and shrub species are eliminated from the burned plots.

2. Limitations of the experiments

Despite and/or because of efforts to conduct burning experiments under tightly controlled conditions, the studies have been subject to a variety of critiques. In an early critique, Ramsay and Rose-Innes (1963) note that early and late fire dates were often not recorded. The authors also criticized several experiments for their lack of methodological rigor (in spite of Aubréville's argument to the contrary). In particular, they note that little consideration is made of the context of the study sites. Specifically, the composition of the surrounding vegetation, the main seed source for re-vegetation, is not recorded and the experiments were not controlled for variations in edaphic conditions, which are known to have a strong impact on vegetation cover. Also, many sites were clear-felled before the experiments or performed on abandoned agricultural land and there was little consistency in study design.

More recently, Furley et al. (2008) criticized the experiments for their lack of rigor and rigid design:

> There have been several other serious criticisms of some burning trials, relating to the lack of an initial sound protocol and the inevitability of a rigid design. The experimental plots have often been relatively small in relation to the area represented (to permit adequate control), contrived (since wildfires are frequently spontaneous and irregular), and artificial (in the sense that they try to simplify conditions whereas the reality is a heterogeneous ecosystem). The experimental conditions may also be considered untypical of the areas outside the fire trials. (Furley et al., 2008: 613)

With the exception of the comment that savanna wildfires are "frequently spontaneous and irregular" (fires in Africa are often planned and highly regular, see below), this critique generally holds true for the West African savanna studies.

Table 1. Sample of long-term burning experiments in Africa with initial conditions and results.

Author	Site	Precip. (mm)	Additional findings	Impact of soils	History	Burn dates
Aubréville, 1953; Louppe et al., 1995	Kokondero, Ivory Coast	1200–1250		Soil fertility is decisive on early burn plots, poor soils akin to late fires	6-year Fallow	15 Dec.–1–15 May
Ramsay and Rose-Innes, 1963	Olokomeji, Nigeria		*Andropogon gayanus* a key perennial prefers early burning	Late fires severely damaged woody vegetation on poor soils		Early Nov. April
Brookman-Amissah et al., 1980	Navrongo, Ghana	1100 mm	Grass biomass (*Andropogon gayanus*) is highest on early burn		Felled plots	Mid-Nov. April
Afolayan and Ajayi, 1979	Nigeria		Focus on grasses: early burning produces perennials			Early and late
Ramsay and Rose-Innes, 1963	Bamako, Mali	1000		Soil conditions determine development of seedlings and suckers		Early and late
Chidumayo, 1988, 1997	Zambia (Miombo)		Early fire and no fire were similar		Felled plots	Early and late

The experiments were also not designed to account for the influence of the spatiotemporal patterns of fire and environmental heterogeneity, which more recent research has found to be critical (Laris, 2011; Parr and Brockett, 1999). As such, efforts by Aubréville and others to isolate their fire studies created artificial conditions for study.

Finally, Moss (1982) critiqued the experiments on different grounds. He argued that the experiments do not reflect the reality of burning practices in Africa because the dates of experimental burning do not coincide with the actual burn timing in the areas studied. For example, areas surrounding Aubréville's research site in Ivory Coast usually burn in mid-season (January or February), yet the study only tests the impact of early (December) or very late (April–May) fires. Similarly, the dates used by Ramsay and Rose-Innes are for the extreme ends of the fire season (Figure 2).

3. Lessons from the early experiments

These early burning experiments were effective at isolating one important variable—fire timing—and documenting its impacts on tree cover over time. According to most contemporary savanna ecological models, however, savanna vegetation structure is understood to be a function of numerous *interacting* factors, including site history, soil moisture and nutrient content, topography and the spatial relationships between these factors (Cole, 1986; Mistry, 2000; Scholes and Archer, 1997; Weigand et al., 2006).

Interestingly, the results of some of the early burning experiments can be quite revealing in regard to the effects of some of these factors. Indeed, the Aubréville plot subjected to early burning demonstrates a marked difference in tree density from the up-slope end to the down-slope end, suggesting that fire, soils and topography have a combined effect on fire impacts (see Figure 1). Ramsay and Rose-Innes (1963) also note the influence of soils on early and late burned plots in their study, "The canopy on better soils has closed, herbaceous vegetation is in some places too sparse to support fire, and new species have appeared. Vegetation on the poorer lower slope has not advanced so well" (45). Others similarly concluded that soil moisture and/or grass types were important (Menaut et al., 1995).

III. Contemporary savanna ecological theory and fire science

While contemporary savanna research on fire and savanna tree cover has shifted from long-term studies to shorter term research on factors governing tree growth and transition rates, the convention of using early and late fire dates in experiments persists. According to the new "demographic" models that govern this research, the fire regime—the frequency, intensity, severity, type and pattern of fire that prevails in a given area (Gill, 1975; Van Wilgen and Scholes, 1997)—is a critical determinant of tree cover because periodic fires prevent the transition of saplings and juveniles to mature trees (e.g. Higgins et al., 2007; Sankaran et al., 2004). While this more recent body of work makes clear that the fire regime is critical to determining tree survival and growth, especially in mesic savannas, the specifics as to why and how critical factors, such as fire intensity, severity and ecosystem responses, are related to fire seasonality are still being investigated and theorized.

West (1965) was one of the first to theorize the reasons why fire seasonality matters. He considered the impact of fire timing from three perspectives, that of the trees, the grasses and the weather patterns. From the perspective of trees, he noted that in the later months of the dry season:

i. plants have higher temperatures and are thus heat stressed;
ii. most trees have produced new leaves; thus, reserves are depleted;

iii. there is less bark protection because moisture is low;
iv. new leaves are susceptible to heat damage and further loss of leaves saps trees of already depleted reserves.

From the perspective of grasses, he noted that they had lower fuel moisture later in the dry season and that the taller, often perennial grasses, were set to fire later. Finally, in terms of weather he noted that the later dry season tends to have higher temperatures and winds as well as lower humidity, which result in higher fire intensity.

From the work of West, it can be seen that seasonality impacts both savanna fire intensity and severity as well as ecosystem responses, such as tree re-sprouting or death. Intensity is the product of heat yields of fuels, the amount consumed and the rate of spread of fire (Bryam, 1959), while severity is a measure of the impact of a fire on vegetation (see below). Fire intensity is predominantly controlled by fuel load and moisture, as well as weather conditions (Cheney et al., 1998). It is well established as a critical determinant of vegetation impact and it is the most frequently used variable in fire ecology studies. Intensity does have some important limitations, however, particularly in how it is measured and the ability to make cross-ecosystem comparisons (Keeley, 2009). As such, most research reporting intensity does not measure it directly; rather, they use surrogate measures that are assumed to be allometrically related. Typically, flame length (or scorch height) is used because empirical studies show there is a significant relationship between flame length and intensity in many ecosystems (Keeley, 2009). Fire line intensity does not correlate with all fire effects, however, as tree mortality can be more a function of total heat output reflected in flame residence time (Keeley, 2009) or, as West noted, a function of tree moisture content.

The term "fire severity" was born out of the need to provide a description of how fire intensity affected ecosystems, particularly following wildfires where direct information on fire intensity was absent. Most empirical studies that have attempted to measure fire severity have had a common basis that centers on the loss or decomposition of organic matter, both above- and below-ground. Fire severity can be determined vertically—in terms of leaf scorch height or charring—or horizontally—in terms of burn patchiness or completeness (Russell-Smith and Edwards, 2006).

Ecosystem responses, such as soil erosion and vegetation regeneration, can be correlated with other variables, such as burn intensity or fire severity, but these relationships should not be considered universal. As Keeley (2006, 2009) notes, the linkages between intensity, severity and tree re-sprouting or death need to be empirically established. The relationships between these factors are often not clearly distinguished in the literature (Keeley, 2009). For example, it is argued that fires burning late in the dry season burn more *intensely* (because vegetation has a low moisture content) and tend to be more *severe* (consume greater amounts of biomass) and are more damaging to trees (especially juveniles) than fires burning early in the dry season, but specifics are sometimes vague (Govender et al., 2006; Menaut et al., 1995; Russell-Smith and Edwards, 2006; Sawadogo et al., 2002).

Finally, the effects of additional variables (none of which were considered in the original African burning experiments) have also been explored, including grass type (annual or perennial), wind speed, fuel load and fire type (head or back). Here we briefly review selected recent research exploring the effects of these factors from African and Australian savannas.[1]

1. African cases

In general, recent fire studies in Africa (much of them from southern Africa) find that fire intensity is linked to fire timing more so than frequency, but that wind speed and direction have a strong influence on intensity and severity.

Studies of Kruger National Park in South Africa have produced a wealth of fire data over the years. It is important to note, however, that Kruger is somewhat dryer (average precipitation = 500–700 mm) than the mesic savannas of West Africa (average precipitation >750 mm), where most early burning experiments were conducted. Govender et al. (2006) found that fire timing significantly affected fire intensity, which was lower in the early dry season and highest in the late season. They found that fire intensities did not vary between annual, biennial, triennial and quadrennial intervals—thus, there was no obvious impact of frequency on intensity, suggesting that seasonal fuel moisture effects overrode those of fuel load. Devine and colleagues (2014) also found that fire frequency was not a critical factor as it did not display a consistent effect on woody cover. They also found that fire was much more influential in lowering tree abundance in the mesic savanna than the dry savanna.

Ryan and Williams (2011) studied the impacts of different intensity fires late in the mesic Miombo savanna. In a novel study design, they manipulated fire intensity by setting fires at different times of the day resulting in various wind and relative humidity conditions. Their data shows that that large (>5 cm dbh) stems are vulnerable to fire, with top-kill rates of up to 12% in intense fires.

Trollope et al. (2002) demonstrated that wind direction was a critical determinant of fire intensity. They found head fires were on average seven times more intense but that they also had greater variation than back fires (head fire intensity average 1359 kJ/s/m and back fire 194 kJ/s/m). Head fire's top kill of trees was 75% while back fire's was 42%.

Finally, in one of few recent fire intensity studies from West Africa, Savadogo et al. (2007) found that fires in annual grasses had higher maximum temperatures than perennials for both head and back fires. They found that plots dominated by perennial grasses had higher values for vegetation height, total fuel load and the quantity of live fuel load. They concluded that fire intensity was closely related to wind speed and that both wind direction and speed have a strong effect on fire behavior in a savanna of Burkina Faso.

2. Australian cases

Recent research in Australia has produced by far the most thorough and detailed data on savanna fire behavior and impacts. In general, this body of work finds that while fire seasonality is the most important determinant of tree re-sprouting or death, additional factors are also critical. Key factors influencing fire severity and intensity include grass type, wind speed and fire direction. This research also finds that grass type in conjunction with fire timing determines fire patchiness.

Williams et al. (1999) compared tree death rates for early (early June), late (September) and unburnt savannas plots. They found that annual early dry season fire intensity averaged 2200 kW/m, while the late dry season fire treatment average was much higher, 7700 kW/m (although there was a great amount of annual variation). They found that despite considerable differences in fire intensity between regimes, whole tree survival was relatively high (82–99%), and there was little difference between regimes. At the level of the individual stem, however, the fire regime had dramatic effects. Stem survival decreased linearly with increasing fire intensity: it was 96% in the unburnt regime 72% in the early dry season regime and only 30% in the late dry season regime.

Werner (2005) compared growth rates for trees subjected to a single season of early, late and no fire. She found that the two main canopy species grew faster the year after early dry season fire compared to the same trees when unburnt, but more slowly after late dry season fires compared to the same trees when unburnt. She notes that this was perhaps due to reductions in competing understory and/or "fertilization" from the release of nutrients with fire.

Prior and colleagues (2006, 2009) found that the effects of fire on tree recruitment were better explained by season than severity of fire, while fire severity had a stronger influence on mortality. Interestingly, they also found that height growth of juvenile trees was reduced by early fires but was increased by late fires, probably because juveniles are physiologically active early in the dry season, but are effectively dormant in the late dry season.

Contrastingly, Murphy et al. (2010) argued that fire severity was a more important factor than fire season in their work on the mesic savannas of northern Australia. They found that frequent fires substantially reduced tree growth rates, with the magnitude of the effect markedly increasing with fire severity. Murphy et al. (2010) suggest that fire severity and seasonality were confounded in the studies by Prior and colleagues, preventing those authors from gauging the relative importance of the factors. Specifically, some severe fires occur in the early dry season and some mild fires occur in the late dry season. They note, however, that direct effects of fire seasonality on tree growth cannot be ruled out because the effects of fire seasonality on savanna tree demography, independent of fire severity, are not well known.

The contrasting findings on the effect of fire seasonality on tree survival and growth suggest that grass types influence intensity and severity. Indeed, a number of studies found that grass type is a critical variable, because intensity is higher in annual than perennial grass fires. Werner and Franklin (2010) conducted studies comparing the impacts of fire treatments on plots dominated by a native annual grass (sorghum, which dries early) with those with perennial native grasses and forbs (which remain green longer). They determined that top-kill rates were higher for fires in annual grasses, although most trees did re-sprout. Although late fires were generally more damaging to trees and especially saplings (because fires were more severe and saplings retain leaves, making them more vulnerable), they were surprised to find that early fires in annual grasses killed over 20% of the juvenile trees. They conclude that the phenology of grasses and juvenile trees are important because annual grasses dry (and burn) early during a time when juveniles may be most vulnerable because they have yet to store sufficient carbohydrates to re-sprout. Werner (2012) found that growth rates of trees at different life stages differed significantly according to different fire and understory conditions. In general, the greatest proportion of young trees to make the transition to a larger size-class occurred after early dry-season fire and/or fire in annual grass understories.

Werner and Prior (2013) suggest the reason that smallest juveniles grow best in unburnt sorghum plots is that not only have they avoided having to replace tissues lost to a fire, but there is little competitive pressure from the senescent sorghum during the early dry season. In contrast, they argue, almost all of the herbaceous perennial understory species remain green well into the dry season, requiring resources that might otherwise be available to sub-adult trees.

Russell-Smith and Edwards (2006) found that the great majority of early dry season fires were of very low fire-line intensities (<1000 kW/m), whereas fires later in the dry season were typically of substantially greater intensity. Importantly, they found similar trends for all vegetation types in their study area. They also found that fires obtained higher temperatures as winds became stronger, humidity dropped and vegetation moisture dropped. They conclude that fire timing matters and this is in part related to changes in ambient weather conditions. As others have shown, fire intensity invariably increases as the dry season progresses, due to more extreme fire weather (Cheney et al., 1993; Gill et al., 1996).

Finally, Russell-Smith et al. (2014) examined fire severity in terms of combustion completeness for different fuel (grass) types and different fire seasons. They found that, in contrast with previous savanna burning assessments, fire treatments undertaken under early dry season burning conditions for fine tussock grasses resulted in negligible patchiness and very substantial consumption of the fine fuels. Unlike in their previous studies in wooded savannas (Russell-Smith et al., 2013), they found that there was little reduction in fire severity and emissions when shifting the fires from late to early for tussock grasses. They conclude that timing is not the only critical variable with respect to carbon and other emissions, but that grass type (often a function of soil conditions) is key and these two interact in complex ways and have implications for tree establishment and growth at different tree life stages.

In summary, recent research finds that fire seasonality, while important, is but one key factor determining the impact of fire on savanna tree establishment, growth rates, top-kill or death. Studies that examined the effects of understory grass type found grass species to be critical. In addition to the understory, recent fire research shows that within fire season and understory type, factors such as ambient air conditions and fire direction are important, with the latter perhaps being the single most influential factor because it determines fire line intensity and flame height, which strongly affect fire severity and tree survival and growth.

This brief review of contemporary fire research finds that fire timing remains a key variable in experimental design and that fire timing is often defined in terms of late versus early fire. The findings also point to the importance of additional variables, however, especially wind direction and speed and grass type, which can override the impacts of seasonality in some cases while in other cases the effects of seasonality and climate are conflated. The implications of these findings are important for fire management as well as for interpreting the impacts of West African fire regimes, which are strongly a function of human burning practices, as we illustrate below.

IV. Contemporary burning practices and fire regimes in West Africa

Here we summarize recently published data on savanna burning in West Africa from a variety of different data sources, including interviews, survey, transect walks, observations and fine and coarse resolution remotely sensed fire data. These findings are then used to assess and reinterpret the results of fire experiments in the context of actual burning practices and fire regimes in West Africa. We note that findings presented demonstrate that most fires in this region occur in the mid-dry season, the implications of which are also explored. Finally, we present recent findings on fire intensity and severity from field experiments in Ivory Coast.

The study areas for our research are shown in Figure 3. We divided our study into three regions: (i) a northern belt where precipitation is generally below 750 mm; (ii) a central belt where precipitation is from 750 to 1000 mm; and (iii) a southern belt where precipitation is between 1000 and 1250 mm. These belts roughly correspond to different savanna types for the region, the Northern Sudanian, Southern Sudanian and Guinean savanna. Here we specifically focus on the latter two belts, as they represent areas covered by various burning experiments (including our own). In addition, it has been shown that African savannas where precipitation is greater than 750 mm are fire determined as opposed to climatically determined (e.g. precipitation is sufficient to support closed canopy forest; Sankaran et al., 2005).

The climate in the zone can generally be divided into three seasons: a hot and dry period

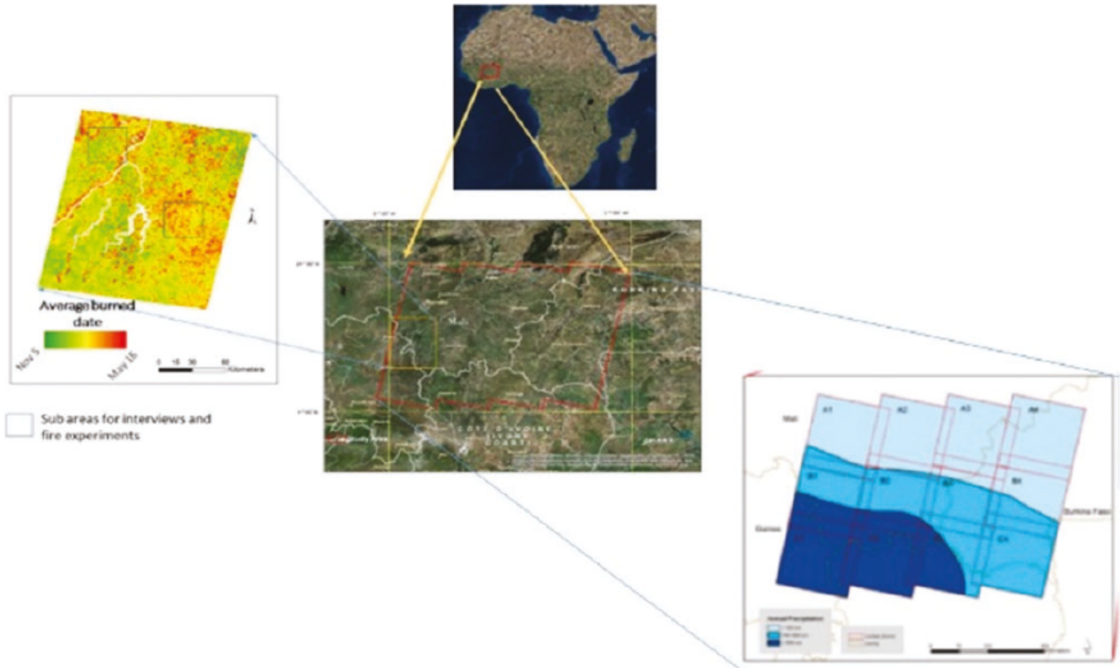

Figure 3. Study areas in West Africa. Area covered by MODIS imagery on the right. Area of Landsat and survey sites on left.

from February to late May; a warm and rainy season from June to October; and a relatively cool dry season from October to February. The fire season begins shortly after the rains ends and typically runs from November to March, with the bulk of the burning occurring in late December and early January.

Vegetation in the Sudan and Guinean savanna is predominantly composed of a mixture of grasses, trees and shrubs arranged in a complex mosaic. Ferricrete outcrops cover up to 25% of the study area, but their distribution is highly uneven. Vegetation on such unproductive soils supports sparse woody vegetation with short annual grasses (principally *Loudetia tongoensis*, less than 1.0 m tall). Except for the intensively cultivated areas, a near-continuous layer of tall perennial grasses (often 2 m in height or taller of *Andropogon gayanus*, *Hyparrhenia dissolute* and *Cymbopogon giganteus*) covers the more fertile soils, although there are pockets where the tree canopy is closed. The land cover in settled areas has been significantly modified. Perennial grasses are less common and large portions of the occupied landscape are covered by annual grasses (1–1.5 m in height), particularly *Andropogon pseudapricus* and *Pennisetum pedicellatum* with scattered trees (Laris, 2011).

V. Methods

We mapped the spatiotemporal patterns of fires based on MODIS active fire data for an 11-year period for each sub-area and for the belts as a whole. The MODIS active fire product is produced daily with a resolution of 1 km (Giglio et al., 2006). We used the active fire product because we are specifically interested in the spatiotemporal pattern of fires. The active fire data were used to produce graphs of the temporal

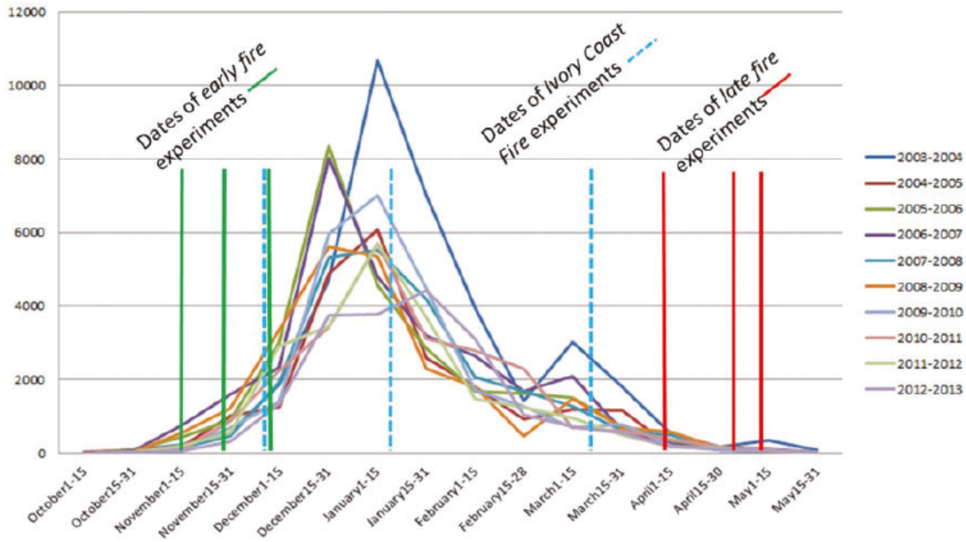

Figure 4. Dates of fire experiments for the study area in Ivory Coast along with annual fire timing and frequency. Historical burning experiment dates are shown for comparison.

frequency of fire over the 11-year period, as well as peaks in the fire cycle. The variation in the mean peak for each area was also determined using a coefficient of variation (CV). The CV is the ratio of the standard deviation to the mean of a distribution and provides a normalized measure of dispersion probability distribution.

We next used the Local Indicator of Spatial Association (LISA; Anselin, 1995) to categorize the regularity of the spatiotemporal patterns of the fires for each sub-area. LISA was used to perform a space–time analysis to investigate the existence of annual seasonal patterns of fires. This allowed a visualization of areas affected by early fires (spatial and temporal proximity of fires burning at the start of the season) and late fires (proximity of those fires burning at the end of the season; Caillault et al., 2015; Laris et al., 2016).

We compared the results of the MODIS-based analysis with previous work for a sub-area for which high quality and fine resolution (Landsat) burned area, vegetation cover maps and survey data were available in order to explain the linkages between the fire regime and vegetation patterns (Laris, 2011).

Finally, to compare intensity and severity data on early-mid and late dry season fires, we report results from fire experiments conducted in Katiali, northern Ivory Coast, in a mesic savanna (precipitation 1150 mm). We conducted 45 experimental burns on 10 m × 10 m plots for three different fire seasons—early dry season burning (24 December to 5 January), middle dry season burning (29 January to February) and late dry season burning (1–5 March) (Figure 4). The effects of fire on five vegetation types—fallow, short grass savanna, shrub savanna, savanna woodland and dry forest—were recorded. We measured fire temperature at the flaming front and estimated burning efficiency, defined as the mass of fuel that is exposed to fire that is pyrolyzed (Russell-Smith et al., 2009). To measure biomass, three quadrats of 1 m × 1 m were delineated in each plot, and all fuels were dried and weighed using an electronic balance. After the fire, ash and any unburned material was weighed for the three adjacent quadrats (Koné, 2013).

VI. Results

1 Active fire data

The temporal regularity of the fire regime based on the analysis of 11 years of MODIS active fire data is shown in Figure 5. The regularity in the peaks of the burn season over multiple years is striking for the southern two belts. The variation in the mean peak for each sub-area was determined using the CV. The lower the CV value, the lower the variation. The CV for the northern belt was 0.39 while it was 0.12 and 0.6, respectively, for more southern belts. Quite clearly, the greatest number of fires occurs each year near the end of December, which is also the end of the legal fire season (Laris et al., 2016).

The regularity of the spatiotemporal pattern was examined through measures of spatial autocorrelation using the LISA statistic. LISA analysis enables the disaggregation of fire points into those that consistently burn late in the dry season, those that consistently burn early and those with no statistically significant relationship in pattern of fire. The LISA analyses indicate a clear spatial pattern—*early* fires (before 31 December) tend to regularly burn specific areas of the landscape, while *late* fires burn others. This pattern is especially strong for the southern two belts (Figure 6).

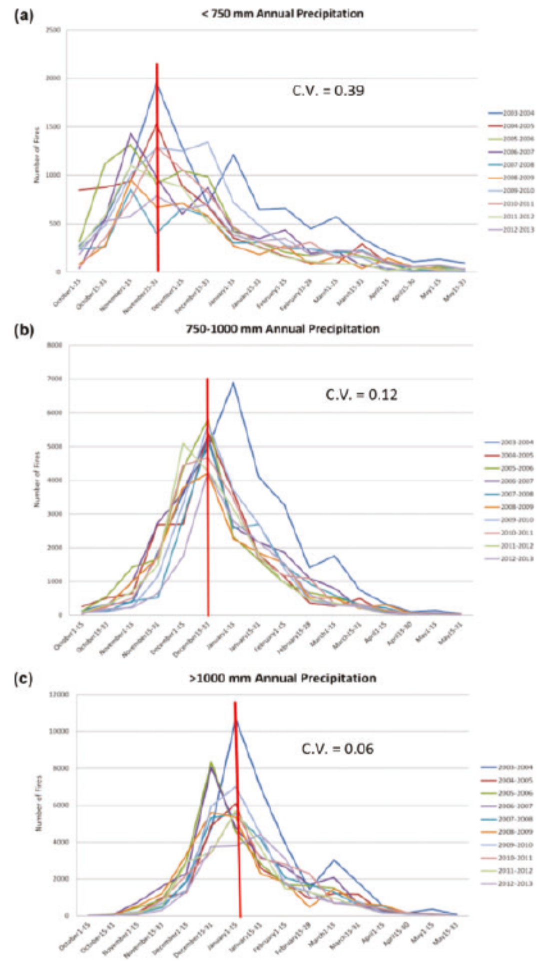

Figure 5. The temporal pattern of fires in the study area for belts representing the Northern Soudan savanna (a), Southern Soudan Savanna (b) and Guinea savanna (c) based on the analysis of 11 years of MODIS active fire data. The regularity in the peaks of the burn season over multiple years is striking especially for the mesic zone (precipitation >750 mm).

2 Landsat and survey data

In addition to the regional analysis presented above, we conducted fine-scale analysis of a sub-set of the study area using a multi-year Landsat data set for burned area and vegetation cover for two sub-areas where annual precipitation is above 900 mm. We combined this with interviews and a survey of over 100 rural inhabitants and numerous transect walks in burned areas (Laris, 2002, 2006, 2011). Results of this work are summarized in Table 2. It is quite clear from these data that burning follows a regular annual pattern and that this pattern is closely linked to vegetation (and especially grass) type.

Recently, a number of case studies have shown that burn timing varies according to topography and vegetation type (Caillault et al., 2015; Devineau et al., 2010; Laris, 2011). These works also demonstrate that

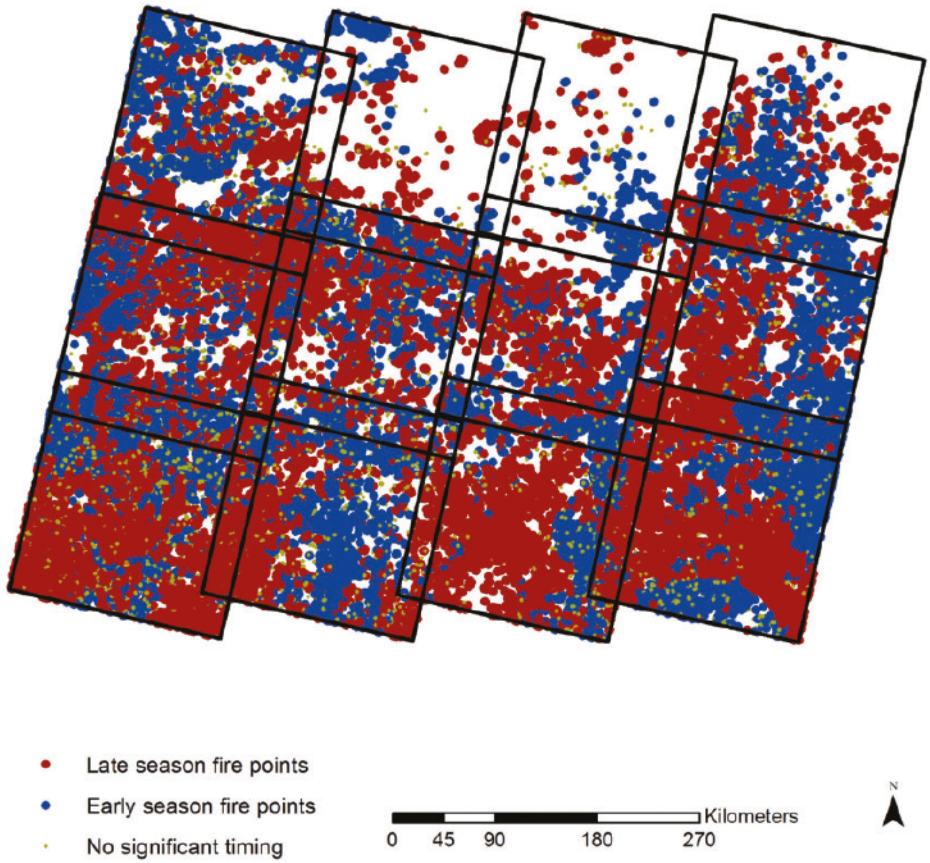

Figure 6. Local Indicator of Spatial Association results for active fires for each sub-area. Points that regularly burn late (LL) are shown in red. Points that regularly burn early (EE) are shown in blue. (Color online only.)

people often systematically set fires to savanna grasses as they reach a point where they are dry enough to carry a fire (Laris, 2002). This research has shown that the burning regime follows the grass types beginning with the shortest annual grasses, followed by taller annuals and lastly by perennials and that fire timing for specific types of vegetation (grasses) is relatively consistent from year to year.

In addition, given that our review suggests that weather plays a critical role in determining fire intensity, we summarize the weather pattern in West Africa as it pertains to fire and human practices. The regional pattern is dominated by the shifting Intertropical Convergence Zone (ITCZ), which moves north bringing rains from late May to September and then shifts south. The desiccating Harmattan wind then blows from the Sahara from November to March. The highest wind speed and lowest humidity (thus the most severe fire season) occurs just after the peak in burning for the region—late January and early February. Wind speed and humidity do not vary greatly during the main months of the fire season (Figure 7). The highest average wind speed of 9 mph (a gentle breeze) occurs around 27 January. The lowest average wind speed of 5 mph occurs around 15 October. Thus, winds vary but not extraordinarily during the dry season (https://

Table 2. Average burn dates by vegetation type and reasons for burning based on satellite image analysis and interview results for a sub-area in Mali.

Vegetation type	Average burn date based on image analysis	Burn timing based on survey	Common reasons for burning
Short grass savanna	8 December	96% of cover type burned by 31 December	To separate areas, clear paths, create fire breaks, prepare pasture and hunting grounds, eliminate pests and danger of late fires
Short fallow/ag	12 December	67% of cover type burned by 31 December	
Long fallow	22 December		
All other savanna	1 January	NA	
Forest/woodland	8 January	36% of cover type burned by 31 December	Hunt, clear grasses and pests to promote gathering, accidents, unknown
All cover types	24 Dec. (69% by 31 December)	71% of cover type burned by 31 December	

weatherspark.com/averages/29176/Bamako-Koulikoro-Mali).

Importantly, the differences in the average values for wind and humidity between early, middle and late fire season are dwarfed by the variation in the values for wind and humidity by time of day. As seen in Figure 8, mid-morning has the highest winds and lowest humidity, for example.

Finally, examination of the time of day of fires using MODIS data finds that 70% of the fires burn at the time when humidity, temperature and wind are dropping—afternoon and evening. Specifically, 353,507 fires were detected and mapped during the afternoon MODIS overpass (1–3 PM) or at night, while only 161,921 were mapped for the morning overpass (10–12 AM). Interviews also indicate that afternoon is the preferred time for setting fires because winds are dropping and humidity rising and, thus, fires are easier to control and tend to burn themselves out at night.

The above findings raise several issues with regard to the existing literature on savanna fires for West Africa. It is clear that the average burn date of fires in the region is the *mid-dry* season, which is prior to the point in the fire season used in the majority of burning experiments. The fire season is several months long and presumably the intensity of fires varies widely as vegetation dries and weather conditions change. The findings thus raise important questions concerning the notion of *what is late* and *what is early* in terms of the fire regime. If most fires burn the savanna at or near the point at which grasses are "just dry enough to burn" (regardless of burn date), then determining fire intensity and severity becomes a more complex endeavor than simply classifying fire timing as early or late, because vegetation moisture content varies by both grass and soil type *as well as* seasonality. In addition, the physical structure of the grasses burning during the early months can be different from those in the mid or late fire season due to animal trampling (see below). Finally, as the

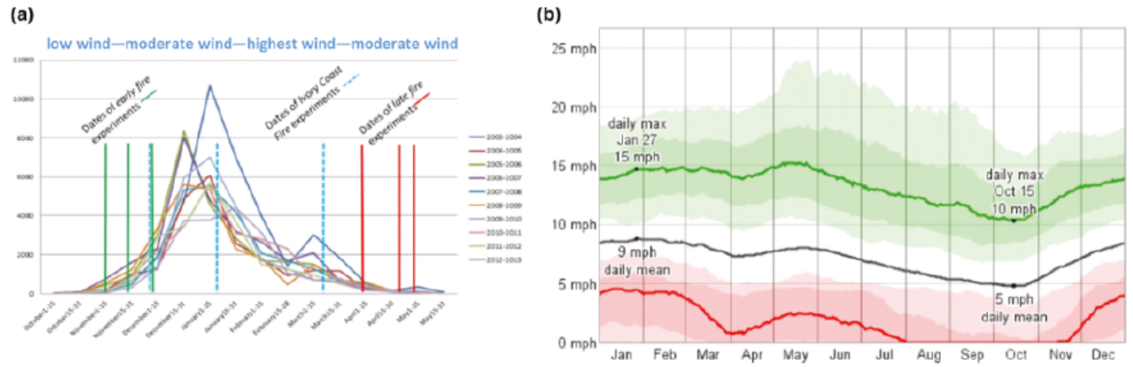

Figure 7. Fire peaks and wind speed for the zone with rainfall >1000 mm (a) and seasonal variation in wind speed for Bamako located in the northern part of the study (b).

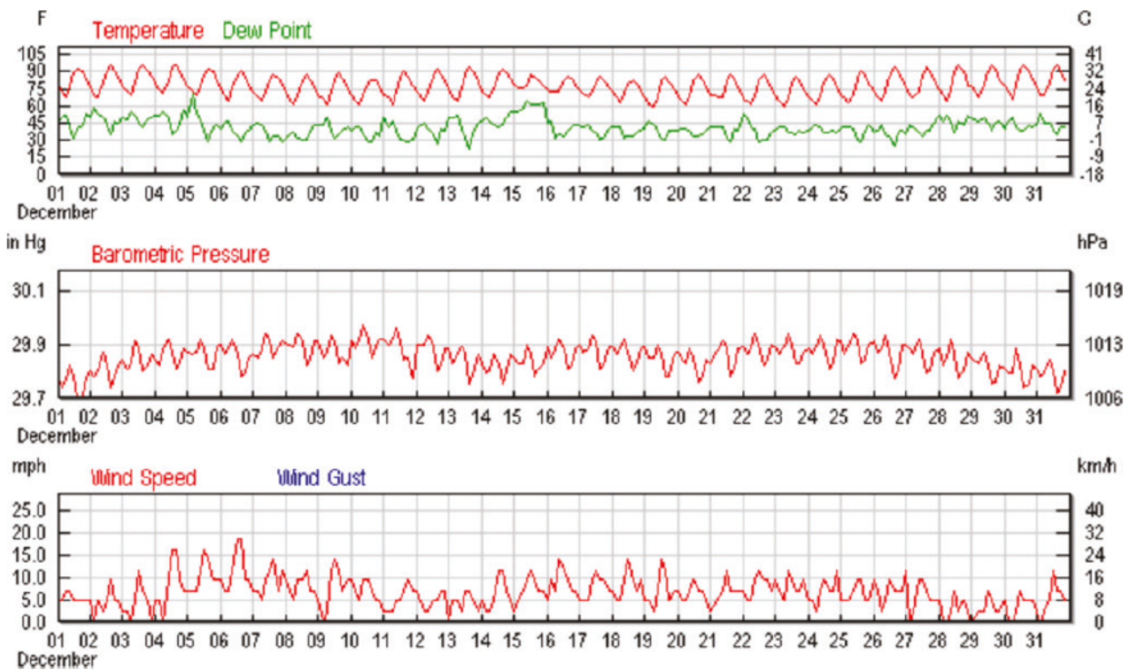

Figure 8. Typical daily fluctuation in temperature, pressure and wind speed shown here for the month of December 2014 (http://www.wunderground.com/ml/bamako).

above review shows, we have little data on the effects of mid-dry season fires because most studies used very early or very late burn dates. Next we present recent findings from fire experiments conducted in early, mid and late season.

3 Fire experiments in Ivory Coast

Results show that mean and maximum fire temperatures were highest in the mid-dry season and that late season had the lowest mean temperature (Table 3). Two factors explain the higher fire

Table 3. Fire temperature (°F) measured in experimental plots for early, middle and late dry season, Katiali, Ivory Coast.

Burning periods	Minimum (°F)	Maximum (°F)	Mean (°F)
Early dry season	76	602	302
Middle dry season	85	1009	329
Late dry season	83	624	291
Entire dry season	76	1009	309

temperatures in mid-dry season; firstly, most biomass is very dry; and secondly, the Harmattan wind is strongest, producing the highest wind speeds and lowest humidity. Fire temperatures top 1000°F in the grass savanna vegetation type.

By the end of the dry season (March–April), fire intensity was generally decreasing due to several factors: firstly, the Harmattan has slowed; secondly, humidity has risen; and thirdly, grasses have been trampled and eaten by livestock. The mean fire temperature in the late dry season averaged 291 F, which was lower than that of the early dry season.

Results also indicate that fire temperatures vary by season *as well as* vegetation type (Table 4). Here there is much less of a discernible pattern, largely due to the different desiccation rates of the grasses associated with the savanna types. Fire was intense in fallow fields (mostly annuals) during all seasons. In short grass savanna (annual grasses), the mean values of fire temperature were highest for all seasons. During the middle dry season, fire intensity reaches its maximum value in grass savanna burned at noon. In savanna woodland, maximum temperatures measured during early, middle and late dry season fires were lower.

Burning efficiency varied little by season (Table 5). According to our observations, fires that take place in the early morning and evening are less intense and less efficient; those ignited during the mid-day are most severe and efficient.

On a seasonal basis, combustion efficiency peaked in the mid-fire season, while the early season had the lowest mean efficiency. Table 6 shows mean values of combustion efficiency by vegetation type and season. Here we see the impact of vegetation (primarily grass type). Only (short) grass savanna burns with high efficiency in all seasons. For all other types, the mid fire season has the highest efficiency (except recent fallow, for which mid and late values are nearly the same).

VII. Discussion

This paper has argued that, although the African burning experiments provide a rare and valuable long-term perspective on the effects of repeated fires on savanna vegetation, the conventions used in, and the results produced by, the experiments need to be reinterpreted in light of the following: (i) a critical review of the origins of the experiments; (ii) data on both historical and current practices of those who set fires and the regimes they produce in West Africa; and (iii) new data on fire regimes and their impacts from a variety of savannas. Here we discuss the implications for both the specific West African case as well as savanna research more globally.

1 Implications for the West African context

What can we conclude about the results of burning experiments in the light of data on actual burning practices of West Africans? Firstly, for the West African context, a review of the history of fire experiments makes it clear that Aubréville's study design was very influential and that his experiments were designed to compare results from not simply early and late fires, but rather from *very* early and *very* late dry season

Table 4. Mean values of fire temperature (°F) for different vegetation types and burning seasons, Katiali, Ivory Coast.

Vegetation type	Early dry season	Middle dry season	Late dry season
Fallow field	284	284	304
Grass savanna	350	460	326
Shrub savanna	340	256	331
Savanna woodland	240	333	260
Dry forest	225	288	295

Table 5. Burning efficiency by dry season period, Katiali, Ivory Coast.

Burning periods	**Minimum (%)**	**Maximum (%)**	**Mean (%)**
Early dry season	20	99	67
Middle dry season	10	99	72
Late dry season	40	99	71
Entire dry season	10	99	71

Table 6. Mean values of burning efficiency by vegetation type and by burning period, Katiali, Ivory Coast.

Vegetation type	Early dry season	Middle dry season	Late dry season
Fallow field	31	56	57
Grass savanna	99	99	99
Shrub savanna	71	88	64
Savanna woodland	57	77	67
Dry forest	55	83	80

fires. Secondly, data presented here and that of others (Caillault et al., 2015; Devineau et al., 2010; Laris, 2011) finds that Aubréville's choice for fire dates do not match the practices of most West Africans; annual fires in this region burn mostly in the middle-dry season with the peak varying by geography but generally occurring in late December/early January. Indeed, few fires occur during the dates chosen for the experiments (Figure 2). Thirdly, data presented here and that of others (Caillault et al., 2015; Devineau et al., 2010; Laris, 2011) demonstrate that burning is not random but has a distinct annual pattern where some areas burn early, others in mid-season, others later and some not at all. Specifically, results clearly demonstrate that the fire regime in the mesic savanna of West Africa is highly regular and has a consistent spatiotemporal pattern from year to year. While there is some variation, of course, the annual pattern tends to follow the desiccation of different grasses. That is, fires tend to be set to coincide with the moment that grasses are dry enough to burn, but not entirely dry, a phenomenon that is consistent across the region. Indeed, Le Page and colleagues (2010) find that the peak in the burning season is consistently prior to the peak in the natural, eco-climatic fire seasonality for West Africa. They used the Chandler burning index (CBI), an index of fire susceptibility based on temperature and relative humidity, to determine whether fires occurred prior to or after the peak fire susceptibility was reached. In the case of West

Africa, the peak in the number of fires set precedes the CBI peak by approximately two months, a finding that is corroborated by our field results.

The field data from West Africa indicates that so-called *early* fires and *late* fires are set to *different types of grasses* (annuals set early and perennials set later, for example) a finding that has important implications for the relationship between fire seasonality and two key variables—intensity and severity. Indeed, as the data from Ivory Coast indicates, early fires in fine annual grasses (grass savanna) burn at high temperatures and with high severity, while late fires burn at lower temperatures and at lower severity when burning perennial grasses (savanna woodland). Importantly, historical accounts suggest that the traditional practices of burning have varied little since Aubréville's time (Laris, 2004) and there is little reason to suggest that fire regimes have shifted dramatically, except in cases where land cover has been heavily altered.

In conclusion, based on the findings presented above, the corollary—*late fires are more intense than early fires and more damaging to trees*—can only be partially confirmed by empirical research in Africa. In general, if all other factors are held equal it holds true, but much contemporary fire research finds that grass type, soil conditions, time of day (ambient air conditions) and, especially, fire direction are all important determinants of fire intensity and severity. As Jon Keeley (2009) has argued, relationships between ecosystem responses (such as tree death and re-sprouting rates) and fire severity and intensity need to be established empirically. As such, an interesting question concerns whether tree responses to fire in savannas are more closely linked to fire intensity and severity (largely functions of biomass burned and ambient air conditions) or to tree conditions at the time of the fire, as West (1965) noted long ago.

It is also important to point out that using flame height as a proxy for fire intensity, while useful in some savanna contexts, may not be appropriate for the West African savannas because grass heights vary enormously (from less than 1 m to over 3 m in our study areas); thus, scorch height is a function of grass species as well as fire intensity. Finally, we note that there is little in the literature about the role of leaf litter in determining fire intensity and severity. Research from Australia indicates that leaf litter results in an increase in fuel load later in the dry season (Williams et al., 2003). We suggest that leaf litter plays an important role in determining fire intensity at near ground level, the importance of which has been less studied.

In terms of the key principle that *fire regime determines vegetation cover in a savanna*, we find again that this is only partially upheld in the context of actual burning practices in the study area. Critically, because fire timing is correlated with vegetation (grass) type, the influence of the fire regime on vegetation is difficult to isolate. Indeed, one can argue the opposite is true for West Africa— *vegetation cover determines fire timing.*

Finally, our review and field study suggest that the greatest unknowns remain the critical factors of time of day and fire type (wind direction) and how these factors (in addition to fire timing) affect tree re-sprouting and survival. While evidence strongly suggests that the majority of fires in our study area are set in the afternoon when winds are falling and humidity rising, we have very little information on the wind direction of actual fires. Fire type and wind speed (a function of time of day and season) appear to have a great impact on fire intensity, severity and tree re-sprouting and most likely affect fire emissions as well.

2 Implications for the global context

There is little doubt that Aubréville's work was highly influential in the African context. Moreover, his research took place during a time of a blossoming of the exchange of ideas on tropical forestry and fire, which was global in scope (Fairhead and Leach, 1996, 1998; Krebs et al., 2010; Pyne, 1990). While the degree to which Aubréville's work had a direct impact on the design of fire experiments on other continents (in Australia, for example, the development of early burning terminology was likely associated with Aboriginal burning practices) is uncertain, his research and that of his followers served to solidify the convention of dividing the savanna fire season into early and late periods.[2] This convention has become the norm, if not hegemonic, in savanna literature (e.g. Cook, 2003; Furley et al., 2008; Governdor et al., 2006; Laris, 2011; Mistry and Berardi, 2005; Russell-Smith et al., 2014; Ryan and Williams, 2011; Werner and Prior, 2013; Williams et al., 1998). Indeed, nearly every paper cited in the review above uses the early/late convention. Moreover, the results of fire research are often represented graphically or in imagery as either early *or* late (e.g. Russell-Smith et al., 2013; http://www.savanna.org.au/all/fire_types.html; but see Laris, 2005, and Caillault et al., 2015, for alternative cartographic displays).

The rather arbitrary nature of the choice of dates dividing early from late remains a critical issue in savanna science. As was the case with Aubréville's original work, there is no clear cut logic or convention for establishing what is early or what is late (or what is "mid", for that matter) in many savannas. In adopting the early/late terminology in their work, Russell-Smith and colleagues (2003a) wrote that the convention is somewhat arbitrary, although convenient:

> Throughout the paper the seasonality of fires in any one dry season is conveniently, if arbitrarily, defined as occurring in the early dry season (EDS), or late dry season (LDS), if fires occur before the end of July, or from August onwards, respectively . . . Given intra- and inter-annual spatio-temporal variability in rainfall patterning mentioned above . . . it follows that the distinction between EDS and LDS fires likewise varies considerably across the region. (2003: 284)

Moreover, the common practice of choosing a single date to determine a cut-off for early fires is problematic in several ways. As Russell-Smith and colleagues note, rainfall variation will influence the point at which vegetation becomes dry and most savannas have highly variable precipitation regimes. Although use of a single date conveniently displays the results of fire research graphically, the use of this convention can greatly oversimplify savanna fire regimes. More importantly the two-tone color images tend to reinforce a dominant view that the impacts of fire on vegetation can be determined along the simple line of early or late fire.

In the Australian context, where the bulk of contemporary fire experiments have been conducted, scientists typically select early and late experimental fire dates separated by several months. May/June is a common choice for early burning and September/October for late (e.g. Andersen et al., 2003). Although these dates may represent the pattern of burning in some areas, as was the case with Aubréville's design, the convention raises questions concerning the impacts of mid-season fires. As researchers have documented, the Aborigines historically set fires throughout the dry season with an emphasis on beginning early and with peak burning often occurring by mid-fire season (Bowman et al., 2004; Preece, 2002; Russell-Smith et al., 1997, 2003a, 2003b; Vigilante et al., 2009). As is the case in much of West Africa today, fires were often set progressively to grasses as they gradually desiccated due to natural variation in soil type and topography, which influence grass type (Russell-Smith et al., 1997; Taylor and Tulloch, 1985; Vigilante et al., 2009). Given that research shows there are rather large differences in the growth and survival rates of trees subjected to early or late fires set several months apart, one wonders whether the impacts of mid-season fires more closely reflect those of early or late season or fall somewhere in between.

It is evident from the review presented here that establishing dates toward the onset of the dry season (before many grasses have thoroughly cured) and near the end of the dry season (when even perennials grasses are desiccated) has produced useful results on the impacts of fire timing. However, there is also a clear need for a more universal convention for determining what distinguishes early from late. The work of Le Page and colleagues (2010) suggests a way forward in that the CBI could be used to set a universal cut-off date for early and late fire. Fires occurring before vegetation peak fire susceptibility (say 90%, for example) could be defined as early and those after, late. A more appropriate solution would be to determine the early cut-off empirically based on documented impacts on vegetation and to then relate this to a CBI index, which could also be used to distinguish between mid- and late-season fires.

Developing a universal convention for distinguishing early from late will help make data comparable between regions, although the problem of variation within regions will remain. The heterogeneity of savanna formations, due largely to variations in soil, land use and grass types, assures that some areas burning at an *early* date will burn intensely while other burning at a *late* date will burn less intensely, as our date from Ivory Coast indicates. Moreover, as West (1965) long ago noted and others have reiterated (e.g. Williams et al., 2003), the conditions of trees and the leaf litter produced by them are also shifting over the course of a dry season. A fuel bed of fallen leaves not only increases fuel load, but it can also change combustion efficiency. Finally, given that wind speed and direction are critical determinants of fire intensity and severity, it may not make sense to speak of early and late outside of a broader context of multiple variables.

One outcome of the enduring influences of the African burning experiments is that much emphasis focuses on altering fire timing by seeking to establish policies that encourage early burning under the assumption that earlier fires will be less damaging to trees (e.g. Laris and Wardell, 2006). More recently, this convention has been incorporated into climate-change policies. An essential premise underlying current GHG emission models is that changes in fire timing will result in changes in intensity and severity and, thus, result in different GHG emissions (Russell-Smith et al., 2014). A shift to earlier fires would be expected to reduce GHG emissions (Williams et al., 2004). However, as Russell-Smith and colleagues' empirical work demonstrates, under some conditions a shift in fire timing from late to early has little impact on reducing fire severity and emissions. As they concluded, timing is not the only critical variable; grass type is also key and that these two factors interact in complex ways. In addition, while earlier fires generally burn less intensely, this can result in lower combustion efficiency and a relative increase in important gases, such as methane, for example. We note that while data on the linkages between fire timing and emissions is still sparse, preliminary results from our own field work (which involved pairwise examination of emissions from head and back fires) indicates there is reason to believe that wind and grass type are critical to determining combustion efficiency and emissions.

This is not to argue that early burning practices do not have clear impacts on fire regimes or that there are few benefits to early burning. On the contrary, as research has shown, a key effect of early burning is the fragmentation of the landscape, which prevents sweeping late season fires and allows for patch- and seasonal-mosaic burning that can create heterogeneity. These burning regimes are known to be ecologically and socially beneficial (Laris, 2011; Parr and Brockett, 1999; Russell-Smith et al., 1997) and they have been shown to reduce emissions by reducing the total area burnt (Russell-Smith et al., 2013). It is important to note as well that mosaic burning regimes are not simply the result of early and late fires, but rather the outcome of fires set to different grasses at various points during a long dry season (Laris, 2002; Russell-Smith et al., 1997).

Finally, it is also important to remember that "savanna" is a rather broad and loosely defined term. A savanna may be more or less wooded depending upon a variety of variables, including precipitation soil moisture and texture as well as fire regime and human land uses. Moreover, what we refer to as "savanna" is scale dependent. At the landscape level, a "savanna" includes patches of dense woodland and floodplains, as well arid outcrops. As noted above, people have long used this heterogeneity as a means to manage fire by burning mosaics. Most early fire experiments focused on a micro-scale. Only recently has it been possible to compare results from experimental burning rather different forms of savanna vegetation. There is still much to be done in this regard.

VIII. Conclusion

Aubréville's work was pioneering. He established an experimental design for studying the impacts of savanna fires that continues to be replicated to this day. That his original experiments continued to be carried out long after his death is tribute to his influence on the field. While he is remembered for his many scientific achievements, it is important to recognize that the design of his fire experiments was politically motivated and shaped by his belief that the savanna was naturally a dry forest that had been degraded by humans' careless use of fire. The latter theory has been strongly rebuked (e.g. Fairhead and Leach, 1996), but the negative views of African land managers continues to hold sway in policy in spite of a growing body of evidence that human fire use is complex and strategic and has many positive as well as some negative aspects, depending upon how it is used (e.g. Laris and Wardell, 2006). In Australia, by contrast, the impetus for establishing fire experiments was in part to document the benefits of Aboriginal burning and to highlight the importance of setting fires early to avoid the negative consequences of late fires (Russell-Smith et al., 2009). Although they had starkly different origins, both cases resulted in a similar convention of dividing fires into early and late.

As Sayre (2015) has argued, it is important for critical physical geographers to examine the origins and use of key concepts, especially in cases where repeated use over time has cemented concepts into the literature and occluded the assumptions that underlay them at the outset. At its best, the early/late fire dichotomy has been useful in helping to determine the impacts of fire on savannas. At its worst, the dichotomy has become hegemonic in that it is uncritically accepted as a dominant way of categorizing savanna fires.

As the West African case illustrates, Aubréville's early/late experimental design was useful for documenting differences in the impacts of fires occurring at different times of year. At the same time, however, the convention of early/late resulted in a lack of research on effects of the majority of fires in West Africa, which are set neither early nor late. His design also placed the emphasis on timing at the expense of other key factors, such as fuel type, wind speed and fire direction, which are known to determine fire impacts in many environments (e.g. Keeley, 2009), as well as the impacts of grazing animals (which can alter fuel load throughout the dry season).[3]

In conclusion, it is time to revisit the concept of fire timing in savanna ecology. Is an early/late dichotomy sufficient? Or, is it best to have three periods—early, mid and late—as we recommend for West Africa? Can the cut-off dates be determined in a less arbitrary manner, perhaps using an index such as the CBI? Finally, how do the other critical determinants—grass cover, wind speed and direction—interact with fires set at different frequencies and over the course of a long savanna dry season to determine fire intensity, severity and, most critically, tree survival and growth?

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Notes

1. See Furley et al. (2008) for a review of the literature on South American savanna fires.
2. See Krebs et al. (2010) for an interesting discussion of how the terminology for the fire regime developed in the French colonies and was then transferred to areas under British influence before eventually going global.
3. Note that for many experiments, fires are set under peak daily wind speed, highest temperatures and lowest humidity conditions (e.g. Russell-Smith and Edwards, 2006).

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