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Greenhouse gas emission from prescribed fires is influenced by vegetation types in West African Savannas

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Greenhouse gas (GHG) emissions from prescribed fires are poorly investigated, resulting in a high uncertainty in GHG budgets. Using, a carbon mass balance approach and experimental prescribed fires in 80 plots, this study assessed carbon emissions and established emission factors (EFs) for carbon dioxides (CO_2), carbon monoxide (CO), and methane (CH_4) across climate zones and vegetation types. In grass and shrub savannas, fires could burn intensely due to the lower moisture content and continuous spatial distribution of biomass fuel, causing greater carbon emissions with 1.61 ± 0.13 t C ha^{-1} and 1.01 ± 0.13 t C ha^{-1}, respectively. Despite their low carbon emissions, tree savannas (1658.17 ± 11.13 g kg^{-1}) and woodlands (1629.94 ± 12.23 g kg^{-1}) have the highest EFs, which can be attribute to the high carbon content of biomass fuel in these vegetation types. Vegetation types and their interaction with climate zones have a substantial impact on carbon emissions and carbon species EFs, and should therefore be considered in assessing GHG emissions from fires. The findings from this study provide a useful basis for improving the national measurement, reporting, and verification of GHG emissions and for improving the measurement of the global balance of GHG emissions from fires.

Keywords Vegetation types, Climate zones, Prescribed fires, Carbon emissions, Emission factors

In Africa, fires from terrestrial ecosystems including wildfires, deforestation-related fires, fires from burning of agricultural residues, and fires for energy[1] are important sources of GHG emissions. Such fires contribute approximately 62% of the global fire carbon emissions[2] with 4.92 $PgCO_2$ per year[3]. Reducing GHG emissions through fire management has become a major challenge for many regions across the continent. Studies in West Africa that sought to identify ecological factors that influence fire-related GHG emissions found that vegetation types and seasonality play a crucial role in fire emissions[4–7]. Activity data (AD) and emission factors (EFs) were also developed to assess the potential of GHG emissions from fires. These two parameters are commonly used to model GHG emissions from fire, understand their impact on climate change[8], and develop emission control and mitigation strategies[9]. In West Africa, the burnable biomass fuel in savanna ecosystems is estimated to be around 5 t ha^{-1}, with CO_2 EFs varying between 1465.55 g kg^{-1} and 1716.51 g kg depending on land use and vegetation types[6,10,11]. While these estimates are derived from wildfires and/or simulation of wildfires studies[12–14], there is little information on GHG emissions in relation to prescribed fires, which are management fires, generally carried out in the early stages of the dry seasons to minimize the severity of the effects of wildfires on ecosystems. In addition, the effect of climatic conditions on fire behaviors is poorly investigated in the region because previous works were mostly local site-related.

Prescribed fires have emerged as a crucial management tool in the conservation and sustainable management of savanna ecosystems across Sub-Saharan Africa[15]. These controlled burnings play a pivotal role in achieving political land management objectives[16]. They serve as a proactive measure for mitigating the potentially

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devastating impacts of uncontrolled wildfires[17] while also achieving a significant reduction in GHG emissions caused during the dry season[3,18]. Beyond this immediate utility, prescribed fires also offer multiple ecological benefits, such as breaking seed dormancy in certain seeds and, facilitating germination[19]. However, the need to examine the dynamics of GHG emissions associated with prescribed fires is growing due to the ongoing climate change[20,21]. A comprehensive understanding is needed not only of the ecological consequences but also of the climate implications of prescribed fires.

The main greenhouse gases emitted from biomass burning are carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4)[22,23]. Among these gases, CO_2 is the major gas produced from plant respiration, decomposition, and rapid oxidation during fires[22]. Some studies assert that during the growing season, and following fire occurrences, CO_2 gets re-captured by long-lived, woody plants, thus making a compensatory effect on the CO_2 balance in ecosystems managed by the use of prescribed fires[24,25]. However, new woody vegetation covering burned areas may take several decades to assimilate the CO_2 released during forest fires[26]. Also, the recurrence of fires in conjunction with climate change may limit the ability of ecosystems to recover from fires, resulting in net positive CO_2 emission[27]. Furthermore, fires contribute to the production and storage of pyrogenic carbon (PyC), which comes from the incomplete combustion of biomass[28]. Pyrogenic carbon is more resistant to biological and chemical degradation in the soils and sediments than in the original biomass[29].

Existing EFs from fires are derived from field measurements[26,30], laboratory fire experiments,[31,32] and remote sensing using automatic sensors[6,7]. Although laboratory assessment with the use of chambers enables the determination of emission factors for carbon gas species, they occur in environmental conditions that are different from those of open-field burning, which can lead to biases in emission factor assessments. Regarding EFs from remote sensing, many authors have recommended additional data from local field experiments for more accurate estimation[6,9]. Assessing emissions under natural field conditions in open vegetation is therefore highly useful, but it is challenging to carry out due to the dangerous nature of fires and their unpredictable behavior[33].

The carbon mass balance approach is the most widely used method to assess carbon emissions and gas species emission factors from biomass burning[34,35]. For that, field measurements that estimate the amount of carbon contained in the above-ground biomass fuel is needed[36]. Two main characteristics are associated with biomass fuel that vary in opposite directions along a climate gradient in drylands. These are : (1) fuel load, which decreases with increasing climatic aridity, and (2) fuel flammability, which increases with increasing climate aridity, owing to decreasing moisture content of the biomass[37]. The composition of fuel biomass is a major factor influencing GHG emissions, as it varies considerably across climate conditions and geographic regions[38]. Fuel biomass includes fine and large fuel particles from both ' living and dead parts of plant species. Specific characteristics and carbon contents of biomass fuel particles affect fire regimes and carbon emissions[39]. The composition or predominance of biomass particle types are determined by vegetation characteristics and ecological conditions. For example, in grass savanna, grassy particules are the dominant component of the biomass, while in woodland, leaves in twigs are the dominant components of burnable biomass. The difference in biomass composition makes vegetation types a key parameter that affects carbon emissions and derived emission factors during fires[33].

In Burkina Faso, wildfires are legally prohibited[40]. However, prescribed fires are used in certain zones of the country as a tool for forest conservation and management[41]. Specifically, prescribed fires are carried out in protected areas by the forestry services, who are responsible for monitoring them, or by village land management committees under the supervision of the forestry services. Some studies have been conducted on the impact of prescribed fires on vegetation, regeneration, soil fauna, soil physicochemical properties, soil hydrological properties, and pasture yield[42]. However, GHG emissions from prescribed fires are still poorly assessed. The lack of detailed data on fire-related gas emissions has resulted in a poor understanding of how fires impact GHG emissions and associated emission factors. Greenhouse gas inventories at the national scale are generally based on the IPCC default EFs, which can lead to overestimation or underestimation. To cope with this issue and design appropriate mitigation measures, the Paris Agreement encourages each country to develop its specific EFs from potential sources of GHG emissions. Our study thus aimed at : (i) assessing carbon emissions from prescribed fires and, (ii) determining emission factors for the three main greenhouse gases, namely CO_2, CO, and CH_4. We concomitantly investigated how climate conditions and vegetation types influence carbon emissions and emission factors. Using the carbon mass balance method, field experiment were conducted at the plot level with prescribed fires to assess fine-scale GHG emissions. Our findings will provide accurate data to support GHG inventories at the national level in Burkina Faso. These data will also contribute to the global emissions database by improving existing data in West Africa.

Materials and methods

Study area

The study was conducted in Burkina Faso (West Africa) in two protected areas: classified forest of Dinderesso located in the Sudanian climate zone (11°13′60″ NN et 4°22′0″ W) and classified forest of Gonse located in the Sudano-Sahelian zone (12°22′60″N, 1°18′0″ W) (Fig. 1). Both climate zones are characterized by a single rainy season followed by a dry season[43]. Mean annual rainfall for the last decade (2008–2022) was 1115.61 ± 50.45 mm and 881.76 ± 23.19 mm in the classified forests of Dinderesso and Gonse, respectively according to the National Meteorology Agency of Burkina Faso. The mean annual temperature over the same period was 28.06 ± 0.08 °C for Dinderesso and 29.34 ± 0.07 °C for Gonse. The wind speed during the study period was 2.4 m/s for Dinderesso and 2.3 m/s for Gonse. Relative humidity was estimated at 66% and 60% for Dinderesso and Gonse, respectively. Vegetation in the two protected areas is characterized by various vegetation types including grass savannas, shrub savannas, tree savannas, woodlands, dry forests, and gallery forests. The classified forest of Dinderesso covers an area of 8500 ha with vegetation dominated by annual grasses such as *Andropogon pseudapricus* Stapf. and *Loudetia simplex* (Pilger) C.E. Hubbard, perennial grasses (e.g., *Andropogon gayanus* Kunth. and *Andropogon ascinodis*

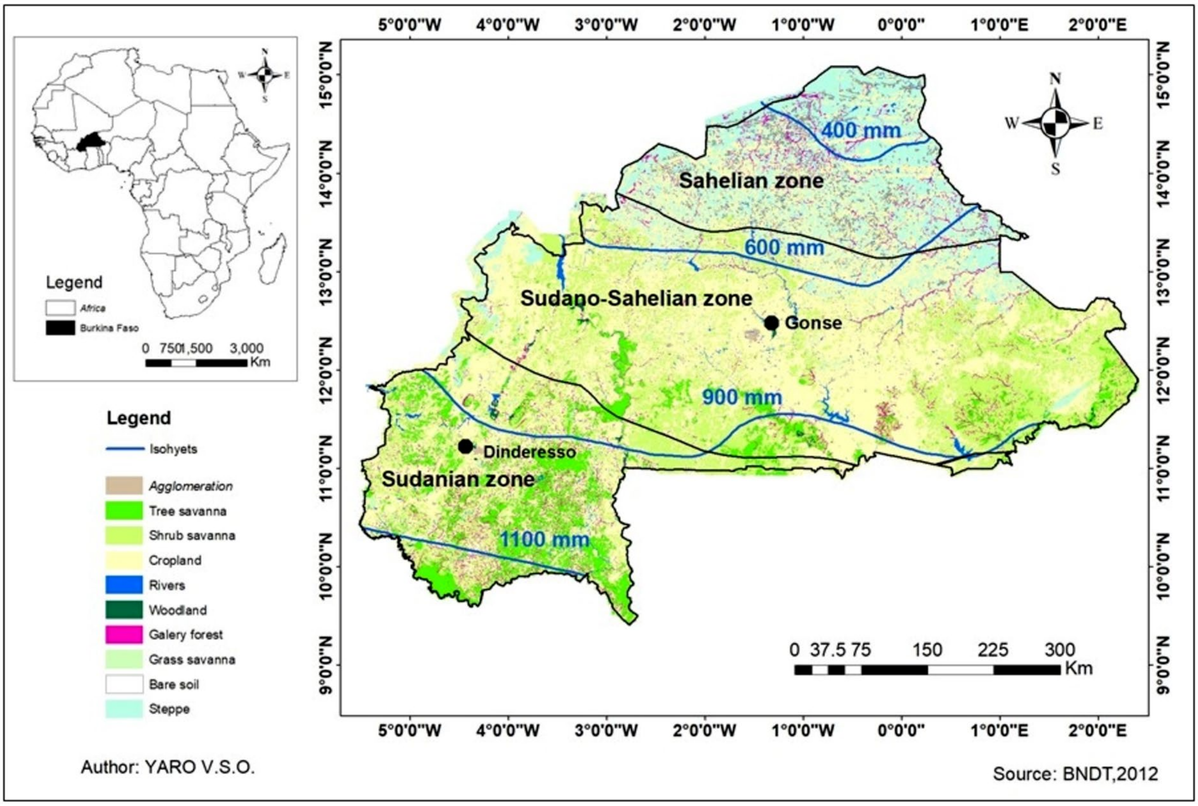

Fig. 1. Location of the two study sites within the Sudanian and the Sudano-Sahelian climate zones in Burkina Faso, West Africa. The climate zones of the country followed the classification based on the annually rainfall amount and the thermal regime[43]. Spatial data of the country were obtained from the geographical institute of Burkina Faso (IGB). The map of the study area was processed using the software ArcGIS Desktop 10.8 software Version 10.7.0.10450 (http://www.esri.com).

C.B.Cl.) and four woody species, i.e., *Combretum nigricans* Lepr. ex Guill. & Perr., *Senegalia macrostachya* Rchb. ex DC, *Anogeissus leiocarpus* (DC.) Guill. & Perr., and *Vitellaria paradoxa* C.F.Gaertn[44]. The aboveground biomass of the herbaceous vegetation is burned annually[45.] The classified forest of Gonse has an area of 6500 ha and is dominated by different species in the herbaceous and woody layers. In the herbaceous layer, annual grasses such as *Pennisetum pedicellatum* Trin., *Tephrosia pedicellata* Baker.; *Zornia glochidiata* Rchb. ex DC. are dominant alongside perennial grasses namely *Microchloa indica* (L.f.) P.Beauv., and *Andropogon fastigiatus* Sw.. The woody layer is dominated by *Anogeissus leiocarpa* (DC.) Guill. & Perr., *Balanites aegyptiaca* (L.) Delile, *Cassia sieberiana* DC., *Combretum micranthum* G. Don, *Sclerocarya birrea* (A. Rich.) Hochst, and *Senegalia gourmaensis* A. Chev.

Sampling design
Climate zones and vegetation types are considered to have a potential influence on biomass production, fuel biomass composition, and fire intensity[46]. Prescribed fires were thus implemented on an experimental basis in two out of the three main climate zones of Burkina Faso (Fig. 1), i.e., the Sudanian and the Sudano-Sahelian zones. The study was restricted to these two climate zones because it is within these zones that prescribed fires are commonly applied in management of protected areas[47], whereas the most arid climate zone (Sahelian zone) was not studied because the practice of prescribed fires is forbidden. For each climate zone, experimental plots of 10×10 m[48] were set up in one protected area along four vegetation types described according to the Yangambi nomenclature of African vegetation types: grass savanna, shrub savanna, tree savanna, and woodland[49]. Vegetation types and their respective characteristics can be found in supplementary Table S1 online. A minimum distance of 500 m was maintained between the plots to account for variations in soil types, fuel size, and plant species. We established 10 plots per vegetation type and 40 plots per climate zone (80 in total).

Experimental design for pre- and post- fire biomass fuel assessment
Each experimental plot, was delimited by a 2 m fire break around to prevent the fire from spreading (Figs. 2 and 3b). Vegetation characteristics, dominant herbaceous species, and their corresponding cover rate were recorded visually before fire. Destructive sampling was used to determine pre-fire biomass fuel (Fig. 3a)[26,50] in three representative quadrats of 1×1 m established along one plot diagonal (Fig. 2) to consider the variability of pre-fire biomass fuel available. Herbaceous vegetation was cut at around 2 cm above ground level using a sickle and mixed with litter and twigs (2 mm diameter) to constitute pre-fire biomass fuel (Fig. 3c). Large pieces of biomass

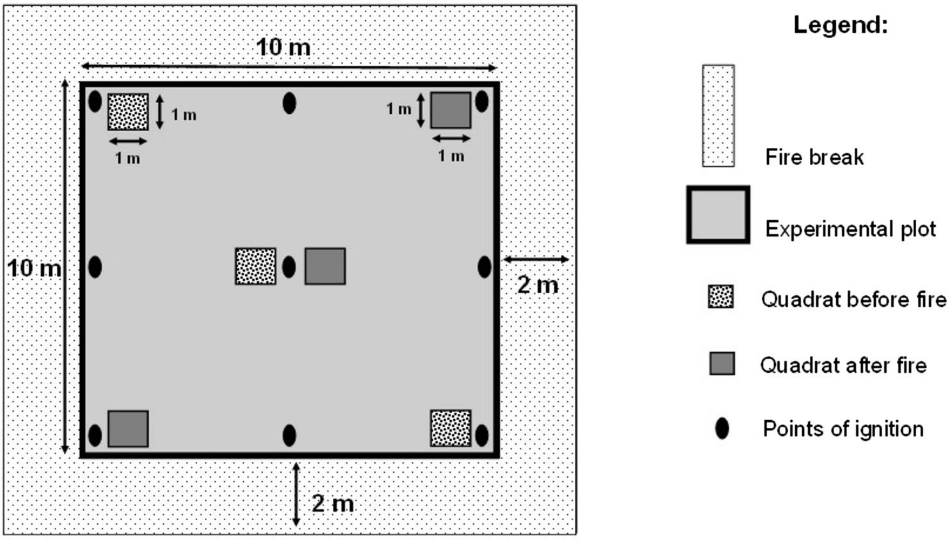

Fig. 2. Experimental design within 10 × 10 m plots, showing the location of quadrats assessed before and after experimental burning, fire break, and the location of ignition points.

Fig. 3. Biomass fuel burning during the experimental prescribed fires in grass savanna: (**a**) Pre-fire biomass fuel, (**b**) Delimitation of the experimental plot using a 2 m fire break for individual observation at the plot level, (**c**) assessment of pre-fire biomass fuel using sub-plot quadrat (1 m × 1 m), (**d**) Fire ignition for assessment of fire cover rate and quantification of post-fire biomass fuel, (**e**) Plot showing post-fire biomass fuel (unburned biomass and residual biomass), (**f**) assessment of post-fire biomass fuel using sub-plot quadrat (1 m × 1 m), (**g**) Pre-fire biomass fuel burning on the metal sheet to determine the proportion of (**h**) residual biomass that remains mixed with the soil after the fire, and (**i**) Pre-fire and residual samples for carbon content determination at the laboratory.

fuels were not included for two reasons: they are less subjected to prescribed fires and rare in classified forests because they are frequently collected by people as firewood. After the pre-fire biomass fuel assessment, ignition was conducted at nine points for each plot to determine fire behavior and to subsequently assess post-fire biomass fuel (Fig. 3f). The fire cover rate (FCR) which represents the proportion of area burned in the experimental plot was estimated visually. FCR is an essential parameter needed for an accurate estimate of biomass burned at the plot scale. After burning (Fig. 3e), the burning degree of pre-fire biomass fuel was heterogeneous in the plot. To account for the spatial heterogeneity of the degree or extent of burning in the plot, post-fire biomass fuel was assessed on the second diagonal in three quadrats of 1 × 1 m (Figs. 2 and 3f) corresponding to three burning levels (high, medium, low) as follows: (i) high burning level: plot areas where biomass fuel was completely burned during fire, leaving mainly ash on the ground; (ii) medium burning level: plot areas where fuel biomass has partially burned with pre-fire biomass and residual biomass in almost equal proportions, and (iii) low burning level: which corresponds to plot areas where pre-fire biomass fuel has hardly burned at all.

Post-fire biomass usually consists of unburned pre-fire biomass fuel and residual biomass, i.e., charcoal and ash. Residual biomass could contain a considerable proportion of carbon whose omission may lead to overestimation of carbon emissions[34]. However, the residual biomass remaining on the ground after the fire was difficult to accurately estimate in our case, as it was mixed with sand (Figs. 3d and 3f). Therefore, at least 500 g of composite pre-fire biomass fuel samples were collected per plot and burned directly on a metal sheet (Fig. 3e). After burning, all three sample types (pre-fire biomass fuel, post-fire unburned biomass fuel, and residual biomass) were directly weighed in the field using an electronic balance (range 0–5 kg, precision 1 g). A sub-sample of 100 g per plot of all sample types (Fig. 3g) was brought to the laboratory for moisture and carbon content determination.

Determination of moisture and carbon content
Carbon content of each sample type was determined using the ash method[51]. The moisture content of each sample type in the field was first determined on a dry weight basis after oven-drying (65 °C, ≥ 72 h). Dry samples were ground in a cutting mill to obtain composite samples of each biomass fuel component. In the next step, composite samples (2 g) were put in porcelain crucibles and placed for 2 h in a muffle furnace set at 550 °C until calcination was complete. After cooling in a desiccator, the carbon content of pre-fire biomass fuel (CC_{pre}) and residual biomass fuel (CC_{post}) was finally assessed by applying Eq. (1) and (2). The carbon content of unburned post-fire biomass fuel was considered to be similar to that of pre-fire biomass fuel. All analyses were carried out at the Plant Biology and Ecology Laboratory of the University Joseph KI-ZERBO, Burkina Faso.

$$Ash\,(\%) = \frac{w_3 - w_1}{w_2 - w_1} \times 100 \tag{1}$$

$$C\,(\%) = (100\% – Ash\%) \times 0.58 \tag{2}$$

where W_1 is the crucible weight, W_2 is the weight of crucibles with samples, W_3 is the weight of crucibles with ash, and 0.58 is the content of carbon in dry organic matter.

Carbon emissions and CO_2 equivalent calculation
Dry biomass samples were used to determine the dry weight of pre-fire and unburned biomass fuel in each quadrat. Data from the three quadrats before the fire were summed to determine total pre-fire biomass per plot (B_{pre}). After the fire, the three quadrats were also summed to determine the total unburned biomass per plot ($B_{unburned}$). Proportions of residual biomass derived from sheet metals after burning were applied to pre-fire biomass fuel to deduce residual dry biomass per experimental plot ($B_{residual}$). For each experimental plot, pre-fire and post-fire carbon content of biomass were assessed by considering: (i) the amount of pre-fire biomass fuel (B_{pre}) and its corresponding carbon content (CC_{pre}); (ii) the amount of unburned biomass and its corresponding carbon content (CC_{pre}); (iii) the amount of residual biomass ($B_{residual}$) and its corresponding carbon content (CC_{post}). The pre-fire carbon fuel (Cpre, t ha^{-1}) and the post-fire carbon fuel (C_{post}, t ha^{-1}) per plot were calculated using Eq. (3) and Eq. (4), respectively. In this study, residual biomass ($B_{residual}$) represents the mix of charcoal biomass ($B_{charcoal}$) and ash biomass (B_{ash}).

$$C_{pre} = B_{pre} \times CC_{pre} \tag{3}$$

$$Cpost = B_{unburned} \times CC_{unburned} + B_{charcoal} \times CC_{charcoal} + B_{ash} \times CC_{ash} \tag{4}$$

The difference between pre-fire biomass fuel and post-fire biomass fuel can be used to determine the biomass's fuel burned and its related carbon emissions[26,50]. Potential carbon emissions per plot was calculated using Eq. (5). Carbon emissions per plot were determined by multiplying the potential carbon emissions by the plot fire cover rate.

$$Carbon\ emissions = C_{pre} – C_{post} \tag{5}$$

Combustion completeness (CC) was also calculated using Eq. 6 to assess carbon emissions rate[10] which is probably correlated to fire severity.

$$\mathrm{CC}\,(\%) = \frac{\mathrm{C_{ash}} + \mathrm{C_{charcoal}} + \mathrm{C_{emission}}}{\mathrm{C_{pre}}} \tag{6}$$

Calculation of emission factors (EFs)
The emission factor relates the mass of emitted pollutant (expressed in g) to the amount of consumed fuel expressed in kg[26]. The carbon mass balance approach assumes that all carbon in biomass will be emitted mainly in the form of the three carbon gas species CO_2, CO, and CH_4. This approach uses fuel carbon contents and the amount of carbon gas species released to estimate fuel consumption[52,53]. Carbon sampled can be related to the mass of fuel combusted when the fuel's carbon fraction is known, resulting in a pollutant mass per fuel mass, i.e., the emission factor[54]. Based on existing emission factors for CO_2, CO, and CH_4 for savannas and tropical forests, we converted these EFs (mass of gas species) into carbon EFs and then calculated percentages (%) of carbon emitted in the form of CO_2, CO, and CH_4, included in the mass balance. The mass of three gas species was approximatively estimated at 97–99% of total carbon emissions[55,56]. For each gas, the mass of carbon contained was calculated using its molar number and molar mass[10]. Emission factors of carbon gas species were assessed

using Eq. (7). A summary of reported emission factors from studies investigating emission factors in savannas and tropical forests[52] can be found in supplementary Table S2 online.

$$EFi = Fc \times MMi/AMc \times Ci/Ctotal \times 1000gkg^{-1} \quad (7)$$

where EFi is the mass of gas species i emitted per kg of dry fuel consumed (g kg^{-1}), FC is the fractional fuel carbon content; 1000 is a unit conversion factor (1000 g kg^{-1}), MMi is the molecular mass of gas species i, AMc is the atomic mass of carbon and Ci/C_{total} is the number of moles of gas species i emitted divided by the total number of moles of carbon emitted.

Statistical analysis

Biomass fuel moisture content (BF_{moist}), fire cover rate (FCR), combustion completeness (CC), CC_{pre}, CC_{post}, pre-fire biomass fuel, biomass fuel burned, carbon emissions, CO_2 equivalent, and emission factors of main carbon species (CO_2, CO, and CH_4) per plot were treated as response variables. Before statistical analyses, all variables were tested for normality and homogeneity of variances by applying Shapiro–Wilk and Levene's tests. Data were log-transformed and tested again for normal distribution with the Shapiro–Wilk test and a Q-Q plot. A one-way analysis of variance (ANOVA) was performed to assess the effect of vegetation type and climate zone on variable responses followed by a Tukey's post-hoc test, when needed, to compare the mean values or the percentages of response variables at a 5% level of significance. To test the simultaneous effect of climate zone and vegetation types on response variables, a two-way ANOVA was applied using climate zones and vegetation types as explanatory factors. All the statistical analyses were performed using the R software version 4.3.1.

Results

Effect of climate zones and vegetation types on fire behavior, pre-fire biomass fuel, biomass fuel burned, carbon emissions, CO_2 equivalent emitted

Climate zones showed significant effects on BF_{moist} but not FCR, CC_{pre}, and CC_{post} (Table 1). However, BF_{moist}, FCR, CC, CC_{pre}, and CC_{post} varied significantly between vegetation types ($P < 0.001$, Table 1). BF_{moist} increased from grass savanna (4.55 ± 0.24%) to woodland (9.38 ± 0.81%). Following a similar trend, pre-fire biomass fuel carbon content (CC_{pre}) increased from grass savanna (45.42 ± 0.31%) to woodland (49.4 ± 0.37%). In contrast, the rates of fire cover after burning decreased from grass savanna (94.6 ± 1.41%) to woodland (16.75 ± 2.12%). The same result was observed for CC with decreasing from grass savanna (87.85 ± 3.3%) to woodland (13.10 ± 1.62%). Furthermore, post-fire biomass fuel carbon content (CC_{post}) was higher in tree savanna (25.13 ± 1.1%) and woodland (23.34 ± 0.48%) than in the other vegetation types.

The results of the two-way ANOVA (Table 2) showed that the climate zone affected pre-fire biomass fuel ($P = 0.001$) and biomass fuel burned ($P = 0.026$) but did not affect carbon emissions and CO_2 equivalent emitted

Characteristics		BF_{moist} (%)	FCR (%)	CC (%)	CC_{pre} (%)	CC_{post} (%)
Climate zones	Sudanian	8.8 ± 0.7[a]	56.3 ± 6.01[a]	54.45 ± 5.01[a]	47.42 ± 0.30[a]	0.30 ± 0.99[a]
	Sudano-Sahelian	6.55 ± 0.47[b]	53.3 ± 5.68[a]	43.04 ± 5.42[a]	47.42 ± 0.37[a]	0.37 ± 0.82[a]
Vegetation types	Grass savanna	4.55 ± 0.24[a]	94.6 ± 1.41[a]	87.85 ± 3.3[a]	45.42 ± 0.31[a]	13.97 ± 0.38[a]
	Shrub savanna	5.23 ± 0.36[a]	77.25 ± 4.91[c]	62.21 ± 5.29[b]	46.54 ± 0.32[a]	16.63 ± 0.88[a]
	Tree savanna	11.55 ± 0.77[b]	30.6 ± 5.8[b]	31.83 ± 4.14[c]	48.34 ± 0.32[b]	25.13 ± 1.1[b]
	Woodland	9.38 ± 0.81[b]	16.75 ± 2.12[b]	13.10 ± 1.62[d]	49.4 ± 0.37[b]	23.34 ± 0.48[b]

Table 1. Biomass fuel moisture content, fire cover rate, combustion completeness, pre-fire and post-fire carbon content following climate zones and vegetation types (mean values ± standard error). BF_{moist} = fuel moisture content, FCR = fire cover rate, CC = combustion completeness, CC_{pre} = carbon content in pre-fire biomass fuel, CC_{post} = carbon content in residual biomass.

Variables	Factors	Df	Sum Sq	Mean Sq	F value	Pr(> F)
Pre-fire biomass fuel	VT	3	0.040	0.013	0.929	0.431
	CZ	1	0.346	0.346	24.422	< 0.001
	VT × CZ	3	0.119	0.040	2.799	0.046
Biomass fuel burned	VT	3	19.347	6.449	59.573	< 0.001
	CZ	1	0.556	0.556	5.14	0.026
	VT × CZ	3	0.661	0.220	2.034	0.117
Carbon emissions	VT	3	20.626	6.875	66.009	< 0.001
	CZ	1	0.161	0.161	1.541	0.219
	VT × CZ	3	0.884	0.295	2.829	0.044

Table 2. Effect of vegetation types, climate zones, and their interaction on pre-fire biomass fuel, biomass fuel burned, carbon emissions, and CO_2 equivalent emitted. VT = Vegetation type, CZ = Climate zone.

($P = 0.219$). Pre-fire biomass fuel was higher in the Sudanian zone (5.44 ± 0.29 t ha^{-1}) than in the Sudano-Sahelian zone (3.87 ± 0.12 t ha^{-1}). Similarly, the highest values of biomass fuel burned were observed in the Sudanian zone (2.6 ± 0.38 t ha^{-1}) and the lowest in the Sudano-Sahelian zone (1.38 ± 0.19) corresponding to 47%, 40% of pre-fire biomass fuel for Sudanian zone and Sudano-Sahelian zone, respectively. Carbon emissions and equivalent carbon emitted were 0.94 ± 0.14 t ha^{-1} and 3.45 ± 0.51 t ha^{-1} in the Sudanian zone while values in the Sudano-Sahelian zone were 0.57 ± 0.08 t ha^{-1} and 2.08 ± 0.29 t ha^{-1}, respectively.

Considering each climate zone individually, the influence of vegetation types on pre-fire biomass fuel depends on the climate zone (Fig. 4a). However, vegetation types significantly ($P < 0.001$) affect biomass fuel burned, carbon emissions, and CO_2 equivalent emitted both for Sudanian and Sudano-Sahelian zones with higher values in grass and shrub savannas while lower values were observed in tree savanna and woodland (Figs. 4b-d).

When Sudanian and Sudano-Sahelian zones are considered together (Figs.4e-h), pre-fire biomass was similar between vegetation types (Fig. 4e). However, biomass fuel burned, carbon emissions, and CO_2 equivalent emitted remained significantly influenced ($P < 0.001$) by vegetation types (Figs. 4f-h; Table 2). The highest biomass fuel burned (4.18 ± 0.4 t ha^{-1}), carbon emissions (1.61 ± 0.13 t ha^{-1}), and CO_2 equivalent (5.91 ± 0.48 t ha^{-1}) was observed in grass savanna while the lowest values were observed in woodland with 0.32 ± 0.06 t ha^{-1}, 0.12 ± 0.02 t ha^{-1}, and 0.44 ± 0.08 t ha^{-1} respectively. The interaction between climate zone and vegetation type showed a significant influence ($P = 0.044$) on carbon emissions and CO_2 equivalent emitted (Table 2).

Effect of climate zones and vegetation types on emission factors of CO_2, CO, and CH_4

Emission factors of CO_2, CO, and CH_4 were not significantly influenced by climate zone (Table 3). They had similar values in both the Sudanian and Sudano-Sahelian zones. In the Sudanian zone, CO_2, CO and CH_4 were 1610.62 ± 9.17 g kg^{-1}, 3.59 ± 0.27 g kg^{-1}, and 76.06 ± 2.56 g kg^{-1}. The respective emission factor values in the Sudano-Sahelian zone were 1610.51 ± 10.59 g kg^{-1}, 76.28 ± 2.77 g kg^{-1}, and 3.61 ± 0.28 g kg^{-1}.

Considering climate zone individually, vegetation types significantly influenced emission factors of CO_2, CO, and CH_4 in Sudanian and Sudano-Sahelian zones (Fig. 5). The highest values of CO_2 emission factors were observed in the tree savanna of each climate zone (Fig. 5a). Concerning CO and CH_4, low and high values were observed in grassy savanna and woodland respectively (Figs. 5a-d).

When climate zones were grouped, vegetation types significantly influenced emission factors ($P < 0.001$) (Figs. 5d-f). Comparing the EFs of CO_2, CO, and CH_4, exhibited different patterns were recorded for the different vegetation types. The highest value of CO_2 was recorded in the tree savanna with 1658.17 ± 11.13 g kg^{-1} and the lowest was recorded in the grass savanna with 1557.94 ± 10.7 g kg^{-1} (Fig. 5d). The highest CO (104.62 ± 0.78 g kg^{-1}) and CH_4 EFs (6.57 ± 0.05 g kg^{-1}) were obtained in the woodland (Figs.5e-f) while the lowest EFs of CO and CH_4 were found in grass savanna with 64.77 ± 0.44 g kg^{-1} and 2.54 ± 0.02 g kg^{-1}, respectively (Figs. 5e-f). Furthermore, the interaction between climate zones and vegetation types revealed a significant influence on emissions factors (Table 3).

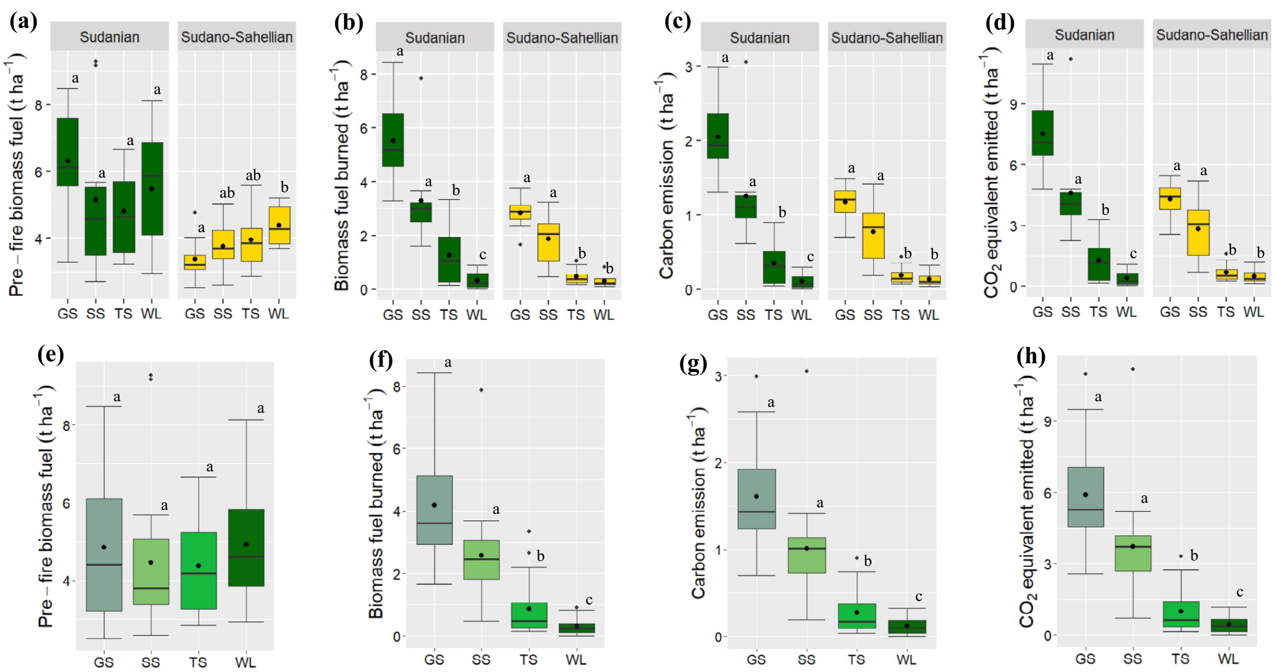

Fig. 4. Variability of pre-fire biomass fuel (**a** and **e**), biomass fuel burned (**b** and **f**), carbon emissions (**c** and **g**), and CO_2 equivalent emitted (**d** and **h**) across climate zones and vegetation types (GS = grass savanna, SS = shrub savanna, TS = tree savanna, WL = woodland). The median and the mean are represented by a horizontal line and a dot in the boxplot, respectively. Different letters above the bars indicate significant differences between vegetation types for each climate zone ($p < 0.05$).

Variables	Factors	Df	Sum Sq	Mean Sq	F value	Pr(> F)
CO_2 emission factor	VT	3	0.008	0.003	16.633	< 0.001
	CZ	1	0.000	0.000	0.002	0.966
	VT × CZ	3	0.002	0.001	4.518	0.006
CO emission factor	VT	3	0.582	0.194	1179.815	< 0.001
	CZ	1	0.000	0.000	0.002	0.966
	VT × CZ	3	0.002	0.001	4.518	0.006
CH_4 emission factor	VT	3	2.415	0.805	4897.153	< 0.001
	CZ	1	0.000	0.000	0.002	0.966
	VT × CZ	3	0.002	0.001	4.518	0.006

Table 3. Effect of vegetation types, climate zones, and their interaction on CO_2, CO, and CH_4 emission factors. VT = vegetation type, CZ = climate zone.

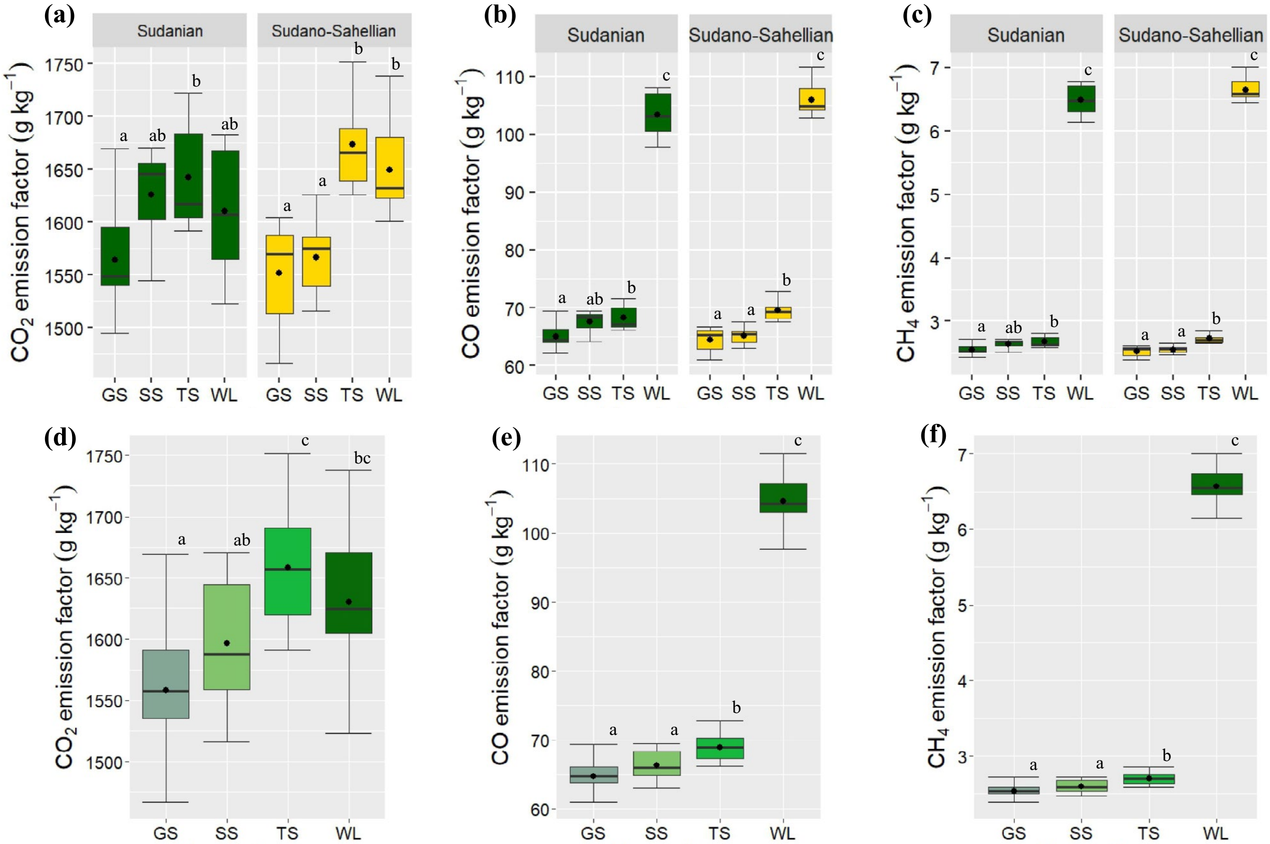

Fig. 5. Variability of emission factors of CO_2 (**a** and **d**), CO (**b** and **e**), and CH_4 (**c** and **f**) across climate zone and vegetation types (GS = grass savanna, SS = shrub savanna, TS = tree savanna, WL = woodland). The median and the mean are represented by a horizontal line and a dot in the boxplot, respectively. Different letters above the bars indicate significant differences between vegetation types for each climate zone (p < 0.05).

Discussion

Pre-fire biomass fuel was significantly influenced by climate zones, increasinged from the dry climate zone (Sudano-Sahelian zone) to the humid zone (Sudanian zone). This difference is probably related to rainfall variability between both zones. Indeed, rainfall is a known climate variable that mostly affects biomass production and burned areas[57]. A previous study revealed that high rainfall in the Sudanian zone was more favorable for biomass production than in the Sudano-Sahelian zone[10]. Also, herbaceous materials which, constitutes the most dominant component of biomass fuel, was found to have a positive correlation with annual rainfall[58]. Carbon emitted in the Sudanian zone was relatively higher than in the Sudano-Sahelian zone, which could be due to the difference in post-fire carbon content between the two climate zones. Pre-fire biomass fuel recorded in the Sudanian and Sudano-Sahelian climate zones were 5.44 ± 0.29 t ha^{-1} and 3.87 ± 0.12 t ha^{-1} respectively. These values are similar to those reported in the savannas of Australia (4.8 ± 1.3 t ha^{-1}), South Africa (4.4 ± 1.4 t ha^{-1}), and Zambia (4.2 ± 0.8 t ha^{-1}) [11].

We discovered that not all of the available biomass was utilized as fuel during prescribed fires. This is in line with previous studies reporting that only a fraction of biomass is consumed during a forest fire[59]. The proportion of biomass fuel burned was 47% in the Sudanian climate zone, compared to 40% in the Sudano-Sahelian zone. Previous studies carried out in Burkina Faso on prescribed fires showed that 51% of the biomass available burned after a fire in Tiogo, whereas 83% burned in Dindéresso[50]. This difference, particularly the one we observed in the same classified forest at Dinderesso, could be explained by differences in the timing of the prescribed fires and the sampling design employed. Our study was carried out during the early part of dry season (October and November)[42] whereas the study of[50] in Dinderesso was carried out in January, which is beyond the indicated period for early prescribed fires. During this period, the biomass's moisture content is relatively lower, enhancing the efficiency and combustion rate of the biomass fuel. Furthermore, the burning experiment carried out as part of this study was performed in Dinderesso separately for different vegetation types: grass savanna, shrub savanna, tree savanna, and woodland. While grass savannas and shrub savannas have a high proportion of burned areas, the low proportions of areas burned by fire in woodland and tree savannas result in a reduction in the overall burned areas when considering the site as a whole.

The results did not reveal a significant difference between the emission factors of the two climate zones. These similarities could be linked to the carbon content of the particles that make up the biomass fuel. The more similar the carbon content of fuels in the climate zones, the closer the emission factors. CO_2 emission factors found in our study area (dry tropical zone) are relatively low comparedto those found from prescribed fires in the sub-tropical humid zone (Kansas, USA)[54], tropical savanna[60] and those from laboratory experiments[31]. On the other hand, they were higher than the values found in the Brazilian Amazonia Forest[30]. The difference in emission factors observed between our study and the above studies could be explained by differences in ecological conditions, geographical location, and plant diversity as well as the methods applied. The carbon content in the plant biomass could be influenced by the plant diversity[61]. Regarding the methods, we applied a field measurement approach based on carbon mass balance to determine emission factors instead of laboratory experiments or gas sensor sampler methods. The methodology that we used to assess GHG emissions from field measurements at the plot level provides fine-scale information that accounts for microclimate effects, fuel biomass composition, and environmental conditions at the plot level. Laboratory experiments are relevant to assess the potential emission from fuel biomass but not really appropriate to assess emissions in natural conditions because environmental variables (e.g., air relative humidity, wind speed) affecting combustion completeness are generally different between the two settings[62]. Studies developing emission factors using gas sensors sampler methods generally combine gas species content detected by sensors and default values of carbon content, which could introduce biases in EF values.

Vegetation types in our study significantly affected pre-fire biomass fuel, biomass burned, and carbon emissions. It was expected that the low moisture content in the biomass fuel would increase burning and carbon emissions[63]. However, this expected trend was only observed in the grass and shrub savannas with a high degree of combustion completeness. The high combustion in these two vegetation types is linked to the predominance of herbaceous biomass (75–90%)[42,64]. and their continuous spatial distribution[65]. Annual herbaceous plants quickly become senescent at the end of the rainy season and are then highly susceptible to burning. Although perennial grasses maintain their moisture content for a longer period than annuals[66] , only their renewal buds remain alive close to the soil surface while their aboveground biomass also become senescent during the dry season thus making them highly flammable[67]. Ours results have shown that fire cover rates were lower in the tree savanna and woodland than the grass savanna, which could be attributed to the higher moisture content of biomass in tree savanna and woodland as well as differences in fuel composition[66]. Additionally, during prescribed fires, a high, thick and compacted layer of leaves, accumulated over several years, were recorded in the woodland and tree savanna. Compaction can lead to restricted oxygen supply in biomass fuels, that can indirectly reduce fuel consumption during fires[30].

The reliability of emission factors means that carbon emissions can be estimated more accurately[68]. This study revealed that the emission factors for the three main carbon gas species varied considerably across vegetation types, with low and high values in vegetation types dominated by herbaceous and woody species, respectively. This variability could be explained by the high carbon content in biomass fuel from the tree savanna and woodland compared to grass and shrub savanna species[69]. Synthesis work[70] has indicated that the emission factors of CO_2 (1660.57 ± 90 g kg^{-1}) in the tropical savannas are similar to those observed in the tree savanna (1658.17 ± 11.13 g kg^{-1}) but are higher than those of the grass (1557.94 ± 10.7 g kg^{-1}) and the shrub savanna (1596.22 g kg^{-1}) of our study area. According to the same synthesis work, only the emission factor of CO_2 in the woodland (1629.94 ± 12.23 g kg^{-1}) is close to that of tropical woodland (1660.57 ± 90 g kg^{-1}). A similar same trend was observed with CO and CH_4 emission factors. The default values of the CO_2 emission factor from the Intergovernmental Panel on Climate Change (IPCC) for savanna (1613 ± 95 g kg^{-1}) are higher than those found in our study except for tree savanna. This difference is mainly due to the differences in the scale of studies. Our emission factors were developed at local scale using Tier 2 approach, while those from IPCC using Tier 1 method were developed at the global tropical region scale.

The interaction between climate zones and vegetation types revealed a significant influence on carbon emissions and emission factors of CO_2, CO, and CH_4. This suggests the existence of a significant relationship between vegetation types and climate zones regarding CO_2, CO, and CH_4 emission factors. These results highlight the importance of vegetation types and their interaction with climate zones in quantifying the emission factors of various gas species.

Conclusion

The study conducted experimental prescribed fires according to climate zone s and vegetation types with the aim to improve global greenhouse gas inventories from biomass fuel burning. This study highlights the importance of vegetation types in determining the extent of carbon emissions and emission factors associated with prescribed fires. Prescribed fires considerably reduced biomass fuel with high carbon and CO_2 equivalent emission recorded in grass and shrub savannas. The highest carbon emissions and CO_2 equivalent emitted in these two vegetation types are attributed to the lower moisture and continuous grass cover which facilitated combustion. Although tree savanna and woodland have the lowest carbon and CO_2 equivalent emitted, they have the highest EF of the major carbon species. The highest E F of CO_2 was observed in tree savanna and the lowest in grass savanna. The highest EF for CO and CH_4 were observed in woodland while the lowest EF for CO and CH_4 were found in the grass savanna. These relatively high values are correlated with the high carbon content in biomass fuel available. Furthermore, results indicate that vegetation types and their interaction with climate zones are important parameters to take into account when assessing carbon emissions and emission factors from fire. This work provided emission factors that could be used to update national inventories and better guide the development of nationally determined contribution (NDC). Our findings will contribute to improve global database and support decision making related to climate change. Further investigations including GHG emissions from uncontrolled fires in other land use types and spatiotemporal dynamics of fire occurrence are needed for a better comprehensive overview of fire-related emissions at the landscape level as well as to support the development of climate models and improve their accuracy in terms of prediction.

Data availability

All data generated or analyzed during this study are upon reasonable request from the corresponding author.

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Author contributions
O.O., L.B., V.S.O.Y., P.C.B., I.S., A.W.G., and A.L. contributed to the study conception and design. Data collection was performed by V.S.O.Y., P.C.B., and I.S. Data analysis was performed by V.S.O.Y., P.C.B., I.S., L.B., and V.S.O.Y. drafted the manuscript. P.C.B.,L.B., A.W.G, R.T.G., O.O., and A.L. provided scientific and critical guidance and reviewed the final version of the manuscript. All authors have read and agreed to the final version of the manuscript.

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Competing interests
The authors declare no competing interests.

Approval for fire experiments in forest
Burkina Faso's Forestry Code, under Law N°003–2011/AN, authorizes prescribed fires in all climate zones except the Sahelian zone. Furthermore, the experimental fires in the forest were approved by the Ministry of the Environment, Water and Sanitation (Burkina Faso).

Additional information
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