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

Paul Laris [1]; Moussa Koné[2]; Fadiala Dembélé [3]; Christine M. Rodrigue [1]; Lilian Yang [1]; Rebecca Jacobs [1]; Quincy Laris[4]

[1] Geography Department, California State University Long Beach, 1250 Bellflower Blvd. Long Beach CA 90840. USA.

[2] Institut de Géographie Tropicale (IGT), UFR-SHS, Université FHB de Cocody-Abidjan, Côte d'Ivoire.

[3] Institut Polytechnique Rural de Formation et de Recherche Appliquée de Katibougou, Mali.

[4] Department of Civil and Environmental Engineering, University of California, Berkeley.

Correspondence to Paul Laris paul.laris@csulb.edu

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

79   because early fires generally burn less completely and more patchily. Indeed, Lipsett-Moore (et al., 2018) recently

80   argued that there are "global opportunities for significant emissions reductions by simply shifting the fire period in

81   African savannas to early dry season" (1).

82   Yet, although scientists and policy makers increasingly recognize the important role these fires play in the

83   global carbon cycle, there are few accurate estimates of their emissions especially in terms of the key factors that

84   determine the type and quantity of GHG emissions. Critically, most studies of emission are global scale and use

85   average biome level EFs. EFs show large variability, however, between and within biomes due to differences in fuel

86   type and composition, burning conditions, and tree density (Andreae and Merlet, 2001; Korontzi, 2005; van

87   Leeuwen and van der Werf, 2011; Russell-Smith et al., 2021). There are few regionally specific emissions estimates

88   because accurate quantification of such emissions is difficult, being dependent upon reliable estimation of the

89   various parameters, many of which require intense fieldwork (Russell-Smith et al., 2009).

90   Nowhere is this truer than for West Africa, the continent's most active fire region. To date, measurements

91   of emissions from African savannas are limited to a few broad-scale studies, largely based in the continent's

92   southeast that rarely adequately account for changes in fuel classes, seasonality, or a host of other key factors

93   including fire type and intensity (Bonsang et al., 1995; Lacaux et al., 1995; Hoffa et al., 1999; Korontzi 2005).

94   Indeed, the most recent catalogs of EFs and fuel consumption (FC) for savannas includes a *single* data point from

95   West Africa (van Leeuwen et al., 2014; Andreae 2019). Studies from other regions find there is great variation in

96   study results (Russel-Smith 2009; van Leeuwen and van der Werf 2011); and, as Murphy et al., (2012) note, the

97   variability *between* samples collected *within* fires can be greater than the differences between fires of different

98   season. These authors were unable to draw general conclusions about seasonal variation in methane emissions and

99   EFs. Among the key issues cited were the variations in the fraction of tree-leaf litter in the fuels of different savanna

100   environments.

101   In fact, there is very little data in the literature on fine fuel mixtures (the primary fuel for savanna fires)

102   used to estimate EFs in Africa, although the amount of woody vegetation clearly affects emissions (Korontzi, 2005;

103   van Leeuwen and van der Werf, 2011). In the Brazilian cerrado, for example, Vernooij et al. (2020) found that the

104   seasonal effect on methane EF was stronger in more woody savanna vegetation with LDS fires having 20% lower

105   EF than EDS ones in shrub dominated areas.

106   Fuel moisture is also an issue; Russel-Smith et al. (2009) noted there are currently no comprehensive

107   measurements of the seasonality of emissions gas composition, yet fuel moisture is a key determinant. This is a

108   critical problem because although evidence suggests that early dry season (EDS) fires consume less biomass and

109   burn more patchily; they also tend to have a lower combustion efficiency than later fires due to their higher fuel

110   moisture levels. A lower combustion efficiency theoretically causes a higher emission factor for CH_4. Indeed, one

111   study in Africa found that the bulk of CH_4 emissions come from EDS fires (Hoffa et al., 1999) because the decrease

112   in area burned is more than offset by the increase in the CH_4 EF. Elsewhere in southern Africa, Russell-Smith et al

113   (2021) found that emission factors varied significantly by season for some vegetation types, but not others, although

114   notably that the latter study involved only "cured" grasses. We would argue that "early" fires burn *uncured* fuels by

115   definition.

116   In sum, while savannas undoubtedly harbor great theoretical potential to sequester more carbon, and emit

117   less through a change in fire regime there exists a great deal of uncertainty as to what the *actual* carbon shifts might

118   be, should regimes change. Fire regimes are themselves complex; we define them as the characteristic fire activity

119   prevailing in a region, typically determined by frequency, intensity, seasonality, size distribution, type of fire and

120   fuels consumed (Pausas and Keeley 2021). Changes in one or more of these factures can alter fire emissions. We

121   suggest the key sources of uncertainty in terms of carbon emissions arise largely from the spatiotemporal complexity

122   of savanna vegetation patterns and fire regimes combined with many unknowns or biases associated with a lack of

123   consideration of human fire setting and land management practices in these complex landscapes (Laris 2021).

124   Savannas are patch mosaic landscapes, in which vegetation and soil types vary dramatically—on the order

125   of tens of meters—across landscapes (Duvall 2011). This variation creates a seasonal-mosaic landscape in which the

126   fuel conditions (fuel moisture, fuel load and mix, and fuel stature) vary over space and time (figure 1). As the fuel

127   conditions change, people commonly set fire to different patches in accordance with grass species drying rates as

128   well as other land management concerns (e.g., crop harvests and grazing patterns). In many parts of West Africa,

129   people control the time (time of day and season), location and type of savanna, and type of fires they set. By

130   controlling these variables, human acts determine the conditions of the fuels as well as the ambient air conditions

131   and the specific fire properties. To take one simple example, a fire in wooded savanna with tall perennial grasses

132   (figure 1d) will have very different fuel moisture levels as the fire season progress (shifting high to low), different

133   percentages of leaf litter and total fine fuel biomass (shifting low to high) (figure 1f), and variable wind conditions

134   (peaking in mid-dry season). Critically, the seasonal timing of a fire not only affects the fuel moisture of grasses, but

135   also the leafy biomass, which burns green on shrubs and small trees in the early fire season, but as fallen leaf litter

136   that creates a bed of compact and less aerated fuels by late dry season. As such, the incomplete combustion of leafy

137   biomass is a function of high fuel moisture in one season, and low oxygen conditions in another, with unknown

138   implications for methane gas emissions.

139

140

141   Figure 1. Different savanna vegetation types used in fire experiments for the study areas of Tabou and Faradiele,

142   Mali. Note grass species, height and density, woody cover and leaf litter amounts vary dramatically over space and

143   time.

144

145   Human fire uses determine the pyrogeography of fire—the specific location, timing, type of fire and

146   vegetation burned—creating complex spatiotemporal patterns of fires and emissions. People tend to set fires to fine

147   annual grasses (figure 1a) as soon as they are dry, while waiting to burn perennials (which are too moist to burn in

148   the early dry season) (figure 1d) until later often igniting them in a flurry of fires at the end of the harvest in late

149   December (below). This creates a seasonal-mosaic fire regime where some patches burn early, others later and some

150   not at all. Purposeful fires are most often set as backfires in the late afternoon as temperatures, wind speeds are

151   falling, and humidity rising, which limits fire intensity (Laris et. al. 2020). Lower intensity fires tend to self-

152   extinguish at the edge of moister vegetation patches and in the evening; they have lower flame heights reducing the

153 reach of fires into leafy tree canopies (Laris et. al. 2021). Later in the fire season, fires are less likely to be

154 purposefully set and are more likely to burn as intense, uncontrolled head-fires.

155 It is clear that any effort to predict future changes in emissions or to implement policy to reduce emissions

156 requires more detailed information on how emissions vary according to the key factors noted above, many of which

157 are a function of human land management practices (see appendix). Specifically, given the spatiotemporal

158 complexity of savanna environments, whether a shift to an earlier fire regime will result in a decrease in methane

159 emissions for a given savanna must be determined empirically and proposed policies to apply generalized findings

160 from one continent to another may not achieve desired emissions reductions.

161 This study aims to fill a knowledge gap by incorporating data on human burning practices, the

162 characteristics of the fire regimes they produce, the vegetation conditions on the landscapes they burn and the

163 resulting emissions of key GHG gases. Through a novel geographic approach, we designed our experiments to

164 gather data in ways that reflect actual *on-the-ground* burning practices of people living in working landscapes at two

165 mesic savanna sites in Mali, West Africa. By "working landscapes," we mean savanna lands that are occupied and

166 worked by people as opposed to areas managed as reserves (e.g., Charnley et al., 2014); the latter are most often

167 used in fire research. The biomass (fuels) in working landscapes are a function of land use practices including

168 rotational agriculture, annual burning, and animal grazing and can differ significantly from those found on non-

169 working lands (Figures 1d and 1e), which can affect fire intensity, combustion completeness and combustion

170 efficiency with implications for gas emissions. The burning regimes studied, which are determined by such factors

171 as seasonality, time of day, (ambient weather), fire type (with or counter to the wind), grass type and woody

172 vegetation cover, were selected to reflect *local practices* and based on over a decade of field and remotely sensing

173 research.

174 To determine the factors that influence fire emissions of methane gas from anthropogenic fires we

175 conducted experimental fires using a field-based method to measure key factors. We collected canister samples of

176 smoke emissions for 36 fires during the early and middle seasons, which we report on here. We also collected data

177 for savanna type, grass type, biomass composition and amount consumed; scorch height, speed of fire front, fire type

178 and ambient air conditions for two mesic savanna sites in Mali.

179

180 **2 Study Area and Methods**

181 We based our research in two working landscapes located in the southern Sudanian savanna of southern

182 Mali (Fig. 2). We chose areas with annual precipitation over 900 mm because they burn frequently and are typical of

183 this broad mesic savanna belt in West Africa. The climate is divided into two seasons: a wet period from

184 approximately June through October and a dry season from November through May. We also recognize cool dry

185 period from approximately November through February and a hot dry period from March through May. This

186 distinction is important because the Harmattan wind, which is dry and desiccates vegetation while creating unique

187 fire weather, dominates in the cool season. The mean annual rainfall is 991 mm for Tabou and 1,177 mm for

188 Faradiélé (based on data from the nearby urban centers of Bamako (latitude: 12.64°, longitude: −8.00°) and

189 Bougouni (latitude: 11.42°, longitude: −7.47°) for each study area respectively) (Henry, 2011). The fire season

190 follows the rains and typically runs from November through April. The regime follows a regular annual
191 spatiotemporal pattern with the majority of fires occurring in late December and early January (Laris et al., 2016).
192
193
194 Figure 2. Study areas in southern Mali (figure by S. Winslow).
195
196
197   The vegetation is southern Sudanian savanna and is predominantly composed of a mixture of grasses, trees,
198 and shrubs in a complex mosaic. The landscape heterogeneity is a function of topography, underlying soil and
199 hydrology, as well agricultural uses, the combinations of which produces unique patterns of land cover (Duvall,
200 2011; Laris, 2011). Ferricrete outcrops on hard pan cover considerable areas. Soil in these areas generally has high
201 gravel content and is very shallow, creating xeric conditions. Vegetation is dominated by short, annual grasses
202 (principally *Loudetia togoensis* but also *Andropogon pseudapricus*) and usually have few widely scattered trees.
203 They form up to 25 percent of the savanna in southern Mali. Except for the intensively cultivated areas, a near-
204 continuous layer of tall (over 1 m in height) perennial grasses (principally *Andropogon gayanus*, *Hyparrhenia*
205 *dissolute*, *Cymbopogon giganteus*, and *Schizachyrium pulchellum*) covers the more fertile soils, although there are
206 pockets where the tree canopy is closed and there is little grass cover. The land cover in settled areas has been
207 significantly modified. Perennial grasses are less common (except on long-fallow plots), and large portions of the
208 landscape are covered by annual grasses, particularly *Andropogon pseudapricus* and *Pennisetum pedicellatum* with
209 scattered trees.
210
211 **2.1 Data Collection**
212   We studied 36 experimental fires. Data on the following variables were collected in the field for each fire:
213 average plot biomass, grass proportion of biomass, grass species, biomass consumed, fuel moisture, wind speed,
214 scorch height, ambient humidity, temperature, fire type, time of day, fire duration, burn patchiness and fire season.
215 Vegetation characteristics including grass type (annual or perennial), grass species, and leaf height were also
216 recorded for each site. Fuel load (plot biomass) was measured in each of the experimental plots by delineating three
217 representative pre-fire quadrats of 1 x 1 m. Grasses were cut at the base using a scythe and weighed with an
218 electronic balance to determine the average. When present, we weighed leaf litter separately. Sixteen of the 36 fires
219 were set in the EDS and 20 in the MDS. As the purpose of the study was to replicate local burning practices, the
220 majority of these fires were set as backfires (25) with head-fires (11) set for the purpose of comparison.
221   Most grasses burned were fully cured; however, for those that were not, we cut a sample and
222 weighed wet, then dried and reweighed to determine the cure rate, which was taken as the average for the
223 plot. Fuel moisture content for the cured fuels was calculated using the method developed by Viney (1991)
224 based on McArthur (1967) for savanna fuels:

225

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

227

228 where H is relative humidity and T is ambient temperature at the time of the burn. We calculated dry biomass

229 weight by subtracting the fuel moisture content from the wet biomass weight and the amount of fuel consumed

230 was by subtracting the average ash and unburned fuels remaining in three quadrats per plot from the pre-fire dry

231 biomass weight.

232   We used a Kestrel 5500 Weather Meter station (KestrelMeters.com, Boothwyn, Pennsylvania, USA) to

233 collect wind speed, ambient humidity, and temperature during the burning of each plot. We recorded values every

234 five seconds and averaged them for each burn. The weather station was placed up wind and near each

235 experimental plot 2 m off the ground in an open area. We recorded wind speed relative to the direction of each

236 fire.

237

238 **2.2 Plot design**

239   We selected plots to represent an array of savanna vegetation types dominated by different amounts of

240 woody cover and grass species. To aid in the selection of the burn plots, we used a long-term fire database to select

241 sites with known fire seasonality—fires known to burn during the early, mid, or late fire season on an annual basis

242 (Laris, 2011). We divided the sites into plots of 10 x10 meters and applied fire treatments of head and back burns.

243 Fire timing was set according to the historical pattern of burning with early fires set in November through

244 December, middle fires in January, and late fires in late-February and March (Laris et al., 2016). We conducted

245 multiple burns per site to account for plot level heterogeneity. Plots at each site were located in close proximity with

246 attention paid to maintaining consistency in grass type and woody cover. Head and backfire plots were located

247 directly adjacent.

248   We noted ignition time and each fire was timed until the flaming front reached the end of the 10 meter

249 plot. We set the majority of fires in late afternoon, which is in accordance with local practice, although we set

250 some fires earlier for comparative purposes. Post-fire ash and any unburned material were weighed for areas of

251 similar composition to the 1 m x 1 m pre-fire quadrats to determine the amount of biomass consumed. Scorch

252 height was averaged for each plot by measuring the height of scorch marks on several small trees. Burn

253 patchiness—the percentage of the plot affected by fire—was estimated by two observers.

254   There are several key limitations of this study. First, the number of gas samples is relatively small due to

255 the high price of shipping gas samples (we collected only 36 emissions samples for a total of 97 experimental burns

256 and no samples were from the LDS). The majority of the samples were for backfires to replicate local practices with

257 head-fire samples taken for comparative purposes. We only sampled each fire once and thus caution against

258 assuming a single sample represents the typical emissions for the entire fire (see Murphy et al., 2012 above), but we

259 do think the mean values for the data we collected provide a useful sample of typical West African fire emissions. In

260 addition, we burned different savanna vegetation types (with different grasses and woody vegetation amounts) at

261 different times of the fire season in accordance with local practices; as such, we do not have systematic results for

262 burning all grass types for all fire seasons (e.g., few perennials grasses burn in the EDS).

263

264 **2.3 Field data analysis**

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

266

267 (1) $I = Hwr$

268

269   where I is Byram's fireline intensity (kW/m), H is the net low heat of combustion (kJ/kg), w is the

270 fuel consumed in the active flaming front (kg/m^2), and r is the linear rate of fire spread (m/sec^1). The net

271 low heat of combustion (H) was selected following Williams et al. (1998) with 20,000 kJ/kg as an

272 appropriate value for savanna fires.[1] The amount of fuel consumed was calculated by subtracting the

273 average ash and unburned material remaining in three quadrats per plot from the pre-fire measurement of

274 dry biomass. Variable r was derived from the time it took for the base of the first flaming front to reach the

275 end of the 10 m plot. We calculated fire-line intensity for all samples possessing all the variables for

276 analysis. Finally, combustion completeness was calculated by dividing the biomass consumed by the pre-

277 fire biomass.

278

279 **2.4 Gas emissions sampling and analysis**

280   We collected samples of smoke from a sample of 36 of our experimental fires for early and mid-season

281 along with background air samples for each different site prior to burning. (The high cost of shipping canisters

282 prohibited collecting data for the late-season using this method). Samples were collected in stainless steel vacuum

283 canisters by mounting the canister on a pole and holding the canister with open flow-restricting valve about 40

284 centimeters above the flame. We sampled all fires a single time once the flaming front had developed

285 (approximately two-thirds of the way through the burn plot). Once filled, the canisters were shipped directly back to

286 California for analysis at the laboratory of the Department of Chemistry at the University of California at Irvine.

287 Mass Spectrometer (MS), thermal conductivity and flame ionization after separation by gas chromatography were

288 used to detect, inventory and measure the quantities of the different species of gas contained in the samples

289 (Katzenstein et al., 2003; Kone et al 2020).

290

291   We calculated EF as:

292

293 (3) $EF_x = F_c 1000 \dfrac{MM_x}{MM_{carbon}} \dfrac{C_x}{C_T}$

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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."

294

295 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

296 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

297 for purposes of comparison (Ward et al., 1996) although Lacaux et al., (1995) found a value of 0.425 for West

298 Africa). MM is the molecular mass of species x (g), and 1000 g/kg is a conversion factor. MM_{carbon} is the molecular

299 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

300 the total number of moles of carbon, calculated as:

301

302
303 (4) $$\frac{C_x}{C_T} = \frac{ER_{x/CO_2}}{\sum\limits_{j=1}^{n} (NC_j ER_{j/CO_2})}$$
304

305 Where ER_{x/CO_2} is the emissions ratio of species x to CO_2, NC_j is the number of carbon atoms in compound j and the

306 sum is over all carbonaceous species (approximated as CO_2, CO and CH_4 for this study).

307

308 The general equation used to quantify the gas species emitted from vegetation fires is the basic biomass

309 burning emissions model of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2003: 49; IPCC 2006:

310 A2.13):

311

312 (5)

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

313

314 Here, Emission is the gas or aerosol flux in tons (t); Area is the total area burnt in hectares (ha); Fuel load is the

315 amount of burnt biomass in tons per hectares (tons/ha); Combustion completeness is the fraction of fuel affected by

316 fire that was pyrolysed in percent (%); Emission factor of a gas is the amount of this gas generated when one kilogram

317 of fuel is burnt. We have revised the formula to include seasonally specific values for area, fuel load, combustion

318 completeness and emission factor and add the variable burn patchiness (BP) which is the fraction of the surface area

319 affected by the fire.

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

321
322 (6) $\text{Emission}_s \text{ (tons)} = \text{BA}_s(ha) * FL_s(tons/ha) * CC_s(\%) * EF_{xs} * BP_s(\%)$
323
324 Here, BA is burned area, FL is fuel load, CC is combustion completeness, EF_x is emission factor of species x. We

325 propose using *seasonal* values for these key factors because these variables vary significantly by season as a

326 function of ambient weather as well as fuel moisture and fuel type (fraction of leaf litter or shrubs) and fuel

327 conditions. We have added BP_s because patchiness varies by season (as well as fuel) and because most estimates of

328 burned area are based on satellite image analysis, which is too coarse to determine the actual surface area burned

329 due to burn patchiness (the actual area burned is thus BP * BA) (Russell-Smith et al 2009). Note that even medium

330   resolution burned area estimates using Landsat contains errors in the percent area burned due to the fragmented

331   patterns fires create across a heterogeneous savanna landscape. We did not determine total BA for this work, but

332   have done so previously using Landsat data covering the study area (Laris 2011). As such, we present our results in

333   terms of emissions per meter-squared according to season of the burn.

334   Complete combustion of vegetation results in release of carbon in the form of CO_2 while incomplete

335   combustion leads to the emission of CO, CH_4 and a large variety of organic compounds (Koppmann et al. 2005).

336   Because many of the factors that control EFs also regulate combustion efficiency, determining the latter is a useful

337   proxy for predicting how individual emission factors will vary under different fire conditions. Modified combustion

338   efficiency (MCE)—the ratio of CO_2 to $CO + CO_2$—is frequently used to estimate combustion completeness as

339   values for MCE are related to different phases in the combustion process. In general, when the MCE exceeds 90% a

340   fire is flaming and combustion temperatures are high. When MCE is less than 85% combustion is smoldering. A

341   savanna fire is typically characterized by a flaming front moving across the landscape leaving smoldering material.

342   As such, the smoke emitted from savanna fires is typically a product of both flaming and smoldering on different

343   fragments of fuel.

344   Bivariate statistical analyses were performed to test the significance of the difference of means (t-tests) in

345   CH_4EF by season (EDS and MDS) and by fire direction (head-fires and backfires) and in MCE by season and fire

346   direction. F-tests established the similarity of variances, all t-tests were done with pooled estimates of variance.

347   These were done in the OpenOffice Calc spreadsheet (Apache Software Foundation 2021) and PAleontological

348   STatistics (Hammer et al. 2001), with effect sizes (Cohen's d) and *post-hoc* power calculated in G*Power (Faul et al.

349   2009). We used bivariate regression analysis to look for correlations between the two dependent variables—

350   methane EF and density—and independent variables—Byram's fire intensity, proportion of grass biomass (to

351   woody biomass), total fuel moisture, and Viney fuel moisture (a function of ambient temperature and humidity).

352   These were done in Calc and power was estimated in G*Power.

353

354   **3 Results**

355   **3.1 Plot Characteristics**

356   The mean plot characteristics for biomass and weather conditions demonstrate the importance of the inclusion

357   of the mid-season in this study (Table 1) (see Laris et al., 2021 for late dry season values). Average temperature

358   generally increases over the course of the dry season, but dips by 0.4°C in mid-season, which is an established

359   phenomenon in West African climates. Average humidity decreases as the dry season progresses, but the mid-season

360   humidity is considerably more variable than in the early season. Calculated fuel moisture content based on Viney

361   declines over the course of the dry season, but when combined with the measured mean cure rates for moist grasses,

362   the total fuel moisture means rose from 10.8% in the EDS to 15.1% in the MDS with high variability. Mean wind

363   speed peaks mid-season during the Harmattan, although the wind speeds are relatively low—classified as a light breeze

364   on the Beaufort scale. The percent grass of the total plot biomass is greatest in the early season, while the total biomass

365   (total fine fuels—grasses and leaves) is higher in mid-season, reflecting an increase in leaf litter as the dry season

366   progresses. The increase in dry biomass also reflects the changes in species types burned—the taller perennials often

367 burn later in the dry season. Some perennials are too moist to burn during the early months of the dry season and burn

368 less completely in the mid-season due to higher moisture content.

369

370 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)

371

372 **3.2 Fire Characteristics**

373   The characteristics of the fires also vary by season (Table 2). The mean BP increased as the dry season

374 progressed from 77.4% in the EDS to 92.3 in the MDS as expected due to the gradual desiccation of the biomass and

375 slight rise in wind speed. CC also increased from early to mid-season (81.3% to 86.2%). These variables showed

376 great variability in both seasons. Spread rate and intensity increased from early to mid-season with high variation in

377 intensity values reflecting the wide variety of fuel, weather and fire conditions. The data also show that fire type has

378 a large influence on fire intensity as expected; head fire mean intensity was much greater than that for backfires

379 (242.4 kW/m to 100.0). In addition, we found a large variation in the fire-line intensity values especially for head

380 fires.

381

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-β=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$_4$EF 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-β=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-β=0.64), fire intensity (Byram's) was a significant driver of CH$_4$EF (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-β=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-β=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).

443

444   Our results compare favorably with the biome averages from Andreae (2019). Andreae's savanna biome

445   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

446   (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

447   (42.5% based on Lacaux et al 1995 as opposed to 50% used for comparative purposes), then our Methane EF

448   (adjusted) values (2.95g/kg) are quite close to the biome means. It is not surprising that our values had a lower MCE

449   and higher CH_4EF than the biome means because we based our values on emissions from "wooded mesic savannas"

450   as opposed to the "grassland" values used in most savanna biome estimates. Wooded savannas contain small trees,

451   shrubs and leaf litter, which tend to reduce MCE and increase methane EF values (e.g., Vernooij et al., 2020) due to

452   the fraction of ligneous fuel in the mix.

453

454   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 ($\pm$ 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 ($\pm$ 2.2)

455

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

458

459   Our results compare favorably for seasonal changes in methane EFs found by Korontzi's for East African

460   woodland-savanna. Importantly, our data is more in line with Kornontzi's values for "woodlands" (Miombo) than

461   for "grassland" (Damba) savannas (Table 3). We attribute this to the fact that both areas have mesic rainfall regimes

462   and high tree and shrub cover. As noted, we found the percent grass of the total plot biomass is greatest in the EDS,

463   while the total biomass is higher in the MDS reflecting a tripling of leaf litter biomass.

464   Kornontzi (2005) argued that because EDS fires have a much lower CC—near zero in the early EDS to

465   80% by LDS—that total emissions from EDS fires would be less than those for LDS ones. This in spite the fact that

466   they found EDS fires have higher methane EFs by a factor of 1.47 for woodlands and 3.93 for grasslands (compared

467   with our ratio of 1.20). They also found that fuel load increased by about twenty percent from EDS to LDS with a

468   big increase in MDS (we found a smaller increase). Finally, they found that methane EFs were at their peak in MDS

469 as opposed to LDS. As a result, Korontzi concludes that for SE Africa, early fires produce lower methane emissions

470 than either mid or late season fires in contrast to our results. Korontzi found the regional average CH_4 emission

471 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

472 increases by season—less than 5%, which was insignificant. The larger range in emission density values estimated

473 by Korontzi derive largely from the higher range of CC used in their model. Korontzi (2005) also notes that the

474 lower emission densities for CH_4 in the EDS were mainly a result of the larger effect of the increased fuel moisture

475 content on lowering CC compared with its effect on MCE. They note this was opposite of what they found for their

476 grassland fires indicating that the amount of woody vegetation is a critical determinant of CH_4EF.

477   It is important to note that Korontzi's values for early season CC were derived using a model and based on

478 fuel moisture levels alone, not experimental data. We argue that, practically speaking, people do not set fires when

479 grasses are too moist to carry fire in West Africa. As such, we argue that using CC values less than 50%, while

480 theoretically useful, are not at all practical because people are unlikely to set such fires as they would not achieve the

481 desired goals of burning (Laris 2005, 2011). Indeed, it is probable that a fire, which burns less than 50% of biomass,

482 *will burn a second time* late in the season because a fire consuming such a small fraction will not break fuel

483 connectivity. It is also important to note that braking fuel connectivity is a key reason for setting early fires and a

484 critical reason that mosaic fire regime burns less total area (Laris et al., 2018). As such, although theoretically

485 possible, we do not agree that using such low CC values is reasonable for determining emissions from fires in actual

486 African landscapes. Indeed, we have rarely seen burned landscapes with more than 50% of the biomass standing

487 post fire.

488   By comparison, Russell-Smith et al (2021) found that emission factors varied by season for Dambo

489 grasslands but not for savanna woodlands (Table 3). They found that Dambo grasses burned in the EDS had a

490 methane EF of over four times that of those burned in LDS (nearly identical with results from Korontzi).

491 Contrastingly, they found little difference by season in methane EF, for dry wooded savannas and a surprisingly

492 higher EF in late season for more wooded savannas, which contrasts with our findings and those of Korontzi (2005)

493 for wooded savannas. We must note, however, that the date chosen for Russell-Smith's EDS is more comparable

494 with the MDS date used in our study—both dates represent the "middle" of the dry season. Indeed, as Russell-Smith

495 et al. note, trees in wooded savanna had already begun dropping leaves and grasses were fully cured at the time of

496 their "EDS" fires—characteristics we would not associate with early burning in West Africa. As such, we would

497 argue that Russell-Smith et al. (2021) provides good evidence that MDS (not EDS) fires produce lower methane

498 emissions than LDS fires in Africa.

499   Unfortunately, there is no recognized standard for what distinguishes early from middle or late dry season

500 in the savanna literature—a problem hampering fire science. Elsewhere we have argued that the dichotomous

501 (EDS/LDS) view of savanna burning is problematic because the point at which the fire season shifts from early to

502 late has not been adequately defined and varies by context (Laris et. al., 2017; Laris 2021). We note that although

503 adding a third, middle season, is potentially useful for research on gas emissions, the fundamental problem of

504 typology remains. While the EDS clearly begins when the rains end, there are no recognized standards for

505 determining when the MDS or LDS begins. While fuel moisture level hold some promise for developing a typology,

506   the patchy heterogeneous nature of savannas means that some patches could burn "early" (higher fuel moisture) and

507   some "late" (lower fuel moisture) in the same fire. Other factors must be considered as well, the clearest of which is

508   leaf fall. We suggest the onset of leaf fall is a reasonable marker for a division between EDS and MDS. Weather

509   conditions also play a critical role and these differ by region. For example, in West Africa winds peak in MDS but

510   they are stronger in the LDS in southern Africa (Russell-Smith et al. 2021).

511

512   In our previous research involving a large sample of 97 experimental fires, we found that fires set in the

513   MDS (the peak moment in local burning) differed from those set in the EDS or LDS (the seasons used in most fire

514   studies) in key ways (Laris et al., 2020). In our larger study we found that when fires are set in accordance with local

515   practices, MDS fires had the lowest fire intensity and scorch heights while CC increased only slightly from early to

516   mid-season with a larger jump in late season. Mean values for BP gradually increased from early to middle to late

517   season due to the drying of the biomass. Fuel moisture was also slightly higher in the MDS than EDS (due to the

518   burning of more perennials) before dropping dramatically in the LDS. Fuel loads increased in the MDS largely due

519   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

520   decrease in the amount of green leaves burned on trees. In sum, we conclude that seasonal distinctions can be useful

521   if clearly defined, but they should be limited to specific savannas and not used for comparative purposes between

522   regions for the purposes of determining the effects of fire on emissions.

523   When comparing our results for EDS and MDS fires, we find evidence for an emissions trade-off. That is,

524   while EDS fires have a lower BP than MDS fires as well as lower CC the lower amount of biomass burned by EDS

525   fires is offset by the higher methane EF resulting in statistically insignificant differences in methane emission

526   densities by season.[2] We must reiterate, however, that an unknown quantity of standing leaves are combusted during

527   fires (especially the EDS when leaves remain on trees), meaning the fuel loads we measured for the EDS are an

528   underestimation of the leafy fuels consumed. Small trees often dominate mesic savanna woodlands, such as those in

529   West Africa. These so-called "Gulliver" trees are often less than 2-meters tall because they repeatedly burned back

530   to the rootstock by annual fires (Laris and Dembele 2012). We argue that burning of small trees contributes

531   significantly to methane release. As such, we cannot support the policy suggestion put forth by Lipsett-Moore

532   (2018) who promote increased early burning in African savannas to reduce methane emissions. While it is

533   theoretically possible that very early fires would burn a lower fraction of the landscape than we have observed, we

534   argue that such a policy is just as likely to cause an *increase* in methane emissions due to higher methane EF of

535   earlier burning, which may be a function of green leaf combustion (see Korontzi 2005). It is also important to note

536   that higher intensity head fires would be required to increase the burned area of moist perennial grasses in the EDS[3]

537   and because head-fires have a methane EF nearly double that of backfires, burning with head fires would likely

---

[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.

538 counter any advantage of burning early to reduce emissions. In addition, local inhabitants would be very reluctant to

539 set such fires due to the increased risk that setting head fires could damage field crops, which remain unharvested in

540 the EDS.

541   Surprisingly, there are but a few studies of African savanna emission factors for which head and backfire

542 data are available. Wooster et al., (2011) found mean EF methane for head fires to be higher than the backfire mean

543 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

544 MCE and EF methane are function of fire type. Keene et al. (2006) used laboratory fires of fuels from SE Africa and

545 found that the type of fire (backing, heading, or mixed) as well as fuel moisture influenced MCE. The lowest MCE

546 values they recorded were all for heading fires with relatively low moisture content while MCE fell and EF methane

547 rose as fuel moisture increased. Similarly, Surawski et al., (2015) found that heading fires exhibited the lowest MCE

548 and higher methane EF.

549   While the primary purpose of this study was to determine realistic values for methane emissions for a

550 representative working savanna in West Africa, the findings can inform broader-scale modeling efforts for savanna

551 fire burning (Hanston et al 2016) in three ways. First, we do not recommend making crude assumptions about the

552 effects of fire season on methane emissions as these will vary by savanna. Second, there is a need to map fires

553 according to type because head-fires cause higher methane emissions for the two reasons noted above. Third,

554 modelers need to make distinctions between savanna types, because there are large differences between emissions

555 from grass-dominated and wooded savanna landscapes as both theory and empirical results suggest. In sum,

556 modelers should focus on developing methods to determine the direction (type) of fire remotely in addition to other

557 key factors such as fire intensity, fuel moisture, savanna woody cover (especially small trees), and burn severity.

558

559 **5 Conclusions**

560   This study finds that when fires are set in working landscapes in accordance with well-documented burning

561 practices of West African people, methane EFs decreased from early dry season to mid-dry season (although the

562 results were not significant). We also found that methane emission density increased only marginally from EDS to

563 the MDS a difference that was not significant. We found that fire type had a much greater effect on methane

564 emissions than fire season with head-fires having significantly higher methane EF compared to backfires and

565 significantly higher methane densities due to higher fire intensity. We note that we are unaware of any estimates for

566 area burned according to fire type for any of the world's savannas.

567   It is important to reiterate that several key findings of this study arise from documented burning practices of

568 people living in working landscapes. People set fires in West Africa later in the day resulting in fires with lower

569 intensity due to lower wind and air temperature, and higher humidity; and people set predominantly backfires all of

570 which contribute to lower intensity burning, which results on lower methane emissions. In addition, we note that the

571 fuel loads we recorded are nearly 50% lower on working savanna lands compared to reserve lands used in some

572 other studies (Laris et al. 2020). Finally, the number of fires peaks in the West African region in the MDS and

573 although the methane emissions density values for the EDS were slightly lower than for the MDS, a significant

574   reason for this was the increased fuel load from leaf litter in the MDS. We should note that EDS fires tend to burn

575   more green leaves on trees, which are not accounted for in this study.

576   In conclusion, our study finds that several factors influence the emissions from savanna fires including the

577   fire season, fuel load and type, and, most importantly, fire type. Each of these factors are a function of human land

578   and fire management practices. We also conclude there is an emissions trade-off in setting fires earlier and, as such,

579   a policy to increase the amount of early burning in West African would be very difficult to implement because much

580   burning is already "early" and because earlier burning of uncured grasses and green leaves would likely result in

581   higher methane EFs. Moreover, any policy aimed at increasing the amount of early burning would likely require

582   setting head fires, which would decrease burn patchiness and increase combustion completeness further negating the

583   effects of any reduction in burned area while also causing an undesired increase in uncontrolled fires.

584

585 **Appendix**

586 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 CH₄ 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.

587

588

589

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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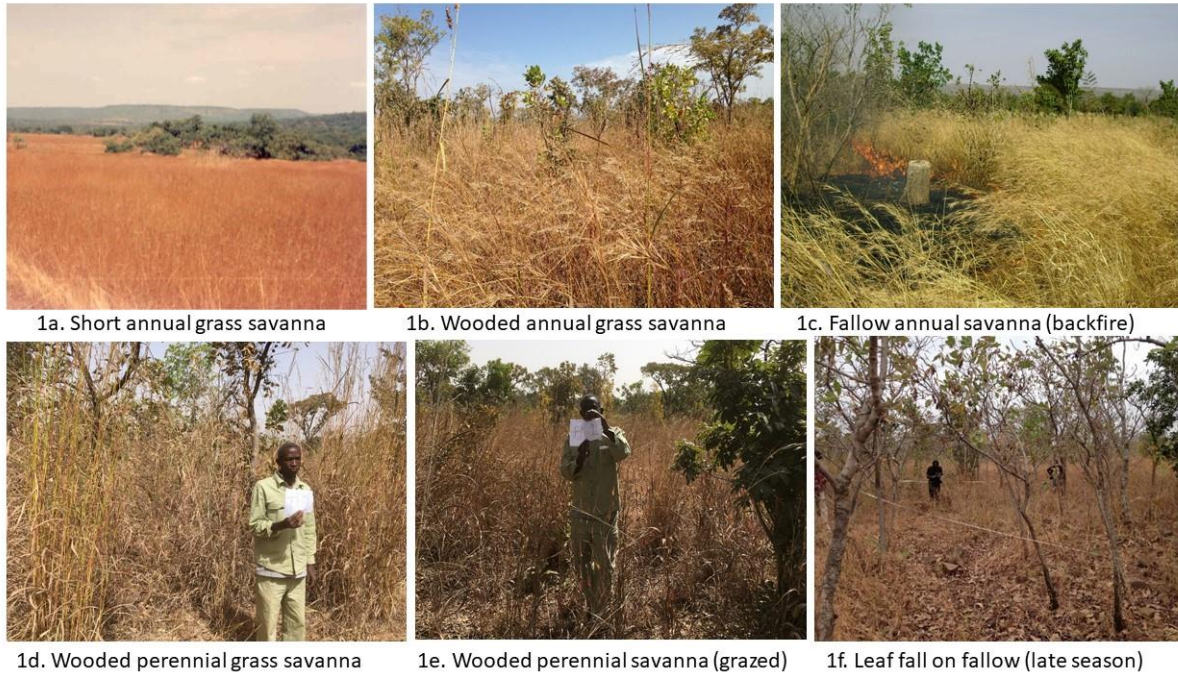
794 **Figures and Tables**

795

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)

796

797 Figure 1. Different savanna vegetation types used in fire experiments for the study areas of Tabou and Faradiele,

798 Mali. Note grass species, height and density, woody cover and leaf litter amounts vary dramatically over space and

799 time.

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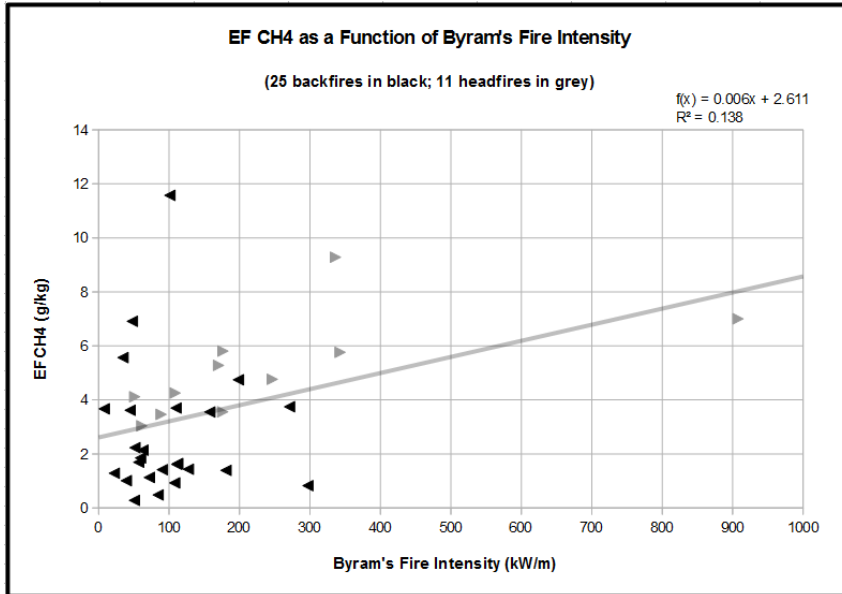
803 Figure 2. Study areas in southern Mali (figure by S. Winslow).

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

808 Mali)

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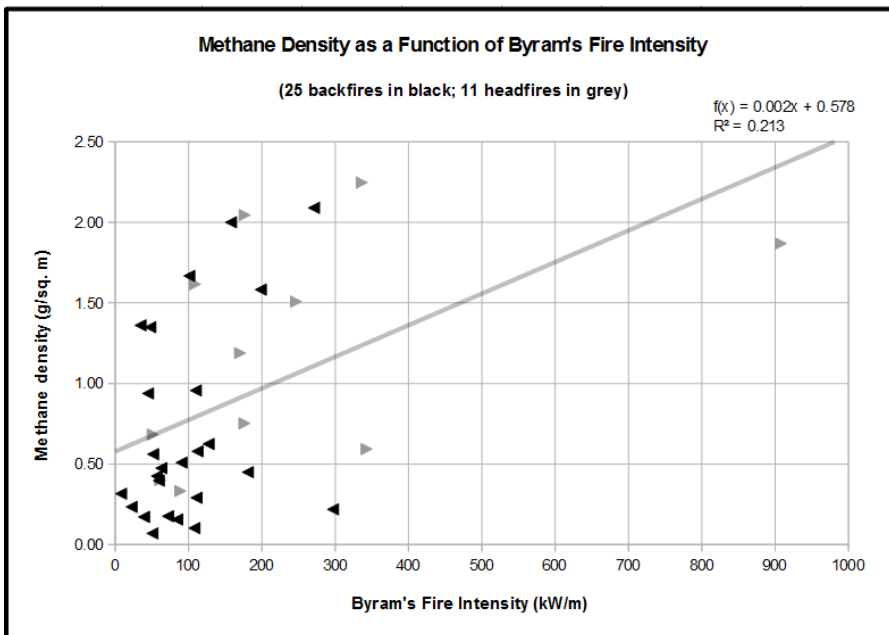
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811 Figure 4. Methane density as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-2016,

812 Mali)

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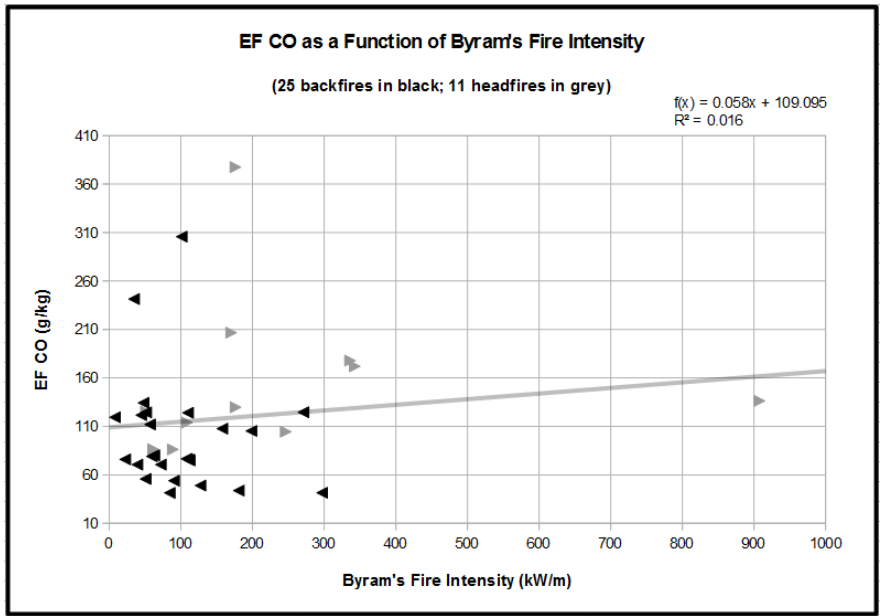
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816   Figure 5. Carbon Monoxide EF as a function of Byram's fire intensity for all fires. Arrows indicate fire type (2014-

817   2016, Mali)

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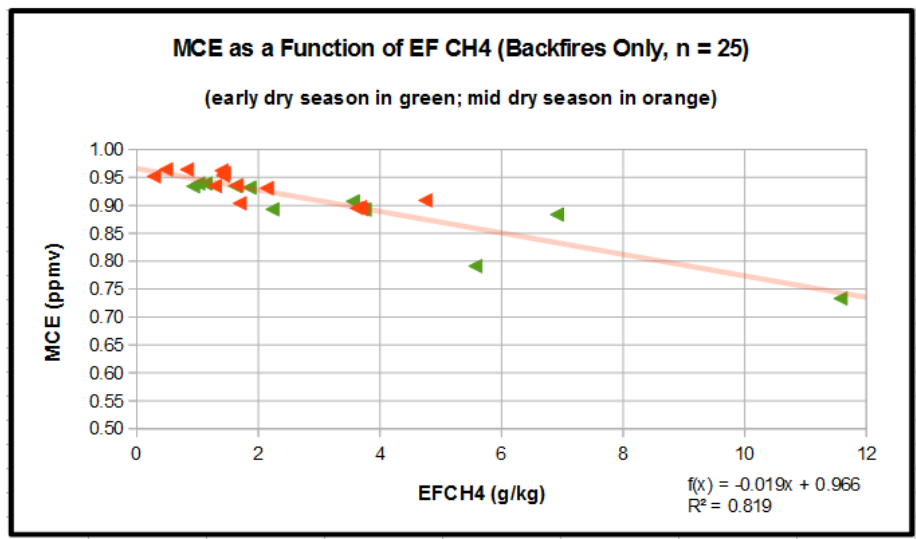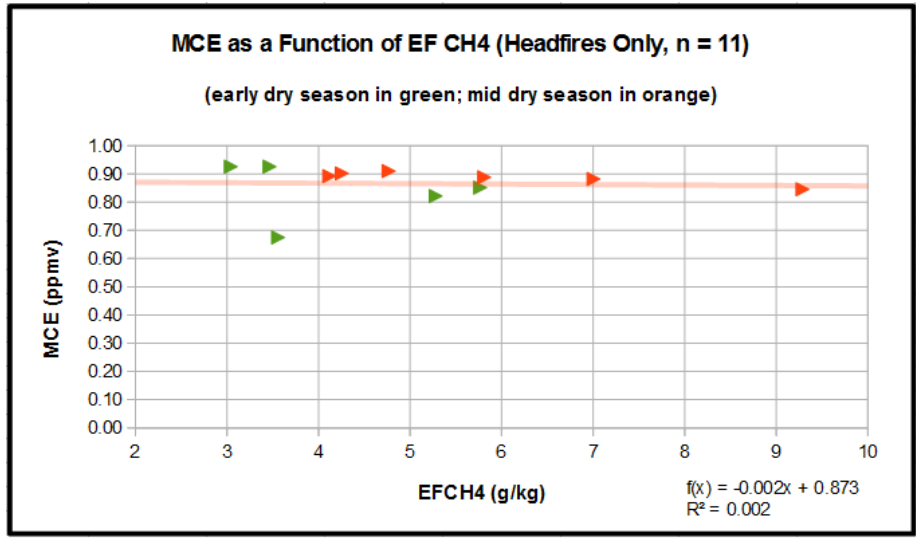
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820   Figure 6. MCE as a function EF CH$_4$ for head- (a) and back- (b) fires. Green fires are EDS and orange are MDS.

821   Arrows indicate fire type (2014-2016, Mali)

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824

825 Figure 7. A head-fire extending from a bed of dry grasses into the green leaves in the tree canopy, Tabou Village,

826 Mali (Photo by P. Laris).