Methane gas emissions from savanna fires: What analysis of local burning regimes in a working West African landscape tell us

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Abstract

Savanna fires contribute significantly to greenhouse gas emissions. While it is recognized that these fires play a critical role in the global methane cycle, there are too few accurate estimates of emissions from West Africa, the continent’s most active fire region. Most estimates of methane emissions contain high levels of uncertainty as they are based on generalizations of diverse landscapes that are burned by complex fire regimes. To improve estimates we used an approach grounded in the burning practices of people who set fires to working landscapes. We collected and analyzed smoke samples for 36 experimental fires using a canister method for the early dry season (EDS) and mid-dry seasons (MDS). We also collected data for savanna type, grass type, biomass composition and amount consumed; scorch height, speed of fire front, fire type and ambient air conditions for two sites in Mali. We report values for fire intensity, combustion completeness, patchiness, modified combustion efficiency (MCE), emission factor (EF) and methane emission density.

Our study found that mean methane EFs ranged from 3.83 g/kg in the EDS to 3.18 in the MDS but the small sample did not provide enough power for this effect to be significant. We found head fires had nearly double the CH_4EF of backfires (5.12 g/kg to 2.74), a significant difference. Byram's Fire intensity was a significant driver of CH_4EF but with weak effect. Methane emission density increased marginally from 0.839 g/m^2 in the EDS to 0.875 g/m^2 in the MDS a difference that was not significant. Head fires, however, had much higher emission densities than backfires—1.203 vs. 0.708 g/m^2—respectively, a significant difference. We suggest the reason for the higher methane emissions from head-fires, which have higher intensity, is the longer flame lengths that burn green leaves on trees releasing methane. We conclude that policies aimed at shifting the burning regime earlier to reduce methane emissions will not have the desired effects, especially if fire type is not considered. Future research should consider the state and amount of leafy biomass combusted in savanna fires.

Key Words: Savanna fires, methane, emission factors, combustion efficiency, Africa

1 Introduction

The African savannas are the Earth's most extensively and frequently burned regions (Giglio et al., 2010) and account for some 64% of the global extent of area burnt annually (Grégoire et al., 2013). Indeed, African savanna fires regularly burn such large areas that they are visible from space, so much so that NASA scientists refer to Africa as the "burn center of the planet" (National Aeronautics and Space Administration, 2005). Savanna fires are a major source of greenhouse gases (GHGs) including carbon dioxide, carbon monoxide, methane, and nitrous oxide (Koppmann et al., 2005, Russell-Smith et al., 2021).

Methane, a critical GHG, is responsible for about 20% of the warming induced by long-lived gases. Although most sources and sinks of methane are known, their relative contributions to atmospheric methane levels remain highly uncertain (Kirschke et al., 2013, Saunois et al., 2016, 2020). Our lack of understanding of the global methane cycle contributed to the recent "methane enigma" a dramatic observed decline in the rate of increase in atmospheric methane, which triggered a search for "missing methane" (Heimann, 2011). Although the decrease was originally and mistakenly attributed to a decline in fossil fuel burning and a shift in farming practices (Kirschke et al., 2013), it was eventually determined that the missing methane was due to a decline in area burned by savanna fires. As NASA researchers determined, the missing methane from a drop in savanna burned area caused a decrease of 3.7 Tg CH_4 per year—a value nearly twice the decrease expected (Worden et al., 2018).

The "missing methane" event demonstrates two important aspects of emissions from savanna fires. First, these emissions are significant, so much so that they can offset increases from the key sources (fossil fuels and agriculture). Second, our knowledge of the processes and factors that regulate the amount of methane emissions from savannas is limited to the point that a large decrease went virtually undetected. Although eventually scientists discovered the source, there remains high level of uncertainty for many key variables that determine the amounts of methane emitted from savanna fires (Worden et al., 2018). In addition, there remains concern about the gap between "top-down" (atmospheric measurements) and "bottom-up" (land-based models) estimates of global methane emissions, which differ by thirty percent; Saunois et al (2020) suggest the reason is an overestimation of emissions from bottom-up models. There is thus a need to improve land-based estimates of emissions from savanna fires.

In general, the crucial parameters for determining GHG emissions from fires include burned area (BA), fuel consumption (FC), and the species specific emission factor (EF), usually defined as the amount of gas or particle mass emitted per kg of dry fuel burned, expressed in units of g/kg dry matter (van Leeuwen and van der Werf, 2011). The precise emissions from savanna fires depend on a variety of factors including those associated with fuel, specifically vegetation type (the mix of grassy, leafy and woody fuels) and fuel moisture (a function of climate and soil and fire season) as well as factors directly related to a fire's properties most of which change during a long fire season.

By one estimate savanna fires contribute 62% (4.92 $PgCO_2$ per year) of gross global mean fire emissions (Lipsett-Moore et al., 2018). Due to their high rates of burning and vast extents, savannas are thought to hold potential as major carbon sinks, if the fire regime could be modified to reduce emissions. The most commonly proposed change in the regime to reduce the impacts of fires is to shift burning to an earlier period in the dry season because early fires generally burn less completely and more patchily. Indeed, Lipsett-Moore (et al., 2018) recently argued that there are “global opportunities for significant emissions reductions by simply shifting the fire period in African savannas to early dry season” (1).

Yet, although scientists and policy makers increasingly recognize the important role these fires play in the global carbon cycle, there are few accurate estimates of their emissions especially in terms of the key factors that determine the type and quantity of GHG emissions. Critically, most studies of emission are global scale and use average biome level EFs. EFs show large variability, however, between and within biomes due to differences in fuel type and composition, burning conditions, and tree density (Andreae and Merlet, 2001; Korontzi, 2005; van Leeuwen and van der Werf, 2011; Russell-Smith et al., 2021). There are few regionally specific emissions estimates because accurate quantification of such emissions is difficult, being dependent upon reliable estimation of the various parameters, many of which require intense fieldwork (Russell-Smith et al., 2009).

Nowhere is this truer than for West Africa, the continent’s most active fire region. To date, measurements of emissions from African savannas are limited to a few broad-scale studies, largely based in the continent’s southeast that rarely adequately account for changes in fuel classes, seasonality, or a host of other key factors including fire type and intensity (Bonsang et al., 1995; Lacaux et al., 1995; Hoffa et al., 1999; Korontzi 2005). Indeed, the most recent catalogs of EFs and fuel consumption (FC) for savannas includes a *single* data point from West Africa (van Leeuwen et al., 2014; Andreae 2019). Studies from other regions find there is great variation in study results (Russel-Smith 2009; van Leeuwen and van der Werf 2011); and, as Murphy et al., (2012) note, the variability *between* samples collected *within* fires can be greater than the differences between fires of different season. These authors were unable to draw general conclusions about seasonal variation in methane emissions and EFs. Among the key issues cited were the variations in the fraction of tree-leaf litter in the fuels of different savanna environments.

In fact, there is very little data in the literature on fine fuel mixtures (the primary fuel for savanna fires) used to estimate EFs in Africa, although the amount of woody vegetation clearly affects emissions (Korontzi, 2005; van Leeuwen and van der Werf, 2011). In the Brazilian cerrado, for example, Vernooij et al. (2020) found that the seasonal effect on methane EF was stronger in more woody savanna vegetation with LDS fires having 20% lower EF than EDS ones in shrub dominated areas.

Fuel moisture is also an issue; Russel-Smith et al. (2009) noted there are currently no comprehensive measurements of the seasonality of emissions gas composition, yet fuel moisture is a key determinant. This is a critical problem because although evidence suggests that early dry season (EDS) fires consume less biomass and burn more patchily; they also tend to have a lower combustion efficiency than later fires due to their higher fuel moisture levels. A lower combustion efficiency theoretically causes a higher emission factor for CH_4. Indeed, one study in Africa found that the bulk of CH_4 emissions come from EDS fires (Hoffa et al., 1999) because the decrease in area burned is more than offset by the increase in the CH_4 EF. Elsewhere in southern Africa, Russell-Smith et al (2021) found that emission factors varied significantly by season for some vegetation types, but not others, although notably that the latter study involved only “cured” grasses. We would argue that “early” fires burn *uncured* fuels by definition.

In sum, while savannas undoubtedly harbor great theoretical potential to sequester more carbon, and emit less through a change in fire regime there exists a great deal of uncertainty as to what the *actual* carbon shifts might be, should regimes change. Fire regimes are themselves complex; we define them as the characteristic fire activity prevailing in a region, typically determined by frequency, intensity, seasonality, size distribution, type of fire and fuels consumed (Pausas and Keeley 2021). Changes in one or more of these factures can alter fire emissions. We suggest the key sources of uncertainty in terms of carbon emissions arise largely from the spatiotemporal complexity of savanna vegetation patterns and fire regimes combined with many unknowns or biases associated with a lack of consideration of human fire setting and land management practices in these complex landscapes (Laris 2021).

Savannas are patch mosaic landscapes, in which vegetation and soil types vary dramatically—on the order of tens of meters—across landscapes (Duvall 2011). This variation creates a seasonal-mosaic landscape in which the fuel conditions (fuel moisture, fuel load and mix, and fuel stature) vary over space and time (figure 1). As the fuel conditions change, people commonly set fire to different patches in accordance with grass species drying rates as well as other land management concerns (e.g., crop harvests and grazing patterns). In many parts of West Africa, people control the time (time of day and season), location and type of savanna, and type of fires they set. By controlling these variables, human acts determine the conditions of the fuels as well as the ambient air conditions and the specific fire properties. To take one simple example, a fire in wooded savanna with tall perennial grasses (figure 1d) will have very different fuel moisture levels as the fire season progress (shifting high to low), different percentages of leaf litter and total fine fuel biomass (shifting low to high) (figure 1f), and variable wind conditions (peaking in mid-dry season). Critically, the seasonal timing of a fire not only affects the fuel moisture of grasses, but also the leafy biomass, which burns green on shrubs and small trees in the early fire season, but as fallen leaf litter that creates a bed of compact and less aerated fuels by late dry season. As such, the incomplete combustion of leafy biomass is a function of high fuel moisture in one season, and low oxygen conditions in another, with unknown implications for methane gas emissions.

Figure 1. Different savanna vegetation types used in fire experiments for the study areas of Tabou and Faradiele, Mali. Note grass species, height and density, woody cover and leaf litter amounts vary dramatically over space and time.

Human fire uses determine the pyrogeography of fire—the specific location, timing, type of fire and vegetation burned—creating complex spatiotemporal patterns of fires and emissions. People tend to set fires to fine annual grasses (figure 1a) as soon as they are dry, while waiting to burn perennials (which are too moist to burn in the early dry season) (figure 1d) until later often igniting them in a flurry of fires at the end of the harvest in late December (below). This creates a seasonal-mosaic fire regime where some patches burn early, others later and some not at all. Purposeful fires are most often set as backfires in the late afternoon as temperatures, wind speeds are falling, and humidity rising, which limits fire intensity (Laris et. al. 2020). Lower intensity fires tend to self-extinguish at the edge of moister vegetation patches and in the evening; they have lower flame heights reducing the reach of fires into leafy tree canopies (Laris et. al. 2021). Later in the fire season, fires are less likely to be purposefully set and are more likely to burn as intense, uncontrolled head-fires.

It is clear that any effort to predict future changes in emissions or to implement policy to reduce emissions requires more detailed information on how emissions vary according to the key factors noted above, many of which are a function of human land management practices (see appendix). Specifically, given the spatiotemporal complexity of savanna environments, whether a shift to an earlier fire regime will result in a decrease in methane emissions for a given savanna must be determined empirically and proposed policies to apply generalized findings from one continent to another may not achieve desired emissions reductions.

This study aims to fill a knowledge gap by incorporating data on human burning practices, the characteristics of the fire regimes they produce, the vegetation conditions on the landscapes they burn and the resulting emissions of key GHG gases. Through a novel geographic approach, we designed our experiments to gather data in ways that reflect actual *on-the-ground* burning practices of people living in working landscapes at two mesic savanna sites in Mali, West Africa. By "working landscapes," we mean savanna lands that are occupied and worked by people as opposed to areas managed as reserves (e.g., Charnley et al., 2014); the latter are most often used in fire research. The biomass (fuels) in working landscapes are a function of land use practices including rotational agriculture, annual burning, and animal grazing and can differ significantly from those found on non-working lands (Figures 1d and 1e), which can affect fire intensity, combustion completeness and combustion efficiency with implications for gas emissions. The burning regimes studied, which are determined by such factors as seasonality, time of day, (ambient weather), fire type (with or counter to the wind), grass type and woody vegetation cover, were selected to reflect *local practices* and based on over a decade of field and remotely sensing research.

To determine the factors that influence fire emissions of methane gas from anthropogenic fires we conducted experimental fires using a field-based method to measure key factors. We collected canister samples of smoke emissions for 36 fires during the early and middle seasons, which we report on here. We also collected data for savanna type, grass type, biomass composition and amount consumed; scorch height, speed of fire front, fire type and ambient air conditions for two mesic savanna sites in Mali.

2 Study Area and Methods

We based our research in two working landscapes located in the southern Sudanian savanna of southern Mali (Fig. 2). We chose areas with annual precipitation over 900 mm because they burn frequently and are typical of this broad mesic savanna belt in West Africa. The climate is divided into two seasons: a wet period from approximately June through October and a dry season from November through May. We also recognize cool dry period from approximately November through February and a hot dry period from March through May. This distinction is important because the Harmattan wind, which is dry and desiccates vegetation while creating unique fire weather, dominates in the cool season. The mean annual rainfall is 991 mm for Tabou and 1,177 mm for Faradiélé (based on data from the nearby urban centers of Bamako (latitude: 12.64°, longitude: −8.00°) and Bougouni (latitude: 11.42°, longitude: −7.47°) for each study area respectively) (Henry, 2011). The fire season follows the rains and typically runs from November through April. The regime follows a regular annual spatiotemporal pattern with the majority of fires occurring in late December and early January (Laris et al., 2016).

Figure 2. Study areas in southern Mali (figure by S. Winslow).

The vegetation is southern Sudanian savanna and is predominantly composed of a mixture of grasses, trees, and shrubs in a complex mosaic. The landscape heterogeneity is a function of topography, underlying soil and hydrology, as well agricultural uses, the combinations of which produces unique patterns of land cover (Duvall, 2011; Laris, 2011). Ferricrete outcrops on hard pan cover considerable areas. Soil in these areas generally has high gravel content and is very shallow, creating xeric conditions. Vegetation is dominated by short, annual grasses (principally *Loudetia togoensis* but also *Andropogon pseudapricus*) and usually have few widely scattered trees. They form up to 25 percent of the savanna in southern Mali. Except for the intensively cultivated areas, a near-continuous layer of tall (over 1 m in height) perennial grasses (principally *Andropogon gayanus*, *Hyparrhenia dissolute*, *Cymbopogon giganteus*, and *Schizachyrium pulchellum*) covers the more fertile soils, although there are pockets where the tree canopy is closed and there is little grass cover. The land cover in settled areas has been significantly modified. Perennial grasses are less common (except on long-fallow plots), and large portions of the landscape are covered by annual grasses, particularly *Andropogon pseudapricus* and *Pennisetum pedicellatum* with scattered trees.

2.1 Data Collection

We studied 36 experimental fires. Data on the following variables were collected in the field for each fire: average plot biomass, grass proportion of biomass, grass species, biomass consumed, fuel moisture, wind speed, scorch height, ambient humidity, temperature, fire type, time of day, fire duration, burn patchiness and fire season. Vegetation characteristics including grass type (annual or perennial), grass species, and leaf height were also recorded for each site. Fuel load (plot biomass) was measured in each of the experimental plots by delineating three representative pre-fire quadrats of 1 x 1 m. Grasses were cut at the base using a scythe and weighed with an electronic balance to determine the average. When present, we weighed leaf litter separately. Sixteen of the 36 fires were set in the EDS and 20 in the MDS. As the purpose of the study was to replicate local burning practices, the majority of these fires were set as backfires (25) with head-fires (11) set for the purpose of comparison.

Most grasses burned were fully cured; however, for those that were not, we cut a sample and weighed wet, then dried and reweighed to determine the cure rate, which was taken as the average for the plot. Fuel moisture content for the cured fuels was calculated using the method developed by Viney (1991) based on McArthur (1967) for savanna fuels:

$$m = 5.658 + (0.04651H) + \left[\frac{(0.0003151H^3)}{T}\right] - (0.1854T^{0.77}) , \quad (2)$$

where H is relative humidity and T is ambient temperature at the time of the burn. We calculated dry biomass weight by subtracting the fuel moisture content from the wet biomass weight and the amount of fuel consumed was by subtracting the average ash and unburned fuels remaining in three quadrats per plot from the pre-fire dry biomass weight.

We used a Kestrel 5500 Weather Meter station (KestrelMeters.com, Boothwyn, Pennsylvania, USA) to collect wind speed, ambient humidity, and temperature during the burning of each plot. We recorded values every five seconds and averaged them for each burn. The weather station was placed up wind and near each experimental plot 2 m off the ground in an open area. We recorded wind speed relative to the direction of each fire.

2.2 Plot design

We selected plots to represent an array of savanna vegetation types dominated by different amounts of woody cover and grass species. To aid in the selection of the burn plots, we used a long-term fire database to select sites with known fire seasonality—fires known to burn during the early, mid, or late fire season on an annual basis (Laris, 2011). We divided the sites into plots of 10 x10 meters and applied fire treatments of head and back burns. Fire timing was set according to the historical pattern of burning with early fires set in November through December, middle fires in January, and late fires in late-February and March (Laris et al., 2016). We conducted multiple burns per site to account for plot level heterogeneity. Plots at each site were located in close proximity with attention paid to maintaining consistency in grass type and woody cover. Head and backfire plots were located directly adjacent.

We noted ignition time and each fire was timed until the flaming front reached the end of the 10 meter plot. We set the majority of fires in late afternoon, which is in accordance with local practice, although we set some fires earlier for comparative purposes. Post-fire ash and any unburned material were weighed for areas of similar composition to the 1 m x 1 m pre-fire quadrats to determine the amount of biomass consumed. Scorch height was averaged for each plot by measuring the height of scorch marks on several small trees. Burn patchiness—the percentage of the plot affected by fire—was estimated by two observers.

There are several key limitations of this study. First, the number of gas samples is relatively small due to the high price of shipping gas samples (we collected only 36 emissions samples for a total of 97 experimental burns and no samples were from the LDS). The majority of the samples were for backfires to replicate local practices with head-fire samples taken for comparative purposes. We only sampled each fire once and thus caution against assuming a single sample represents the typical emissions for the entire fire (see Murphy et al., 2012 above), but we do think the mean values for the data we collected provide a useful sample of typical West African fire emissions. In addition, we burned different savanna vegetation types (with different grasses and woody vegetation amounts) at different times of the fire season in accordance with local practices; as such, we do not have systematic results for burning all grass types for all fire seasons (e.g., few perennials grasses burn in the EDS).

2.3 Field data analysis

To quantify intensity we used Byram's (1959) fire-line intensity, which is defined:

(1) $I = Hwr$

where I is Byram's fireline intensity (kW/m), H is the net low heat of combustion (kJ/kg), w is the fuel consumed in the active flaming front (kg/m^2), and r is the linear rate of fire spread (m/sec^1). The net low heat of combustion (H) was selected following Williams et al. (1998) with 20,000 kJ/kg as an appropriate value for savanna fires.[1] The amount of fuel consumed was calculated by subtracting the average ash and unburned material remaining in three quadrats per plot from the pre-fire measurement of dry biomass. Variable r was derived from the time it took for the base of the first flaming front to reach the end of the 10 m plot. We calculated fire-line intensity for all samples possessing all the variables for analysis. Finally, combustion completeness was calculated by dividing the biomass consumed by the pre-fire biomass.

2.4 Gas emissions sampling and analysis

We collected samples of smoke from a sample of 36 of our experimental fires for early and mid-season along with background air samples for each different site prior to burning. (The high cost of shipping canisters prohibited collecting data for the late-season using this method). Samples were collected in stainless steel vacuum canisters by mounting the canister on a pole and holding the canister with open flow-restricting valve about 40 centimeters above the flame. We sampled all fires a single time once the flaming front had developed (approximately two-thirds of the way through the burn plot). Once filled, the canisters were shipped directly back to California for analysis at the laboratory of the Department of Chemistry at the University of California at Irvine. Mass Spectrometer (MS), thermal conductivity and flame ionization after separation by gas chromatography were used to detect, inventory and measure the quantities of the different species of gas contained in the samples (Katzenstein et al., 2003; Kone et al 2020).

We calculated EF as:

(3) $$EF_{\mathrm{x}} = F_{\mathrm{c}} 1000 \frac{MM_{\mathrm{x}}}{MM_{\mathrm{carbon}}} \frac{C_{\mathrm{x}}}{C_T}$$

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[1] We used the value of 20,000 kJ/kg following Williams et al. (1998) (230) who note: "Given the range and lack of consistency between studies in the value of H, and, in the view of the authors, the misleading precision implied by values rounded to the nearest 100 kJ/kg, 20,000 kJ kg is within the range of reported vales, and is easy and convenient to apply."

EF_x is the emissions factor for species *x* (g/kg). F_c is the mass fraction of carb in the fuel for which we use the value of 0.5 (the majority of studies find the carbon fraction to vary between 0.425 and 0.50; the latter is used most often for purposes of comparison (Ward et al., 1996) although Lacaux et al., (1995) found a value of 0.425 for West Africa). *MM* is the molecular mass of species *x* (g), and 1000 g/kg is a conversion factor. MM_{carbon} is the molecular mass of carbon (12 g), and C_x/C_T is the ratio of the number of moles of species *x* in the emissions sample divided by the total number of moles of carbon, calculated as:

(4) $$\frac{C_X}{C_T} = \frac{\mathrm{ER}_{X/\mathrm{CO}_2}}{\sum_{j=1}^{n} (\mathrm{NC}_j \mathrm{ER}_{j/\mathrm{CO}_2})}$$

Where $ER_{x/CO2}$ is the emissions ratio of species x to CO_2, NC_j is the number of carbon atoms in compound j and the sum is over all carbonaceous species (approximated as CO_2, CO and CH_4 for this study).

The general equation used to quantify the gas species emitted from vegetation fires is the basic biomass burning emissions model of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2003: 49; IPCC 2006: A2.13):

(5)

$$\text{Emission (tons)} = \text{Burned Area (ha)} * \text{Fuel (tons/ha)} * \text{Completeness (\%)} * \text{Emission Factor } (\text{g.kg}^{-1}) * 10^{-3}$$

Here, Emission is the gas or aerosol flux in tons (t); Area is the total area burnt in hectares (ha); Fuel load is the amount of burnt biomass in tons per hectares (tons/ha); Combustion completeness is the fraction of fuel affected by fire that was pyrolysed in percent (%); Emission factor of a gas is the amount of this gas generated when one kilogram of fuel is burnt. We have revised the formula to include seasonally specific values for area, fuel load, combustion completeness and emission factor and add the variable burn patchiness (BP) which is the fraction of the surface area affected by the fire.

We suggest the following revision for determining emissions *by fire season* in savannas (E_s):

(6) $$\text{Emission}_s \text{ (tons)} = BA_s\text{(ha)} * FL_s\text{(tons/ha)} * CC_s(\%) * EF_{xs} * BP_s(\%)$$

Here, BA is burned area, FL is fuel load, CC is combustion completeness, EF_x is emission factor of species x. We propose using *seasonal* values for these key factors because these variables vary significantly by season as a function of ambient weather as well as fuel moisture and fuel type (fraction of leaf litter or shrubs) and fuel conditions. We have added BP_s because patchiness varies by season (as well as fuel) and because most estimates of burned area are based on satellite image analysis, which is too coarse to determine the actual surface area burned due to burn patchiness (the actual area burned is thus BP * BA) (Russell-Smith et al 2009). Note that even medium resolution burned area estimates using Landsat contains errors in the percent area burned due to the fragmented patterns fires create across a heterogeneous savanna landscape. We did not determine total BA for this work, but have done so previously using Landsat data covering the study area (Laris 2011). As such, we present our results in terms of emissions per meter-squared according to season of the burn.

Complete combustion of vegetation results in release of carbon in the form of CO_2 while incomplete combustion leads to the emission of CO, CH_4 and a large variety of organic compounds (Koppmann et al. 2005). Because many of the factors that control EFs also regulate combustion efficiency, determining the latter is a useful proxy for predicting how individual emission factors will vary under different fire conditions. Modified combustion efficiency (MCE)—the ratio of CO_2 to CO + CO_2—is frequently used to estimate combustion completeness as values for MCE are related to different phases in the combustion process. In general, when the MCE exceeds 90% a fire is flaming and combustion temperatures are high. When MCE is less than 85% combustion is smoldering. A savanna fire is typically characterized by a flaming front moving across the landscape leaving smoldering material. As such, the smoke emitted from savanna fires is typically a product of both flaming and smoldering on different fragments of fuel.

Bivariate statistical analyses were performed to test the significance of the difference of means (t-tests) in CH_4EF by season (EDS and MDS) and by fire direction (head-fires and backfires) and in MCE by season and fire direction. F-tests established the similarity of variances, all t-tests were done with pooled estimates of variance. These were done in the OpenOffice Calc spreadsheet (Apache Software Foundation 2021) and PAleontological STatistics (Hammer et al. 2001), with effect sizes (Cohen's d) and *post-hoc* power calculated in G*Power (Faul et al. 2009). We used bivariate regression analysis to look for correlations between the two dependent variables—methane EF and density—and independent variables—Byram’s fire intensity, proportion of grass biomass (to woody biomass), total fuel moisture, and Viney fuel moisture (a function of ambient temperature and humidity). These were done in Calc and power was estimated in G*Power.

3 Results

3.1 Plot Characteristics

The mean plot characteristics for biomass and weather conditions demonstrate the importance of the inclusion of the mid-season in this study (Table 1) (see Laris et al., 2021 for late dry season values). Average temperature generally increases over the course of the dry season, but dips by 0.4°C in mid-season, which is an established phenomenon in West African climates. Average humidity decreases as the dry season progresses, but the mid-season humidity is considerably more variable than in the early season. Calculated fuel moisture content based on Viney declines over the course of the dry season, but when combined with the measured mean cure rates for moist grasses, the total fuel moisture means rose from 10.8% in the EDS to 15.1% in the MDS with high variability. Mean wind speed peaks mid-season during the Harmattan, although the wind speeds are relatively low—classified as a light breeze on the Beaufort scale. The percent grass of the total plot biomass is greatest in the early season, while the total biomass (total fine fuels—grasses and leaves) is higher in mid-season, reflecting an increase in leaf litter as the dry season progresses. The increase in dry biomass also reflects the changes in species types burned—the taller perennials often burn later in the dry season. Some perennials are too moist to burn during the early months of the dry season and burn less completely in the mid-season due to higher moisture content.

Table 1. Mean Plot Characteristics by Study Period (n and standard deviations in parentheses) (2014-2016, Mali)

Mean plot characteristics (n=36)	**EDS** (16)	**MDS** (20)	**All Fires** (36)
Dry biomass (g/m^2)	340 (137)	349 (71.3)	345 (110)
Grass biomass (%)	83.1 (21.1)	78.9 (17.2)	80.8 (19.1)
Total Fuel moisture (%)	10.8 (10.7)	15.1 (12.0)	13.2 (11.7)
Temperature (° Celsius)	33.0 (3.03)	29.2 (3.62)	30.9 (3.86)
Relative humidity (%)	28.7 (4.02)	30.6 (12.2)	29.8 (9.51)
Wind speed (m/s)	0.99 (0.61)	1.63 (0.58)	1.35 (0.68)

3.2 Fire Characteristics

The characteristics of the fires also vary by season (Table 2). The mean BP increased as the dry season progressed from 77.4% in the EDS to 92.3 in the MDS as expected due to the gradual desiccation of the biomass and slight rise in wind speed. CC also increased from early to mid-season (81.3% to 86.2%). These variables showed great variability in both seasons. Spread rate and intensity increased from early to mid-season with high variation in intensity values reflecting the wide variety of fuel, weather and fire conditions. The data also show that fire type has a large influence on fire intensity as expected; head fire mean intensity was much greater than that for backfires (242.4 kW/m to 100.0). In addition, we found a large variation in the fire-line intensity values especially for head fires.

Table 2. Mean Fire Characteristics and Emissions by Study Period and Fire Type (2014-2016, Mali)

Mean Fire Characteristics and Emissions (n=36)	**EDS** (16)	**MDS** (20)	**Head** (11)	**Back** (25)	**All Fires** (36)
Spread rate (m/s)	0.024 (0.019)	0.027 (0.035)	0.046 (0.043)	0.17 (0.012)	0.026 (0.029)
Scorch Height (meters)	1.20 (0.45)	1.14 (0.53)	1.37 (0.42)	1.07 (0.50)	1.16 (0.50)
Burn Patchiness (%)	77.4 (15.5)	92.4 (8.13)	82.1 (16.1)	87.3 (12.9)	85.7 (14.1)
Combustion Completeness (%)	81.3 (12.3)	86.2 (13.7)	82.0 (12.4)	84.9 (13.6)	84.0 (13.3)
Byrams Fire Intensity (kWm^{-1})	118.3 (84.5)	163.7 (191.9)	242.4 (230.9)	100.0 (71.5)	143.5 (155.3)
Modified Combustion Efficiency (MCE)	0.87 (0.18	0.92 (0.19)	0.88 (0.19)	0.90 (0.20)	0.90 (0.18)
Methane Emissions Factor (CH_4 EF g/kg)	3.83 (2.67)	3.18 (2.31)	5.12 (1.74)	2.74 (2.43)	3.47 (2.50)
Methane Emissions Density (g/m^2)	0.839 (0.651)	0.875 (0.667)	1.203 (0.658)	0.708 (0.602)	0.859 (0.660)

3.3 Methane Emissions and MCE

The mean EF for methane was 3.47 g/kg and the mean MCE was 0.90, which is considered on the cusp of flaming and smoldering (Table 2). Our study found that methane EFs ranged from 3.83 g/kg in the EDS to 3.18 in the MDS. These differences yield a weak effect size of 0.25 (Cohen's d) but the small sample did not provide enough power ($1-\beta=0.11$) for this effect to be significant ($p=0.45$). The results indicate that fire type has a larger impact on methane EF than fire season. Head-fires had nearly double the CH_4EF of backfires (5.12 g/kg to 2.74g/kg) and this held regardless of fire season. This difference is both significant ($p=0.02$) and dramatic in effect (Cohen's d=0.92), despite the relatively small sample ($1-\beta=0.69$). MCE was also slightly lower for head- than for backfires and lower for the EDS (0.87 compared to 0.92 for MDS).

Despite the small sample ($1-\beta=0.64$), fire intensity (Byram's) was a significant driver of CH_4EF ($p=0.03$) but the correlation was modest ($R=0.38$) and the effect size was weak ($R^2_{adj}=0.09$) (Figure 3). There was a similar relationship for fire intensity and methane density ($P= 0.006$; $R^2_{adj} = 0.165$) (Figure 4). Methane emission density increased marginally from 0.839 g/m^2 in the EDS to 0.875 g/m^2 in the MDS. This was not significant ($p=0.88$) and the effect size was trivial (Cohen's d=0.05), and the sample size was underpowered ($1-\beta=0.05$). Head fires, however, had much higher emission densities than backfires (1.203 vs. 0.708 g/m^2, respectively. This difference yields a strong effect (Cohen's d=0.81), which is significant ($p=0.04$), even though the study was underpowered ($1-\beta=0.58$).

Figure 3. Methane EF as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-2016, Mali)

Figure 4. Methane density as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-2016, Mali)

We found no significant relationship between Byram's intensity and CO EF (Figure 5) and no significant relationship between $EFCH_4$ and either total moisture or calculated Viney moisture or percent grass in the biomass. We did find a negative and significant relationship between MCE and $EFCH_4$ as expected ($P=0.000001$; $R^2_{adj} = 0.436$), however, the effects of fire type can be seen here as well. When head- and backfires are examined separately, the relationship between CH_4 EF and MCE for back-fires is much stronger than head-fires (Figure 6). Similarly, for MCE and methane density we found a stronger relationship for back- than head-fires.

Figure 5. Carbon Monoxide EF as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-2016, Mali)

Figure 6. MCE as a function EF CH_4 for head- (a) and back- (b) fires. Green fires are EDS and orange are MDS. Arrows indicate fire type (2014-2016, Mali)

4 Discussion

Our study finds that methane EF means were highest for EDS as expected and dropped by about 20% by the MDS. We found, however, that fire type had a greater (and more significant) impact on methane EF than season; head-fire methane EFs were nearly double those for backfires (5.12 g/kg to 2.74 g/kg). In general, methane EFs increased as fire intensity increased and head fires, which have higher fire intensity, had higher methane EF regardless of season. Increased fire intensity results in taller flame heights, which reach into the tree canopies of the numerous small trees and burn greater amounts of fresh green leaves (Figure 7). Indeed, our field observations recorded the highest methane emissions (over 5000 ppm) during the combustion of green leaves on small trees. We were not able to determine the amount of leaves on trees that were combusted in this study, although it is reasonable to estimate that more green leaves would burn on trees in the EDS than other seasons. Interestingly, we did not find a correlation between Byram's fire intensity and EF CO although CH_4 and CO EFs did correlate with each other, as expected. We suggest the latter finding supports our argument that higher flame heights result in increased CH_4 emissions and this suggests that CH_4 and CO EFs may not be as coupled as some research suggests.

Figure 7. A head-fire extending from a bed of dry grasses into the green leaves in the tree canopy, Tabou Village, Mali (Photo by P. Laris).

Our results compare favorably with the biome averages from Andreae (2019). Andreae's savanna biome mean MCE was 0.94 (+ 0.02) and mean EF CH_4 was 2.7 (+ 2.2) g/kg, which compare with our values for our MCE (f) of 0.90 and methane EF (f) of 3.47 (Table 3). If we use the lower percent carbon value for West African savannas (42.5% based on Lacaux et al 1995 as opposed to 50% used for comparative purposes), then our Methane EF (adjusted) values (2.95g/kg) are quite close to the biome means. It is not surprising that our values had a lower MCE and higher CH_4EF than the biome means because we based our values on emissions from "wooded mesic savannas" as opposed to the "grassland" values used in most savanna biome estimates. Wooded savannas contain small trees, shrubs and leaf litter, which tend to reduce MCE and increase methane EF values (e.g., Vernooij et al., 2020) due to the fraction of ligneous fuel in the mix.

Table 3. A comparison of Methane EF values for seasonal savanna and woodland fire studies

Methane EF	**EDS**	**MDS***	**LDS**	**Ratio (E/L)**	**Mean**
This study Wooded savanna	3.82	3.18	NA	1.20	3.47 (+ 2.5)
Korontzi (2005) Miombo Woodlands	3.82	NA	2.61	1.47	3.22
Korontzi (2005) Damba Grasslands	3.14	NA	0.80	3.93	1.97
Russell-Smith et. al. (2021) Dambo Grass Savanna	NA	6.12	1.45	4.22	3.72
Russell-Smith et. al. (2021) Dry Savanna	NA	1.34	1.31	1.02	1.33
Russell-Smith et. al. (2021) Wooded Savanna	NA	1.51	2.22	0.68	1.87
Andrea (2019) Savanna biome	NA	NA		NA	2.71 (+ 2.2)

*Although Russell-Smith et al (2021) refer to their fires as EDS for comparative purposes, they are more in line with MDS burning for reasons noted below.

Our results compare favorably for seasonal changes in methane EFs found by Korontzi's for East African woodland-savanna. Importantly, our data is more in line with Kornontzi's values for "woodlands" (Miombo) than for "grassland" (Damba) savannas (Table 3). We attribute this to the fact that both areas have mesic rainfall regimes and high tree and shrub cover. As noted, we found the percent grass of the total plot biomass is greatest in the EDS, while the total biomass is higher in the MDS reflecting a tripling of leaf litter biomass.

Kornontzi (2005) argued that because EDS fires have a much lower CC—near zero in the early EDS to 80% by LDS—that total emissions from EDS fires would be less than those for LDS ones. This in spite the fact that they found EDS fires have higher methane EFs by a factor of 1.47 for woodlands and 3.93 for grasslands (compared with our ratio of 1.20). They also found that fuel load increased by about twenty percent from EDS to LDS with a big increase in MDS (we found a smaller increase). Finally, they found that methane EFs were at their peak in MDS as opposed to LDS. As a result, Korontzi concludes that for SE Africa, early fires produce lower methane emissions than either mid or late season fires in contrast to our results. Korontzi found the regional average CH_4 emission densities more than doubled from 0.24 g/m^2 in the EDS to 0.55 g/m^2 in the LDS. By comparison, we found smaller increases by season—less than 5%, which was insignificant. The larger range in emission density values estimated by Korontzi derive largely from the higher range of CC used in their model. Korontzi (2005) also notes that the lower emission densities for CH_4 in the EDS were mainly a result of the larger effect of the increased fuel moisture content on lowering CC compared with its effect on MCE. They note this was opposite of what they found for their grassland fires indicating that the amount of woody vegetation is a critical determinant of CH_4EF.

It is important to note that Korontzi's values for early season CC were derived using a model and based on fuel moisture levels alone, not experimental data. We argue that, practically speaking, people do not set fires when grasses are too moist to carry fire in West Africa. As such, we argue that using CC values less than 50%, while theoretically useful, are not at all practical because people are unlikely to set such fires as they would not achieve the desired goals of burning (Laris 2005, 2011). Indeed, it is probable that a fire, which burns less than 50% of biomass, *will burn a second time* late in the season because a fire consuming such a small fraction will not break fuel connectivity. It is also important to note that braking fuel connectivity is a key reason for setting early fires and a critical reason that mosaic fire regime burns less total area (Laris et al., 2018). As such, although theoretically possible, we do not agree that using such low CC values is reasonable for determining emissions from fires in actual African landscapes. Indeed, we have rarely seen burned landscapes with more than 50% of the biomass standing post fire.

By comparison, Russell-Smith et al (2021) found that emission factors varied by season for Dambo grasslands but not for savanna woodlands (Table 3). They found that Dambo grasses burned in the EDS had a methane EF of over four times that of those burned in LDS (nearly identical with results from Korontzi). Contrastingly, they found little difference by season in methane EF, for dry wooded savannas and a surprisingly higher EF in late season for more wooded savannas, which contrasts with our findings and those of Korontzi (2005) for wooded savannas. We must note, however, that the date chosen for Russell-Smith's EDS is more comparable with the MDS date used in our study—both dates represent the "middle" of the dry season. Indeed, as Russell-Smith et al. note, trees in wooded savanna had already begun dropping leaves and grasses were fully cured at the time of their "EDS" fires—characteristics we would not associate with early burning in West Africa. As such, we would argue that Russell-Smith et al. (2021) provides good evidence that MDS (not EDS) fires produce lower methane emissions than LDS fires in Africa.

Unfortunately, there is no recognized standard for what distinguishes early from middle or late dry season in the savanna literature—a problem hampering fire science. Elsewhere we have argued that the dichotomous (EDS/LDS) view of savanna burning is problematic because the point at which the fire season shifts from early to late has not been adequately defined and varies by context (Laris et. al., 2017; Laris 2021). We note that although adding a third, middle season, is potentially useful for research on gas emissions, the fundamental problem of typology remains. While the EDS clearly begins when the rains end, there are no recognized standards for determining when the MDS or LDS begins. While fuel moisture level hold some promise for developing a typology, the patchy heterogeneous nature of savannas means that some patches could burn "early" (higher fuel moisture) and some "late" (lower fuel moisture) in the same fire. Other factors must be considered as well, the clearest of which is leaf fall. We suggest the onset of leaf fall is a reasonable marker for a division between EDS and MDS. Weather conditions also play a critical role and these differ by region. For example, in West Africa winds peak in MDS but they are stronger in the LDS in southern Africa (Russell-Smith et al. 2021).

In our previous research involving a large sample of 97 experimental fires, we found that fires set in the MDS (the peak moment in local burning) differed from those set in the EDS or LDS (the seasons used in most fire studies) in key ways (Laris et al., 2020). In our larger study we found that when fires are set in accordance with local practices, MDS fires had the lowest fire intensity and scorch heights while CC increased only slightly from early to mid-season with a larger jump in late season. Mean values for BP gradually increased from early to middle to late season due to the drying of the biomass. Fuel moisture was also slightly higher in the MDS than EDS (due to the burning of more perennials) before dropping dramatically in the LDS. Fuel loads increased in the MDS largely due to a rise in the percentage of leaf litter in the total biomass. It should be noted that an increase in leaf litter means a decrease in the amount of green leaves burned on trees. In sum, we conclude that seasonal distinctions can be useful if clearly defined, but they should be limited to specific savannas and not used for comparative purposes between regions for the purposes of determining the effects of fire on emissions.

When comparing our results for EDS and MDS fires, we find evidence for an emissions trade-off. That is, while EDS fires have a lower BP than MDS fires as well as lower CC the lower amount of biomass burned by EDS fires is offset by the higher methane EF resulting in statistically insignificant differences in methane emission densities by season.[2] We must reiterate, however, that an unknown quantity of standing leaves are combusted during fires (especially the EDS when leaves remain on trees), meaning the fuel loads we measured for the EDS are an underestimation of the leafy fuels consumed. Small trees often dominate mesic savanna woodlands, such as those in West Africa. These so-called "Gulliver" trees are often less than 2-meters tall because they repeatedly burned back to the rootstock by annual fires (Laris and Dembele 2012). We argue that burning of small trees contributes significantly to methane release. As such, we cannot support the policy suggestion put forth by Lipsett-Moore (2018) who promote increased early burning in African savannas to reduce methane emissions. While it is theoretically possible that very early fires would burn a lower fraction of the landscape than we have observed, we argue that such a policy is just as likely to cause an *increase* in methane emissions due to higher methane EF of earlier burning, which may be a function of green leaf combustion (see Korontzi 2005). It is also important to note that higher intensity head fires would be required to increase the burned area of moist perennial grasses in the EDS[3] and because head-fires have a methane EF nearly double that of backfires, burning with head fires would likely

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[2] We note that results from our larger study of 97 fires found a less dramatic rise in BP and CC from EDS to MDS to LDS than for the sample of 36 fires used here. In the larger study, BP increased marginally as the dry season progressed to a near complete burn by the late season (85.3% to 92.3 to 99.2). CC increased very slightly from early to mid before increasing substantially in late season (85.1% to 86.4 to 92.8) (Laris et al., 2020). These findings suggest a stronger emissions trade off than reported here.

[3] We made several attempts to burn perennial grasses in December and could not get them to ignite. Only under windy, head-fire conditions will perennial grasses burn in the EDS.

counter any advantage of burning early to reduce emissions. In addition, local inhabitants would be very reluctant to set such fires due to the increased risk that setting head fires could damage field crops, which remain unharvested in the EDS.

Surprisingly, there are but a few studies of African savanna emission factors for which head and backfire data are available. Wooster et al., (2011) found mean EF methane for head fires to be higher than the backfire mean by a 3.35 g/kg to 1.88 g/kg (a similar ratio to what we found). Several laboratory results also support our finding that MCE and EF methane are function of fire type. Keene et al. (2006) used laboratory fires of fuels from SE Africa and found that the type of fire (backing, heading, or mixed) as well as fuel moisture influenced MCE. The lowest MCE values they recorded were all for heading fires with relatively low moisture content while MCE fell and EF methane rose as fuel moisture increased. Similarly, Surawski et al., (2015) found that heading fires exhibited the lowest MCE and higher methane EF.

While the primary purpose of this study was to determine realistic values for methane emissions for a representative working savanna in West Africa, the findings can inform broader-scale modeling efforts for savanna fire burning (Hanston et al 2016) in three ways. First, we do not recommend making crude assumptions about the effects of fire season on methane emissions as these will vary by savanna. Second, there is a need to map fires according to type because head-fires cause higher methane emissions for the two reasons noted above. Third, modelers need to make distinctions between savanna types, because there are large differences between emissions from grass-dominated and wooded savanna landscapes as both theory and empirical results suggest. In sum, modelers should focus on developing methods to determine the direction (type) of fire remotely in addition to other key factors such as fire intensity, fuel moisture, savanna woody cover (especially small trees), and burn severity.

5 Conclusions

This study finds that when fires are set in working landscapes in accordance with well-documented burning practices of West African people, methane EFs decreased from early dry season to mid-dry season (although the results were not significant). We also found that methane emission density increased only marginally from EDS to the MDS a difference that was not significant. We found that fire type had a much greater effect on methane emissions than fire season with head-fires having significantly higher methane EF compared to backfires and significantly higher methane densities due to higher fire intensity. We note that we are unaware of any estimates for area burned according to fire type for any of the world’s savannas.

It is important to reiterate that several key findings of this study arise from documented burning practices of people living in working landscapes. People set fires in West Africa later in the day resulting in fires with lower intensity due to lower wind and air temperature, and higher humidity; and people set predominantly backfires all of which contribute to lower intensity burning, which results on lower methane emissions. In addition, we note that the fuel loads we recorded are nearly 50% lower on working savanna lands compared to reserve lands used in some other studies (Laris et al. 2020). Finally, the number of fires peaks in the West African region in the MDS and although the methane emissions density values for the EDS were slightly lower than for the MDS, a significant reason for this was the increased fuel load from leaf litter in the MDS. We should note that EDS fires tend to burn more green leaves on trees, which are not accounted for in this study.

In conclusion, our study finds that several factors influence the emissions from savanna fires including the fire season, fuel load and type, and, most importantly, fire type. Each of these factors are a function of human land and fire management practices. We also conclude there is an emissions trade-off in setting fires earlier and, as such, a policy to increase the amount of early burning in West African would be very difficult to implement because much burning is already “early” and because earlier burning of uncured grasses and green leaves would likely result in higher methane EFs. Moreover, any policy aimed at increasing the amount of early burning would likely require setting head fires, which would decrease burn patchiness and increase combustion completeness further negating the effects of any reduction in burned area while also causing an undesired increase in uncontrolled fires.

Appendix

Table A. Factors affecting methane emissions from West African savanna fires, human influence and uncertainty

	Impact on Emissions	**Human Influence**	**Level of Uncertainty**
Fire Season	**High.** Theory suggests that early season fires burn uncured fuels resulting in a lower combustion efficiency, higher CH_4 EF and higher burn patchiness.	People often begin burning the moment rains end. They determine the seasonal timing of fires by selecting to burn when grasses are just dry enough to carry a fire with consideration given to the agricultural calendar.	**High**. There is no agreed upon definition for distinguishing fire seasons. Approaches vary from the use of crude typologies based on month of low rainfall to more sophisticated ones based on vegetation or soil moisture level. Physiological measures could also include leaf fall or leaf flush.
Fuel load	**Medium**. Total emissions are a function of fuel load, including the *type* of fuel and amounts (below).	In occupied areas, human land uses determine fuel load. Grazing and rotational agricultural practices have large effects. In other areas, wild animals graze and browse.	**Medium**. Much research has been conducted on reserves or protected areas where grassy fuel loads are higher. Realistic values for fuel loads on working lands should be used based on ground or remotely sensed methods.
Fuel Moisture	**Medium**. Higher fuel moisture (in grasses or leaves) can reduce combustion efficiency and raise CH_4 EF. Higher fuel moisture can also increase patchiness of burning. Fuel moisture declines over the fire season.	People play a critical role determining the point at which fires are set often according to fuel moisture level of grasses at fine spatial resolution.	**High**. Fuel moisture is often considered to be a function of seasonality; however, there is high spatial heterogeneity in savannas. A single fire can burn one type of grass with high fuel moisture and another with low moisture with implications for CH_4 EF.
Patchiness	**High**. Fires tend to burn in a patchy manner especially when vegetation is not uniformly dry and when burning as a backfire. Patchiness created by earlier fires, prevents spread of later ones.	People create a patch-mosaic by systematically burning the driest patches on the landscape first fragmenting the landscape and creating a patch-mosaic with new, old and unburned patches.	**Low**. Advances in remote sensing and image processing algorithms have improved estimates of patchy burning although the smaller, often earlier, fires are still most often underestimated. Higher-resolution data eliminates this problem.
Dry or Green Leafy Biomass	**High**. Green leaves burned on trees have high CH_4 EF. Leaf fall commences in mid dry season adding to the fuel load, altering fuel composition, increasing fuel connectivity while reducing airflow through the fuel bed affecting combustion.	People determine the timing of fires which has implications for whether leaves are burned green (early dry season) or dry (later dry season)	**High**. Amounts of leaf litter vary by savanna type and season. While amounts of dry leaf litter have been estimated in some cases, green leaf combustion on standing trees and shrubs is relatively understudied.
Fire Type	**High**. Head-fires burn more intensively, with higher flame lengths scorch heights causing more of the tree canopy to burn.	People purposefully set backfires although fires can change direction and accidental fires may more often burn as head-fires.	**High**. There is a potentially large and unknown impact on emissions of methane. There are few studies of fire type for savannas but remotely sensed methods offers potential.
Fire Time of Day	**Medium.** Ambient weather conditions can affect fire intensity and combustion and these are a function of time of day.	People determine the time of day to set fires, most often late afternoon.	**Low**. Although rarely considered in the literature, satellite data can provide an estimate of fire timing.
Grass Type	**Low**. Perennial grasses hold moisture longer and are often taller than annuals. Grass types vary dramatically on savanna landscapes.	Human actions modify grass species over the short and long term. Perennials are highly valued, but are being replaced by annuals.	**High**. Few studies consider variations in grassy vegetation cover at fine resolution. Remotely sensed methods can potentially distinguish between annuals and perennials.

Woody Vegetation Type	**Medium**. Savannas are highly heterogeneous with varying levels of tree cover, which affects CH_4 EF especially when small trees burn.	Woody vegetation type is partially a function of long-term human land use patterns of agriculture and grazing.	**Medium**. Improved remote sensing techniques can increase accuracy of vegetation mapping including canopy cover.

Code availability

NA

Data availability

https://cla.csulb.edu/departments/geography/savannalabo/data/

Author Contributions

PL was principal investigator on the project, supervised all aspects of the research and wrote the manuscript. MK was involved in the fieldwork and the gathering cleaning and organizing of all data as well as commenting on manuscript. FD was head of the field research team and advisor on the field. RJ and LY were involved in data organization and analysis as well as discussing and commenting on manuscript. C.M.R. was responsible for the statistical analysis with assistance from Q.L.

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"The authors declare that they have no conflict of interest."

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References

Ahern, F.J., Goldammer, J.G., Justice, C.O. (Eds). Global and Regional Vegetation Fire Monitoring from Space: Planning a coordinated international effort. SPB Academic Publishing, The Hague, The Netherlands, 2001.

Andela, N., Morton, D., Giglio, L., Chen, Y., van der Werf, G., Kasibhatla, P., Kloster, S. A human-driven decline in global burned area. Science 356:1356–1362. 2017.

Andreae, M.O. Emission of trace gases and aerosols from biomass burning – an updated assessment. Atmos. Chem. Phys. 19:8523-8546, 2019.

Andreae, M.O., Merlet, P. Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15:955–966, 2001.

Bonsang, B., Boissard, C., Le Cloarec, M.F., Rudolph, J., Lacaux, J.P. Methane, carbon monoxide and light non-methane hydrocarbon emissions from African savanna burnings during the FOS/DECAFE experiment, Journal of Atmospheric Chemistry 22:149-162, 1995.

Byram, G.M., Combustion of forest fuels, edited by: Davis, K.P., Forest fire: Control and use. McGraw-Hill, New York, pp 61-89, 1959.

Caillault, S., Laris, P., Fleurant, C., Delahaye, D., Ballouche, A. Anthropogenic fires in West African Landscapes: a spatially explicit model perspective of humanized savannas. *Fire*. 3.https://doi.org/10.3390/fire3040062, 2020.

Charnley, S., Sheridan, T.E., Nabhan, G.P. (Eds). Stitching the West Back Together: Conservation of Working Landscapes. Chicago, The University of Chicago Press, 2014.

Coughlan, M.R., Petty, A.M. Linking humans and fire: a proposal for a transdisciplinary fire ecology. International Journal of Wildland Fire 21:477 – 487, 2012.

Duvall, C.S. Biocomplexity from the ground up: Vegetation patterns in a west African savanna landscape. Annals of the Association of American Geographers 101:497- 522, 2011.

Faul, F., Erdfelder, E., Buchner, A., Lang, A.-G. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. Behavior Research Methods 41: 1149-1160, 2009.

Giglio, L., Randerson, J.T., van der Werf, G.R., Kasibhatla, P.S., Collatz, G.J., Morton, D.C., Defries, R.S. Assessing variability and long-term trends in burned area by merging multiple satellite fire products, Biogeosciences 7:1171–1186, 2010.

*G*Power. Statistical Power Analyses for Mac and Windows, 2021. Available at https://www.gpower.hhu.de/ (last accessed 16 July 2021).*

Grégoire, J-M., Eva, H.D., Belward, A.S., Palumbo, I., Simonetti, D., Brink, A. Effect of land-cover change on Africa's burnt area. Int. J. Wildland Fire 22:107-120, 2013.

Hammer, O., Harper, D.A.T., and Ryan, P.D. PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica 4, 1: 1-9, 2001.

Hammer, O., Harper, D.A.T., and Ryan, P.D. PAleontological STatistics program. Available at https://www.nhm.uio.no/english/research/infrastructure/past/, 2021. (last accessed 16 July 2021).

Hantson, S., Arneth, A., Harrison, S. P., Kelley, D. I., Prentice, I. C., Rabin, S. S., Archibald, S., Mouillot, F., Arnold, S. R., Artaxo, P., Bachelet, D., Ciais, P., Forrest, M., Friedlingstein, P., Hickler, T., Kaplan, J. O., Kloster, S., Knorr, W., Lasslop, G., Li, F., Mangeon, S., Melton, J. R., Meyn, A., Sitch, S., Spessa, A., van der Werf, G. R., Voulgarakis, A., and Yue, C.: The status and challenge of global fire modelling, Biogeosciences, 13, 3359–3375, https://doi.org/10.5194/bg-13-3359-2016, 2016.

Heimann, M. Enigma of the recent methane budget. Nature 476:157–158, 2011.

Henry, C. An integrated approach to estimating groundwater storage, variability and recharge in Southern Mali, Africa. M.Sc Thesis. Department of Earth Sciences, Simon Fraser University, Canada, 2011.

Hoffa, E.A., Wakimoto, R.H., Ward, D.E., Hao, W.M., Susott, R.A. Seasonality of carbon emissions from biomass burning in a Zambian savanna. Journal of Geophysical Research 104: 13,841–13,853, 1999.

Katzenstein, A.S., Doezema, L.A., Simpson, I.J., Blake, D.R., Rowland, F.S. Extensive regional atmospheric hydrocarbon pollution in the southwestern United States, Proc. Natl. Acad. Sci. U. S. A. 100:11,975–11,979, 2003.

Keeley, J. E., Pausas, J. G. Distinguishing disturbance from perturbations in fire-prone ecosystems. International Journal of Wildland Fire 28: 282-287, 2019.

Keene, W.C., Lobert, J.M., Crutzen, P.J., Maben, J.R., Scharffe, D.H., Landmann, T., Hély, C., Brain, C. Emissions of major gaseous and particulate species during experimental burns of southern African biomass, J. Geophys. Res., 111, D04301, 2006.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M. et al. Three decades of global methane sources and sinks. *Nature Geoscience* 6:813-823, 2013.

Koné, M., Dembele, F. Laris, P. Inventaire, typologie et estimation quantitative des gaz émis par les feux de brousse en savane soudanaise dans le sud Mali. *Revue de Géographie Tropicale et d'Environnement*. 2: 26-39, 2020.

Koppmann, R., von Czapiewski, K., Reid, J.S. A review of biomass burning emissions, part I: gaseous emissions of carbon monoxide, methane, volatile organic compounds, and nitrogen containing compounds. Atmos. Chem. Phys. Discuss. 5:10455–10516, 2005.

Korontzi, S. Seasonal patterns in biomass burning emissions from southern African vegetation fires for the year 2000. Global Change Biology 11:1680–1700, 2005.

Intergovernmental Panel on Climate Change (IPCC). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, IPCC National Greenhouse Gas Inventories Programme, Hayama, Kanagawa, Japan, 2000.

Lacaux, J.P., Brustet, M., Delmas, R. Biomass burning in the tropical savannas of Ivory Coast: An overview of the field experiment Fire of Savannas (FOS/DECAFE 91). J Atmos Chem 22:195–216, 1995.

Laris, P. Burning the seasonal mosaic: preventative burning strategies in the wooded savanna of southern Mali. Hum. Ecol. 30:155–186, 2002.

Laris, P. and Dembele, F. Humanizing savanna models: integrating natural factors and anthropogenic disturbance regimes to determine tree-grass dynamics in savannas. Journal of Land Use Science 7: 459-482, 2012.

Laris, P. Integrating land change science and savanna fire models in West Africa. Land 2:609–636, 2013.

Laris, P. Spatiotemporal problems with detecting and mapping mosaic fire regimes with coarse-resolution satellite data in savanna environments. Rem. Sens. Environ. 99:412–424, 2005.

Laris, P. Humanizing savanna biogeography: Linking human practices with ecological patterns in a frequently burned savanna of southern Mali. Annals of the Association of American Geographers 101: 1067–1088, 2011.

Laris, P., Dadashi, S., Jo, A., Wechsler S. Buffering the savanna: Fire regimes and disequilibrium ecology in West Africa. Plant Ecology 217:583-596, 2016.

Laris, P., Koné, M., Dadashi, S., Dembele, F. The early/late fire dichotomy: Time for a reassessment of Aubreville's savanna fire experiments. Progress in Physical Geography 41:68-94, 2017.

Laris P., Jo A., Wechsler S., Dadashi S. The Effects of Landscape Pattern and Vegetation Type on the Fire Regime of a Mesic Savanna in Mali. Journal of Environmental Management 227:134-145, 2018.

Laris, P., Jacobs, R., Koné, M. *et al.* Determinants of fire intensity in working landscapes of an African savanna. *Fire Ecology* 16, 27. https://doi.org/10.1186/s42408-020-00085-x, 2020.

Laris, P. On the Problems and Promises of Savanna Fire Regime Change, Nature Communications. *Nature Communications,* 2021.

Le Page, Y., Oom, D., Silva, J., Jönsson, P., Pereira, J. Seasonality of vegetation fires as modified by human action: Observing the deviation from eco-climatic fire regimes. Global Ecology and Biogeography 19:575–588, 2010.

Lipsett-Moore, G.J., Wolff, N.H., Game, E.T. Emissions mitigation opportunities for savanna countries from early dry season fire management. Nature Communications 9:2247, 2018.

Mistry, J., Berardi, A., Andrade, V., Kraho, T., Kraho, P., Leonardos, O. Indigenous Fire Management in the cerrado of Brazil: The Case of the Kraho of Tocantıns. Human Ecology 33. DOI: 10.1007/s10745-005-4143-8, 2005.

National Aeronautics and Space Administration (NASA). Biomass burning, http://earthobservatory.nasa.gov/Features/BiomassBurning/printall.php., 2005.

Randerson, J., Chen, Y., van der Werf, G., Rogers, B., Morton, D. Global burned area and biomass burning emissions from small fires. Journal of Geophysical Research 117 G04012, 2012.

Russell-Smith, J., Murphy, B.P., Meyer, C.P., Cook, G.D., Maier, S., Edwards, A.C., Schatz, J., Brocklehurst, P. Improving estimates of savanna burning emissions for greenhouse accounting in northern Australia: Limitations, challenges, applications, Int. J. Wildland Fire 18:1-18, 2009.

Saunois, M., Jackson, R.B., Bousquet, P., Poulter, B., Canadell, J.G. The growing role of methane in anthropogenic climate change, Environmental Research Letters 11:120207, 2016.

Saunois, M., et al. The Global Methane Budget 2000–2017. Earth Syst. Sci. Data, 12, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020, 2020.

Savadogo, P., Sawadogo, L., Tiveau, D. Effects of grazing intensity and prescribed fire on soil physical properties and pasture yield in the savanna woodlands of Burkina Faso. Agriculture Ecosystems & Environment 118:80-92, 2007.

Surawski, N.C., Sullivan, A.L., Meyer, C.P., Roxburgh, S.H., Polglase, P.J. Greenhouse gas emissions from laboratory-scale fires in wildland fuels depend on fire spread mode and phase of combustion, Atmos. Chem. Phys. 15:5259–5273, 2015.

van Leeuwen, T.T., van der Werf, G.R. Spatial and temporal variability in the ratio of trace gases emitted from biomass burning, Atmos. Chem. Phys. 11:3611–3629, 2011.

van Leeuwen, T.T., van der Werf, G.R., Hoffmann, A.A., et al. Biomass burning fuel consumption rates: a field measurement database, Biogeosciences 11:7305–7329, 2014.

Williams, R.J., Gill, A. M., Moore, P. H. Seasonal changes in fire behavior in a tropical savanna in northern Australia. International Journal of Wildland Fire 8:227–239, 1998.

Worden, J.R., Bloom, A., Pandey, S. et al. Reduced biomass burning emissions reconcile conflicting estimates of the post-2006 atmospheric methane budget. Nature Commun. 8:2227, 2017.

Ward, D.E., Hao, W.M., Susott, R.A. et al. Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems. Journal of Geophysical Research, 101:23569–23576, 1996.

Yokelson, R.J., Bertschi, I.T., Christian, T.J. et al. Trace gas measurements in nascent, aged, and cloud-processed smoke from African savanna fires by airborne Fourier transform infrared spectroscopy (AFTIR). Journal of Geophysical Research: Atmospheres. 108, NO. D13, 8478, doi:10.1029/2002JD002322, 2003.

Figures and Tables

1a. Short annual grass savanna 1b. Wooded annual grass savanna 1c. Fallow annual savanna (backfire)

1d. Wooded perennial grass savanna 1e. Wooded perennial savanna (grazed) 1f. Leaf fall on fallow (late season)

Figure 1. Different savanna vegetation types used in fire experiments for the study areas of Tabou and Faradiele, Mali. Note grass species, height and density, woody cover and leaf litter amounts vary dramatically over space and time (Photographs by P. Laris).

Figure 2. Study areas in southern Mali (figure by S. Winslow).

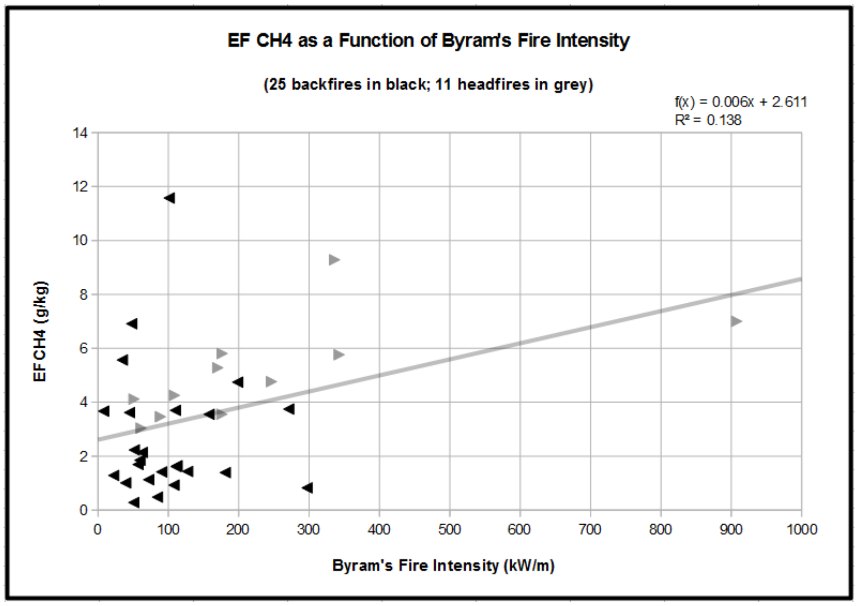

Figure 3. Methane EF as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-2016, Mali)

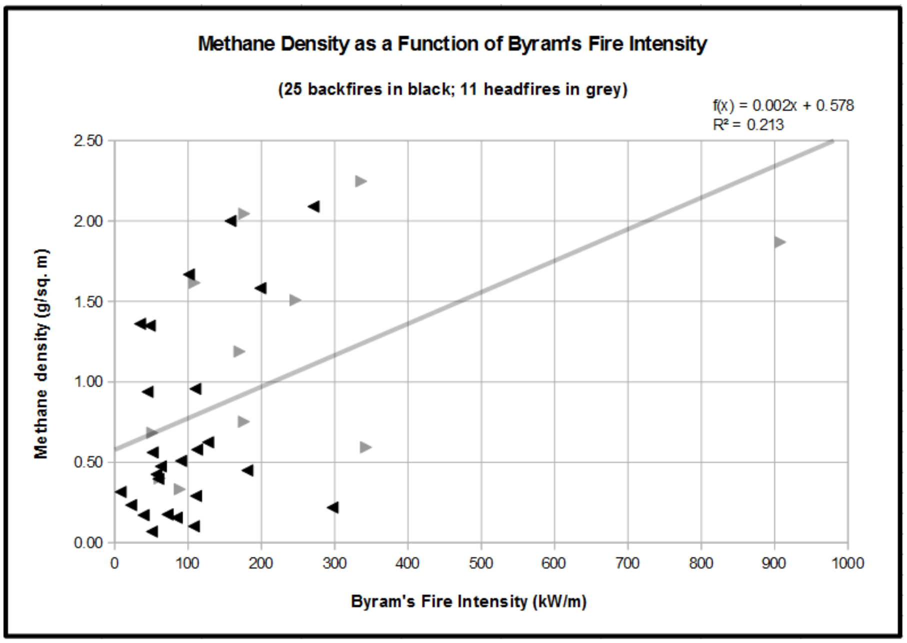

Figure 4. Methane density as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-2016, Mali)

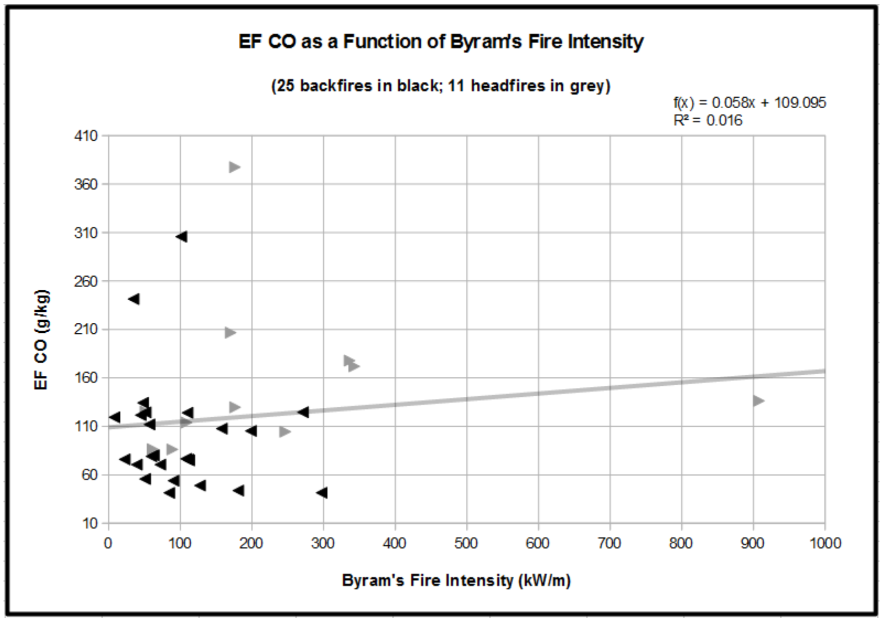

Figure 5. Carbon Monoxide EF as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-2016, Mali)

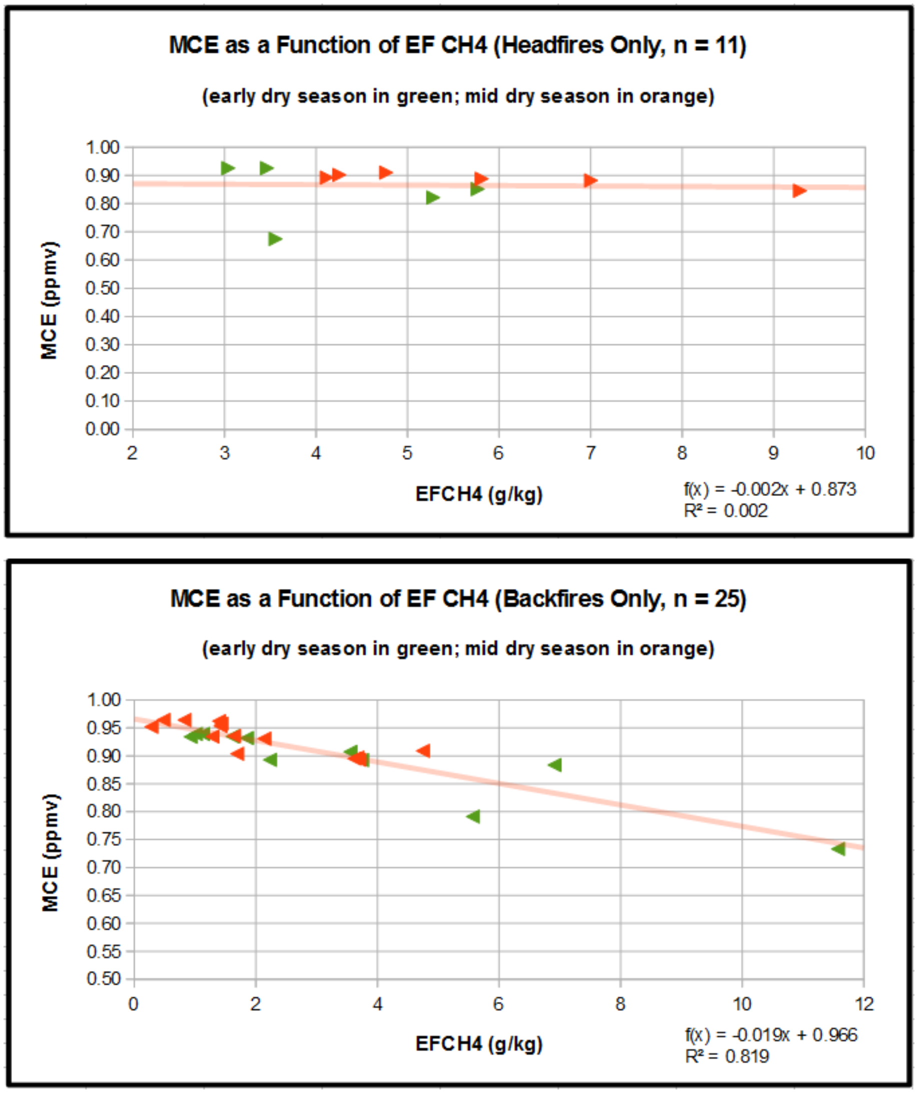

Figure 6. MCE as a function EF CH_4 for head- (a) and back- (b) fires. Green fires are EDS and orange are MDS. Arrows indicate fire type (2014-2016, Mali)

Figure 7. A head-fire extending from a bed of dry grasses into the green leaves in the tree canopy, Tabou Village, Mali (Photo by P. Laris).