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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 conducted 97 experimental fires collecting 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 collected smoke samples for 36 fires using a canister method. We report values for fire intensity, combustion completeness, patchiness, modified combustion efficiency (MCE) and emission factor (EF). Our study finds that methane EFs ranged from 3.71 g/kg in the early dry season (EDS) to 2.86 in the mid-dry season (MDS). We found head fires had nearly double the CH_4 EF of backfires (4.89 g/kg to 2.92). Fires during the MDS have the lowest intensity values and the lowest methane emissions 0.981 g/m^2 compared with 1.030 g/m^2 for EDS and 1.102 g/m^2 for the late dry season (LDS). 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. We recommend using the adjusted mean value of 0.862 g/m^2—based on the carbon content for West African grasses—for calculating emissions for West African savannas

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

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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).

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.

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. 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).

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

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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). 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 was 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 the emissions from savannas (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) note 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 finds 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. As such, 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.

In sum, while savannas undoubtedly harbor great theoretical potential to sequester more carbon, and admit less through a change in fire regime, there exists a great deal of uncertainty as to what the *actual* carbon shifts might

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be, should fire regimes be altered. Elsewhere we identify five key sources of uncertainty largely arising from the complexity of the patterns of savanna vegetation and fire regimes as well as biases associated with a lack of consideration of the actual human fire setting and land management practices in these complex landscapes (Laris et al., 2020, Laris 2020). 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.

This study aims to fill a knowledge gap by incorporating data on a variety of human burning practices, the characteristics of the fire regimes they produce, the vegetation conditions on the landscapes burned 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 (precipitation > 750 mm) 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, and these 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 we conducted 97 experimental burns using a field-based method to measure key factors. Vegetation plots, fire timing, and season (early, middle or late) were selected based on local burning practices. We collected canister samples of smoke emissions for 36 of these 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 Sudanian savanna of southern Mali (Fig. 1). We chose areas with annual precipitation over 900 mm because they burn frequently. 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, with the majority of fires occurring in late December and early January.

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Fig 1. Study areas in southern Mali

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).

2.1 Data Collection

We studied 97 experimental fires. Data on the following variables were collected in the field for each fire: average plot biomass, grass percentage of biomass, grass species, biomass consumed, fuel moisture, wind speed, scorch height, ambient humidity, temperature, fire type, time of day, fire duration, burn efficiency or 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. 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 was calculated for each plot using the method developed by Viney (1991).

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. Wind direction relative to the direction of each fire was recorded.

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 efficiency—a measure of the patchiness of the burn—was estimated by two observers.

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

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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.

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.

Fuel moisture content for the cured fuels was calculated using the method developed by Viney (1991) based on McArthur (1967) for savanna fuels:

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

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.[2]

2.4 Gas emissions sampling and analysis

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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."

[2] We note that while a portion of the unburned material was likely mineral as opposed to carbon based ash, the majority of the unburned fuels were in the form of grass and leaf remains.

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

EF_x is the emissions factor for species *x* (g/kg). F_c is the mass fraction of carb in 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) $$\frac{C_{\mathrm{x}}}{C_T} = \frac{\mathrm{ER}_{\mathrm{x/CO_2}}}{\sum_{j=1}^{n} (\mathrm{NC}_j \mathrm{ER}_{j/\mathrm{CO_2}})}$$

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)

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

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 burnt 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 efficiency (BE) which is the fraction of the surface area burned by the fire. We suggest the following revision for determining emissions *by fire season* in savannas (E_s):

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

Here, BA is burned area percent FL is fuel load, CC is combustion completeness, EF_x is emission factor of species x and BE is burn efficiency. 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 BE_s because most estimates of burned area are based on satellite image analysis, which is too coarse to determine the actual surface area burned accurately (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.

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). 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 and especially the late seasons. Calculated fuel moisture content declines over the course of the dry season from a mean of 4.62% in the EDS, to 4.09% in the MDS and 3.65% LDS. When combined with the measured mean cure rates for wet grasses; however, the total fuel moisture was 8.41% in the EDS, 12.04% and 3.65% in the LDS. 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 later in the dry 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 (standard deviations in parentheses) (2014-2016, Mali)

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3.2 Fire Characteristics

The characteristics of the fires also vary by season (Laris et al., 2020) (Table 2). The mean BE increased as the dry season progressed to a near complete burn by the late season (85.3% to 92.3 to 99.2) as expected due to the gradual desiccation of the biomass. CC increased slightly from early to mid before increasing substantially in late season (85.1% to 86.4 to 92.8). Both variables showed greater variability in the early and mid-seasons and much less variability in the late season. Burn time and scorch height (both closely related to intensity) show a different pattern. The middle season has the lowest mean values for scorch height and highest variability, while burns also take substantially longer and are more variable in the MDS. This is in spite of higher wind speeds, perhaps reflecting the slight drop and greater variability in temperatures as well as the higher moisture content of perennial grasses burned in the MDS. Fire intensity was highest in late season (288 kW/m), as expected but surprisingly slightly lower in the mid-season compared to the early season (242 Kw/m to 221). While the minimum intensity increased non-monotonically over the fire season, dipping in mid-season, the maximum intensity decreased monotonically. The standard deviation of the seasonal intensity values indicates high variability, especially for EDS. The high variation in intensity values with respect to the mean reflects the wide variety of fuel, weather and fire conditions. Calculated intensity values ranged from 46.6 to 829.6 kWm^{-1} for head fires and 10.8 to 460.3 kWm^{-1} for back-fires.

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

3.3 Methane Emissions and MCE by Fire Type and Season

The findings from the analysis of the 36 fires for which canisters of smoke were collected fires are shown in Table 3 along with results for fire type and season for the larger data set (n=97). 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. The results indicate that fire type has a larger impact on methane EF than fire season. Head fires had much higher methane EF values than backfires (4.9 to 2.5 g/kg) and this held regardless of fire season. MCE was also lower for head- than for back-fires. The mean EF for early season was 3.71 g/kg about 30% higher than the mid-season value of 2.86. MCE was also lower for the EDS as expected. 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 back-fires (313.4 kW/m to 109.0). In addition, we found a large variation in the fire-line intensity especially for head fires.

We next used the mean values for methane EFs and the FL, BE and CC data for the complete data set to determine methane emissions per meter-squared (Table 3). For the purposes of comparison, we used the mid-season values for methane EF for the late-season emissions calculations.[3] We found methane emission densities of 0.981 g/m^2 in the EDS, 1.030 g/m^2 in the MDS and 1.102 g/m^2 in the LDS for an average of 1.022 g/m^2. Based on our past research, about 49.5% of the total area burned is EDS 39.5% is MDS and 11% LDS (Laris 2011). If we then use the lower value of carbon content from Lacaux et al 1995 (West Africa), we estimate the average methane emissions per

[3] We used the methane EF value from mid-season for the late season emissions calculation (which potentially overestimates LDS emissions because fuel moisture drops further in the late season likely affecting MCE and methane EF). All other values used in the calculation were from the late season burn experiments.

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fire in southern Mali to be 0.862 g/m^2. Finally, we found emissions from head fires were nearly double those from backfires based on an average fuel load (1.635 g/m^2 to 0.948 g/m^2).

Table 3. Methane Emission Factor (EF), Combustion Completeness (MCE) and Key Fire Characteristics Emissions by Fire Type by Study Period (standard deviations in parentheses) (2014-2016, Mali)

4 Discussion

The findings from our study indicate that fires set in the mid-dry season (the peak moment in local burning) differ from those set in the early or late dry season (the seasons used in most fire studies) in key ways. MDS fires have lower intensity than both EDS and LDS fires while CC increased slightly from early to mid-season with a larger jump in late season. Mean values for BE gradually increase from early to middle to late season as expected due to the gradual drying of the biomass. Fuel loads increased in the MDS as did the percentage of leaf litter in the total biomass. These factors had differing effects on seasonal methane emissions.

Our study finds that methane EF means were highest for EDS (as expected) and drop by about 23% by the MDS. We also found, however, that fire type had a greater impact on methane EF than season; head fire methane EFs were nearly double those for back-fires. In general, methane EFs increased as fire intensity increased and head fires, which have higher fire intensity had higher methane EF regardless of season.

Our results compare favorably with the biome averages from Andreae (2019). Andreae's savanna biome mean MCE was 0.94 ($\pm$ 0.02) and mean EF CH_4 was 2.7 ($\pm$ 2.2) g/kg, which compare with our values for our MCE (f) of 0.90 and methane EF (f) of 3.47 (Table 4). 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 values are quite close to the biome means at 3.15g/kg. It is not surprising that our values had a lower MCE and higher EF CH_4 than the biome means because our values were based 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 (22% on average in our case). Indeed, we suspect the reason head-fires have significantly higher methane EFs than back-fires is that head fires have a higher scorch height and burn a greater amount of fresh green leaves in the juvenile tree canopy. In addition, we note Wooster (2011) found that ground based measurements were generally higher for carbon-based EFs than airborne ones used in most previous studies.

Our results compare more 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 4). 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.

Table 4. A comparison of Methane EF values for seasonal savanna and woodland fire studies

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Kornontzi (2005) argued that because EDS fires have a much lower combustion completeness values—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 1.30). 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 that either mid or late season fires in stark contrast to our results. Korontzi also 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—about 20% for the entire fire season (EDS-LDS). 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 the combustion completeness 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 and leaf litter are critical determinants of EFs.

It is important to note; however, that Korontzi's values for early season CC were derived using a model and based on fuel moisture levels alone (as compared to our study based on empirical results). 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, *can 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 a seasonal-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 working African landscapes. Indeed, we have rarely seen burned landscapes, even EDS ones, with more than 50% of the biomass standing post fire.

In terms of BE or "burn patchiness", our values are similar to Yates et al (2015) who found patchiness was 79% in EDS and 97% in LDS for a large study in Australian savannas (our values were 85% to 92% to 99% respectively for EDS to MDS to LDS). We argue that our values combining burn efficiency and combustion completeness give reasonable estimates of biomass consumed for the *actual* burning conditions in West African savannas.

Korontzi (2005) also notes that woodland fires dominate burning in SE Africa and thus they use the woodland as supposed to grassland values. Based on our fieldwork, however, grassland fires make up the bulk of *early* season burning because woodland and wooded-savanna areas have higher fuel moisture content making them difficult to burn in the EDS. Moreover, while Korontzi found fuel load increased by about 20% from EDS to LDS we did not; fuel load values changed very little because biomass is being consumed by animals on working lands throughout the dry season, thus although leaf litter increased, total biomass did not continue to increase after the mid-season.

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 of 2.5±0.9 g/kg for their ground-based study in SE Africa. They too found mean EF methane for head fires to be higher than the backfire mean, 3.35 g/kg to 1.88 g/kg. 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 (in part a function of season) 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.

As noted above, we find the middle season to have unique fire, fuel and ambient weather characteristics. These coupled with the practices of local inhabitants to set fires progressively to grasses as they gradually become just dry enough to burn, creates the conditions under which emissions should be determined for West African landscapes. EDS fires primarily burn shorter (1-1.5 m tall) annual grasses, which dry earlier. Early fires are limited to these dry annual grasses because at this time of year the taller perennials (up to 3 m) are often too moist to carry a fire (Laris et al 2020). As the dry season progresses past mid-December (for our region), the number of fires and area burned increases rapidly with a peak in late December.

When comparing our results for EDS and MDS fires, we find strong evidence for an emissions trade-off. That is, while EDS fires have a much lower BE than MDS fires (85% to 92%) they have only slightly lower CC (85% to 86%), as such, the lower amount of biomass burned by EDS fires is offset by the 30% higher methane EF resulting in the higher methane emission density values for the EDS. Thus, we disagree with 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 very early burning (see Korontzi 2005).

Finally, it is important to note that higher intensity head fires would be required to increase the burned area of moist perennial grasses in the EDS[4] and because head-fires have a methane EF nearly double that of backfires, burning with head fires would likely 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.

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 ranged from 3.71 g/kg in the early dry season to 2.86 g/kg in the mid-dry season. We also found that fire type has a greater effect on methane emissions than fire season with head-fires having significantly methane EF compared to back-fires (4.9 to 2.9 g/kg). We note that we are unaware of any estimates for area burned according to fire type for any of the world's savannas. We thus recommend using the

[4] 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.

adjusted mean value of 0.862 g/m^2—based on the carbon content for West African grasses—for calculating emissions for West African savannas. We suspect based on interview results and field observations in West Africa (Laris 2002, 2011) that early- and mid-season fires tend to be planned burns and are thus likely set as backfires (although fires can shift direction and winds can change) while late fires are more accidental and potentially burn as head fires. As such, the actual mean might be lower given that EDS and MDS fires comprise the bulk of the fires in the region. In terms of methane emission densities by season, we find no significant difference between the values for early and mid-season fires with a ten percent increase occurring in the late season due primarily to the higher CC and BE for this season. It is possible; however, that the higher LDS emissions might simply be an outcome of using the methane EF from the mid-season and that the actual late-season methane EF would be lower offsetting the increase in fuel consumed. Indeed we conclude that due to the *emissions trade-off*—methane EF declines as the dry season progresses while fuel consumed (BE*CC) increases—there is only a small difference in emissions density values by season (< 10%) for the region.

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. 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). Lower fuel loads also produce lower intensity fires, which produce lower methane emissions. Finally, the number of fires peaks in the West African region in the MDS (Laris et al., 2016), which, we find, have a lower methane EF and emissions density than EDS fires.

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 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 increase burn efficiency and combustion completeness further negating the effects of any reduction in burned area while also causing an undesired increase in uncontrolled fires.

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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.

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Figures and Tables

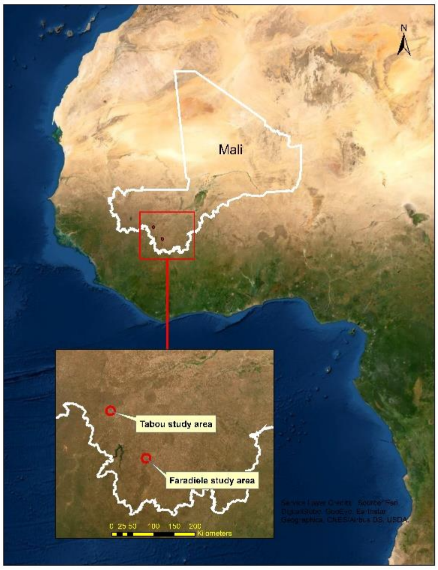

Fig 1. Study areas in southern Mali

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

Mean plot characteristics	Early	Middle	Late
Dry biomass (g/m^2)	376 (125)	445 (201)	423 (203)
Grass biomass (percent)	90.39 (18.68)	75.25 (23.74)	78.30 (22.98)
Total Fuel moisture (percent)	8.41 (0.57)	12.04 (0.73)	3.65 (0.26)
Temperature (° Celsius)	32.45 (3.37)	32.03 (3.32)	36.80 (3.28)
Relative humidity (percent)	29.62 (5.12)	20.64 (7.92)	19.34 (1.48)
Wind speed (meters/second)	1.16 (0.55)	1.45 (0.60)	0.85 (0.53)

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

Mean fire characteristics	Early	Middle	Late
Spread rate (meters/second)	0.031 (0.02)	0.028 (0.03)	0.034 (0.01)
Burn time (seconds)	599.7 (488)	736.6 (591)	357.6 (172)
Scorch Height (meters)	1.39 (0.52)	1.31 (0.68)	1.70 (0.63)
Burn efficiency (%)	85.3 (12.44)	92.3 (11.42)	99.2 (1.06)
Combustion completeness (%)	85.1 (12.50)	86.4 (11.68)	92.8 (3.49)
Byrams Fire Intensity (kWm^{-1})	242.1 (259.58)	221.2 (226.91)	288.1 (213.87)

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639 Table 3. Methane Emission Factor (EF), Combustion Completeness (MCE) and Key Fire Characteristics Emissions
640 by Fire Type by Study Period (standard deviations in parentheses) (2014-2016, Mali)
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Fire and Emissions (n)	**Head** (47)	**Back** (50)	**Early** (34)	**Middle** (45)	**Late** (18)	**Mean** (97)
Modified Combustion Efficiency (MCE) n=36	0.88 (0.19)	0.92 (0.20)	0.88 (0.18	0.92 (0.19)	NA	0.90 (0.18)
Methane Emissions Factor (EF CH_4 g/kg) n=36	4.89 (1.64)	2.92 (2.59)	3.71 (2.81)	2.86 (1.93)	NA	3.30 (2.36)
Byrams Fire Intensity (Kw/m)	366.9 (287.4)	124.8 (81.9)	242.1 (259.6)	221.2 (226.9)	288.1 (213.87)	242.1 (235.0)
Burn efficiency (%)	93.6 (8.2)	91.0 (14.0)	85.3 (12.44)	92.3 (11.42)	99.2 (1.06)	91.4 (11.7)
Combustion Completeness (%)	86.7 (10.6)	87.9 (12.1)	85.1 (12.50)	86.4 (11 .68)	92.8 (3.49)	87.3 (11.0)
Methane emissions (g/m^2)	1.635 (0.797)	0.948 (0.388)	0.981 (0.488)	1.030 (0.386)	1.102 (0.506)	1.022 (0.446)

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643 Table 4. A comparison of Methane EF values for seasonal savanna and woodland fire studies

Methane EF	Early	Mid/Late	Ratio	Mean
This study Wooded savanna	3.71	2.86	1.30	3.30 (± 1.9)
Korontzi (2005) Woodlands	3.82	2.61	1.47	3.22
Korontzi (2005) Grasslands	3.14	0.80	3.93	1.97
Andrea (2019) Savanna biome	NA	NA	NA	2.71 (± 2.2)

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