Vol. 11(4), pp. 164-175, October-December 2020
DOI: 10.5897/JSSEM2017.0673
Article Number: 8533F5865637
ISSN: 2141-2391
Copyright ©2020
Author(s) retain the copyright of this article
http://www.academicjournals.org/JSSEM

Journal of Soil Science and Environmental Management

Full Length Research Paper

Modifications induced in soil physicochemical properties by repeated fire for different fuel load treatment in a West African savanna-woodland

Sabine W. M. F. Doamba[1*], **Patrice Savadogo**[2] and **Hassan B. Nacro**[3]

[1]Université de Fada N'Gourma, Ecole Supérieure d'ingénierie, BP 54 Fada N'Gourma, Burkina Faso.
[2]Food and Agriculture Organization of the United Nations (FAO), Sénégal.
[3]Université de Bobo Dioulasso, Institut du Développement Rural, Laboratoire d'Etude et de Recherche sur la Fertilité du Sol 01 BP 1091, Bobo Dioulasso, Burkina Faso.

Received 20 November, 2017; Accepted 13 July, 2020

Fire is known to stimulate growth of savanna vegetation, promote species' diversity, and regulate tree and grass balance. However, the timing and frequency at which savannas are burned and the fuel properties can affect residual soil nutrient content and, ultimately, productivity. The objective of this study is to characterize changes in soil physical and chemical properties in a savanna-woodland subject to different fuel load treatments of burning. To characterize the soil physical and chemical variables, particle size distribution, total carbon, pH, phosphorous content and nitrogen were analyzed for three different soil layers. The results indicated no difference in soil texture between the different topsoil profiles before and after the burning event. Further, there was greater nutrient enrichment of the upper soil layer ($p=0.014$) due to ash deposition. The spatial patterns of soil temperature during the studied experimental fires could affect soil properties, resulting in new spatial pattern of soil nutrients. The findings of the present study have practical implications for savanna management. The current implementation of prescribed early fires should be continued with due consideration of the burning and fuel properties to avoid detrimental effects of intense fire on soil layers.

Key words: Early fire, fire behavior, fire temperature, soil properties, Savanna ecosystem.

INTRODUCTION

Fire is a widespread seasonal phenomenon in savanna ecosystems (Kugbe et al., 2012). In most African savannas, natural or human-induced fires (Archibald et al., 2012) have long been recognized as beneficial for the maintenance of the tree/grass balance (Frost et al., 1986). Fires control vegetation structure, composition, succession and productivity (Midgley et al., 2010), and nutrient budgets and cycling (Certini, 2005). Although savannas are resilient to fire (Frost et al., 1986), frequency and unplanned fires may have long-term consequences for belowground sustainability. Depending on fire regime, changes in belowground components can

---

*Corresponding author E-mail: doambaflore@yahoo.fr. Tel: +226 70133571. Fax: + 226 50 30 29 30.

be either beneficial or deleterious to the entire ecosystem. Soil is an important component of ecosystems which is liable to be affected by fire (Badia et al., 2014), particularly the superficial horizon. Fire may produce a wide array of changes in other ecosystem components owing to their interdependency. The effect of fire on belowground systems appears to be related to burning with greater losses of nutrient occurring in hotter fires (Whelan, 1995). Immediately after the fire, soil desiccation and the change in albedo of the surface may result in high soil temperatures, which further influence the effect of fire on the soil (DeBano et al., 1999). Frequent fires may have a detrimental effect on soil properties by destroying the organic matter contained in the aboveground vegetation and litter (Stoof et al., 2010). The effect of fire on the physical soil properties is primarily due to the indirect effect of biomass removal (Verma, 2012), which is particularly related to the period and intensity of fire exposure, and parameters such as soil structure and texture.

The effect of fire on chemical soil properties is complex and variable, but generally, the changes are most pronounced in the topsoil (Snyman, 2003). Recent information has indicated that the use of prescribed fire for land-management purposes and the incidence and severity of wildfires have increased substantially worldwide (Pricope and Binford, 2012). In the Sudanian savanna-woodland alone, Delmas et al. (1991) have estimated that between 25 and 50% of the total area burns annually primarily due to anthropogenic causes. In most protected areas of Burkina Faso, officially approved early fire (burning taking place between October and December-January depending on the locality, region) has been adopted as a management tool to minimize the risk of severe late fire (occurring from February to May), to improve pasture production for wildlife and to maintain species' composition and richness (Bellefontaine et al., 2000). Much of the previous research on the effects of burning in West African savanna-woodland has focused on vegetation dynamics (Savadogo et al., 2008, 2009; N'Dri et al., 2014) and fire behavior (Dayamba et al., 2010; Savadogo et al., 2007b; Sow et al., 2013; N'Dri et al., 2018), soil macro-fauna (Doamba et al., 2014) particularly the effects of burning during the dry season on soil temperature, root biomass, soil surface CO_2 efflux and soil water properties (Savadogo et al., 2007a, 2012; Van Straaten et al., 2019). Consequently, relatively little is known about the long-term legacy of annual burning on soil properties. There is also a lack of information about the effects of fuel load and fire seasonality on soil properties. More specifically, our aim was to determine the modifications induced in soil physicochemical properties in plots subjected to repeated fire and with varying fuel load treatments.

The study addressed the following hypotheses: (1) The fuel load through increased fire severity induces alterations in soil properties, and nutrient pools will decrease from low to high fuel load treatments; (2) Fuel load treatment will affect vertical nutrient partitioning of the burned soil, that is, available nutrients will decrease from the topsoil to deeper soil levels.

MATERIALS AND METHODS

Study site description

The experiment was conducted in the State forest reserve of Dindéresso (11.225°N, 4.447°W), located at an altitude of 359 m above sea level in Burkina Faso, West Africa. The climate at this location is South Sudanian, with two main seasons; the rainy season occurs from May to October and the dry season from October to April (Fontès and Guinko, 1995). The mean annual rainfall for the study period 2009-2011 was 1010 ± 145 mm (mean ± standard error). Soils at the forest reserve are derived from sedimentary elements and classified as lixisols (Driessen et al., 2001). Soils are mainly deep (> 85 cm) and have relatively high silt fractions and are classified as lixisols (FAO classification system) (van Straaten et al., 2019). Phyto-geographically, the study site is located in the Sudanian Regional Centre of Endemism in the South Sudanian Zone (Fontès and Guinko, 1995). The vegetation type at the site is tree/bush savanna with a grass layer dominated by the annual grasses *Andropogon pseudapricus* Stapf. and *Loudetia simplex* (Pilger) C.E. Hubbard as well as the perennial grasses *Andropogon gayanus* Kunth. and *Andropogon ascinodis* C.B.Cl.

Burning experiment and fuel load treatment

The investigation of soil physical and chemical properties was performed on a permanent experimental site established in August 2009 (Figure 1). The plots were located on flat ground to eliminate the influence of slope on fire behavior (Trollope et al., 2002). The total experimental area (11.16 ha) comprised three non-contiguous blocks (each 3.72 ha) (Doamba et al., 2014; van Straaten et al, 2019). The blocks were located as to minimize variations in aspect, slope and soil type after a preliminary survey. Each block was further divided into seven plots of 0.24 ha (80×30 m). The plots were separated by 10m fire-breaks and each block was surrounded by a 20 m wide fire-break. All the blocks were similar and subject to moderate grazing, mainly by livestock (a mixed herd of cattle, sheep and goats), all year round. The woody vegetation covers an average of 44% in each plot.

The fuel load treatment procedure was as follow: first, except on the control plot, the herbaceous vegetation was harvested manually by cutting at the base, approximately 10 cm above the ground. The harvested biomass and available plant litter were weighed *in situ* before taking the material to the laboratory, where biomass was determined by again weighing. Then it was placed in an oven for 48 h at 105 °C, and finally reweighed. Fire is applied on the same day when the cutting occurred. Based on the dry weight of the material from each plot, three fuel load treatments were considered prior to early and late burning:

(i) Normal fuel load (NF), the initial available fuel in the plot was cut and left having been spread uniformly across the plot to ensure 100% fuel bed continuity by covering any areas of bare soil;
(ii) Reduced fuel load treatment (RF): half of the initial fuel load was left on the plot and the rest removed;
(iii) Increased fuel load (IF): the second half of the fuel removed from RF was added to the initial fuel collected on the IF plots, all of it was spread out evenly.

Further, the following fire treatments, each with 3 replicates, were randomly assigned to the 21 plots starting in 2009: *no fire*: control plots; *early fire*: fire set at the beginning of the dry season in December and late fire: fire set at the beginning of the dry season and just before the next rainy season (Doamba et al., 2014). However, in this study, the activities concerned only early fire and control plots. In each season, fire was initiated early in the morning (6 am to 9 am) when the wind speed and air temperature were lowest. Data were collected at regular intervals, before and immediately after fire event, in three consecutive years. At the same time, sampling was conducted in *no fire* (control plots) and *early fire*.

Fire behavior data collection

The flame temperature of fire was recorded using a universal professional infrared pyrometer with a temperature range of -50 to +1000°C and a high optical resolution of 30:1 (model TP 6 TROTEC, MIS instrumentation, France). The rate of spread was determined by recording the time the fire front took to arrive at a selected distance on either side of the burning plot by using stopwatch. Fire intensity was estimated using Byram´s (1959) Equation 1:

$$I = H\,w\,r \qquad (1)$$

where I = fire intensity (kJ s^{-1} m^{-1}), H = heat yield of the fuel (kJ kg^{-1}), w = weight of fuel consumed per unit area (kg m^{-2}) and r = rate of spread (m s^{-1}). The heat value *(H)* developed for grass fuel head fires (17 781 kJ kg^{-1}) (Trollope and Potgieter, 1985) was used to calculate fire intensity.

Soil sampling and analysis

Soil samples were collected before and immediately after the fire event on burnt plots. On control plots, only one sample was collected, on the assumption that the study period was short enough that no substantial change could have occurred. Litter and ash were removed prior to sampling. Soil samples were taken on the diagonal of the plot in order to obtain a good representation of the sample plot. On the two diagonal of each plot, soil samples were collected from five holes by using an auger. In each hole, three depth layers were considered (0-5, 5-10 and 10-15 cm). Finally, three composites samples were taken in each plot and were bagged and labeled. The following physical and chemical parameters were determined according to standard procedures for soil analysis:

(i) Soil particle size distribution (percent sand, silt and clay) was measured according to the procedure described by Feller (1979).
(ii) Soil pH was measured with a pH meter using soil: soil water ratio of 1/2.5 according to the Afnor (1981) procedure.
(iii) Soil organic carbon was determined after oxidation of organic matter following the procedure described by Walkley and Black (1934).
(iv) For Nt, and Pt, samples were first digested in a mixture of H_2SO_4–Se–H_2O_2 at 450°C for 4h following the method of Walinga et al. (1989). We used aspectrophotometer (CECIL instrument, CE 3020, Serial N'126-288, Cambridge, U.K.) to determine the Nt and Pt contents in the digested solution.
(v) Available P was measured using a Bray-1 extract as described by Olsen (1965).
(vi) Cation exchange capacity (CEC) was determined according to Metson (1956).

Statistical analysis

An analysis of variance (ANOVA) was performed to study the effect of fuel load treatment on the rate of spread, fire temperature and fire line intensity. Fire behavior variables were tested for normality prior to statistical analysis. For soil physical and chemical parameters, data were collected based on pairs of observations before and after fire treatments (*N* pairs of samples) in burned plots and one set of samples for the control plot. Therefore, a Before-After Control-Impact (BACI)-ANOVA approach (Hewitt et al., 2001) was used to examine the modifications induced in soil properties. This approach is designed to detect situations where an environmental disturbance, in this case fire occurrence in a given season, causes a pattern of change in a measured parameter. The data were analyzed using an ANOVA generalized linear model or repeated measures methods with special structural parameters in the covariance matrices to take into account the carry-over effect. The set of data analyses was used to assess the behavior of the two groups of samples from the impact area (before and after) and the reference area (control) through the variable responses observed through time. The model (1) was used for fire affected plots and model (2) for control plots:

$$Y_{ijk} = \mu + \beta_i + \lambda_j + (\beta\,\lambda)_{ij} + \varepsilon_{j(i)} + \varepsilon_{j(k)} \qquad (1)$$

$$Y_{ij} = \mu + Depth_i + \lambda_j + Depth_i \times \lambda_j + \varepsilon_{ij} \qquad (2)$$

where Y_{ijk} and Y_{ij} represent the response variables (values recorded before and after the fire) for soil parameters, μ is the overall mean, β_i is the effect of the between-subject factors, i (fuel load treatment, depth of soil sampling, the pre- and post-fire test and their interaction), λ_j is the effect of the within-subject factor, j, year, and $(\beta\lambda)_{ij}$ is the interaction of the between- and within-subject factors. The parameters $\varepsilon_{j(i)}$ and $\varepsilon_{j(k)}$ are the random unobservable errors of the between-subject and the within-subject factors, respectively and are assumed to be normally distributed. For the soil particle size distribution, data were only available for the first year and were analyzed using the following linear model (3):

$$Y_{ijk} = \mu + Treatment_i + Depth_j + Test_k + (Treatment_i \times Depth_j) + (Depth_j \times Test_k) + Treatment_i \times Depth_j \times Test_k + \varepsilon_{ijk} \qquad 3)$$

When the homogeneity of variance assumption was violated in the time series analysis according to Mauchly's test of sphericity, the degrees of freedom for testing the significance of the within-subject factors were adjusted using a Huynh-Feldt correction factor, which is less biased than other correction factors (Davis, 2002). When a significant difference was detected, a pairwise comparison was made using Tukey's test at the 5% level of significance. All statistical analyses were performed using SPSS 19.0 for Windows (IBM Corporation, USA). Graphs were plotted using Origin 7.5 software (Origin Lab Corporation, Northampton, MA, USA).

RESULTS

Fuel load and fire behavior

Overall, the estimated grass fuel load for the three years of investigation was 0.41± 0.106, 0.75 ± 0.21 and 1.56 ± 0.32 t ha^{-1}on the reduced fuel load (RF), normal fuel load (NF) and increased fuel load (IF) plots, respectively. There was a significant ($F_{[2,35]}$=8.567, P<0.001) inter-annual variation in the amount of fuel load. Plots with initial standing fuel had similar amounts to those with reduced fuel load; lower amounts than the increased fuel

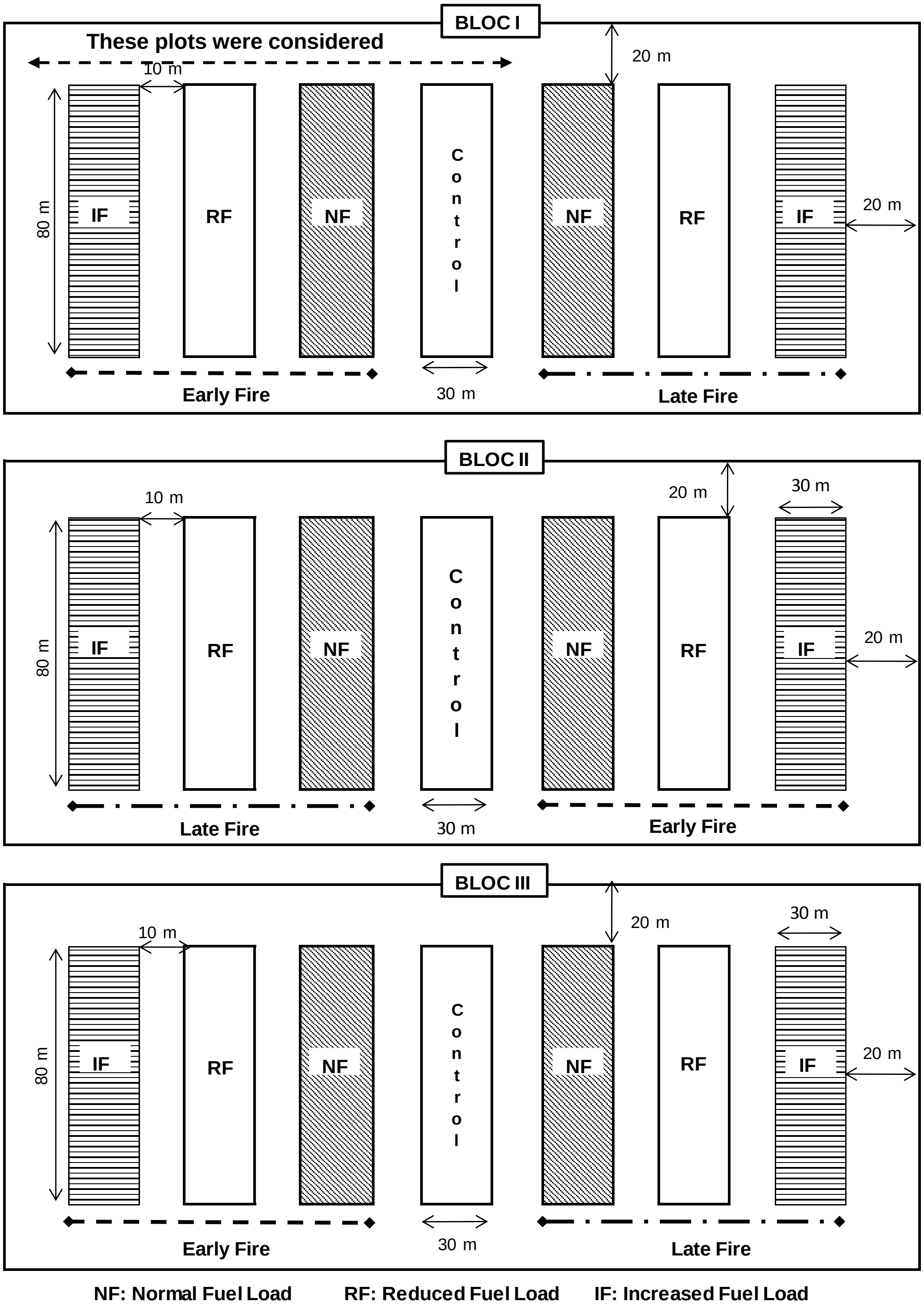

Figure 1. Experimental set up (NF: Normal Fuel Load; RF: Reduced Fuel Load; IF: Increased Fuel Load).This design was replicated at three different locations and only the early fire and control plots were considered for this study).

load plots during the first and third year of study (Figure 2). During the second year of investigation, plots subjected to reduced fuel load treatment had similar amounts of fuel as plots where the initial standing fuel was kept. The overall pre-burn fuel moisture content did not differ widely between the different fuel load treatment

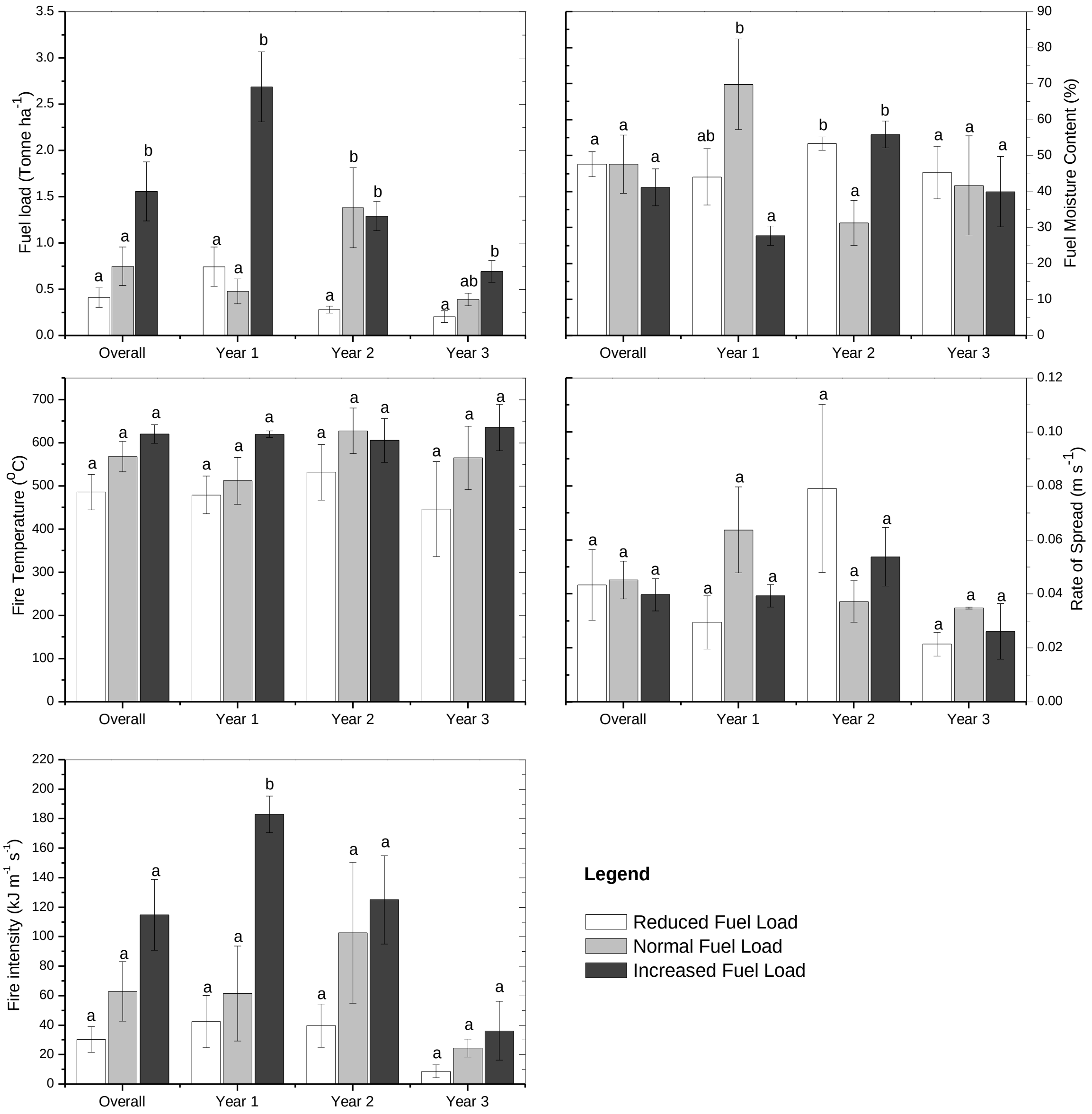

Figure 2. Fuel characteristics and fire behavior parameters in plots subjected to different fuel load treatments in a Sudanian Savanna-woodland. Means with different letters are significantly different (P<0.05) based on Tukey's HSD Test. Capped lines represent standard error.

plots, that is, 47.62 ± 3.46, 47.65 ± 8.08, 41.21±5.14% for the RF, NF and IF plots, respectively (Figure 2). Similarly, no difference was found in the fuel moisture content between the different treatment plots in the third year whereas during the first two years, the moisture of the fuel varied between the plots. The maximum fire temperature for the different fuel load treatments reached 635±54°C in the plots with increased fuel load during the third year of investigation. The maximum fire temperature did not differ significantly with respect to fuel load treatment both temporally and within years. Generally, fires were burnt under a relatively narrow range of weather conditions and their behavior was similar in all the plots with different fuel load treatments. There was no significant difference between the treatment plots in the rate of spread. However, inter-annual variations were observed in fire intensity. In the first year of study this parameter increased significantly in increased fuel load plot (IF) but in the two other years no significant differences were observed. As the fuel was dispersed over the whole plots, it continued smoldering after the fire front had passed, consuming considerable amounts of fuel and litter. In all cases, the fire progression from the start to the lower middle part of the plots was faster than

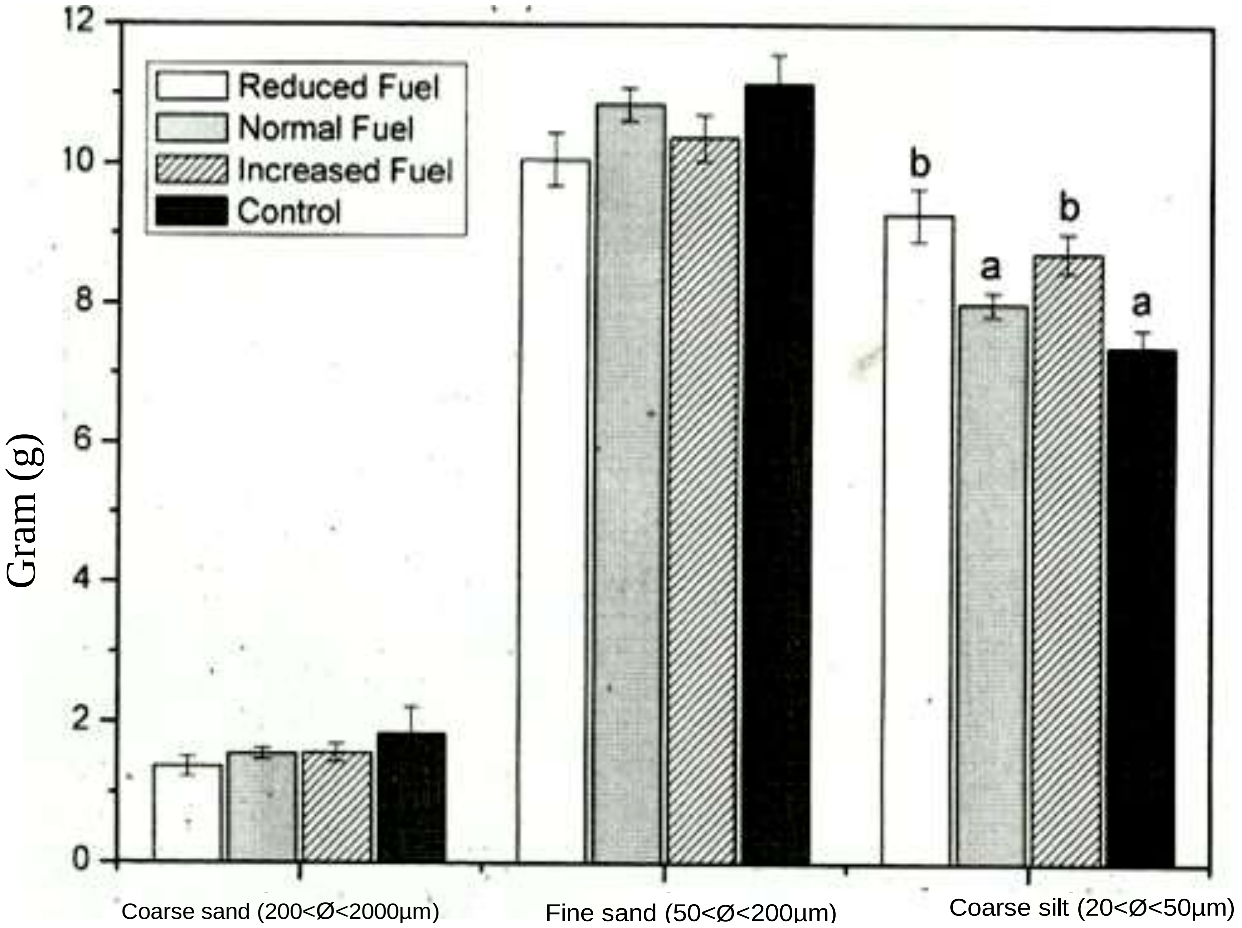

Figure 3. The main effects of fuel load treatment on soil chemical parameters in a Sudanian savanna -woodlands in Burkina Faso. Means with different letters are significantly different (P<0.05) based on Tukey's HSD Test. Capped lines represent standard error.

in the center of the fire front and in its flanks.

Textural changes induced by fires and soil chemical properties in early and control fire

The textural class of all the soils within the studied plots was found to be sandy loam with the sand fraction dominating the particle size distribution at all locations. The results indicated that the coarse silt fraction (20<Ø<50 µm) was similarly higher in plots subjected to increased and reduced fuel loads compared with the control and normal fuel load treatment ($F_{[3, 42]}$= 5.624; p = 0.002). For all fuel load treatments, the content of coarse sand-sized particles was lower than both fine sand and coarse silt fraction (20<Ø<50 µm) (Figure 3).

Overall, on the plots subjected to early fire, pH, soil organic C, C/N, Pt, Nt and CEC were not significantly affected by the fuel load treatment over the three year period (Table 1A, $p > 0.05$). On average, soil pH was nearly 6 and the soil organic C content was 6.5 g/kg. The soil C/N ratio averaged 16 across all fuel load treatments. Pt and CEC averaged 82.52 mg/kg and 3.70 Cmol/kg, respectively (Table 2). The main effect of depth of soil sampling was significant for pH, total C, C/N, and Nt (Table 1A, p < 0.05). Soil pH decreased by 6% from 0-5 cm to 5-10 cm and by 4% from 5-10 cm to 10-15 cm layers. Soil organic C, Nt and CEC were similarly lower in the 5-10 cm and 10-15 cm compared with 0-5 cm. Their quantity decreased by 15, 25 and 30% respectively between 0-5 and 10-15 cm. Fire did not induce changes in soil organic C status as indicated by the non-significant difference between the pre- and post-burn results (p > 0.05). In contrast, soil C/N increased significantly after fire compared to pre-burned soil samples (Table 2). Further, electrical conductivity, Nt, and Pt decreased significantly in the post-fire samples. None of the interaction of the main factors had a significant effect on the measured soil parameters (Table 1). Soil pH, soil organic C and CEC exhibited a highly significant inter-annual variation (Table 1A, within-subject factor). Soil pH in the fire affected soil decreased sharply from the first to

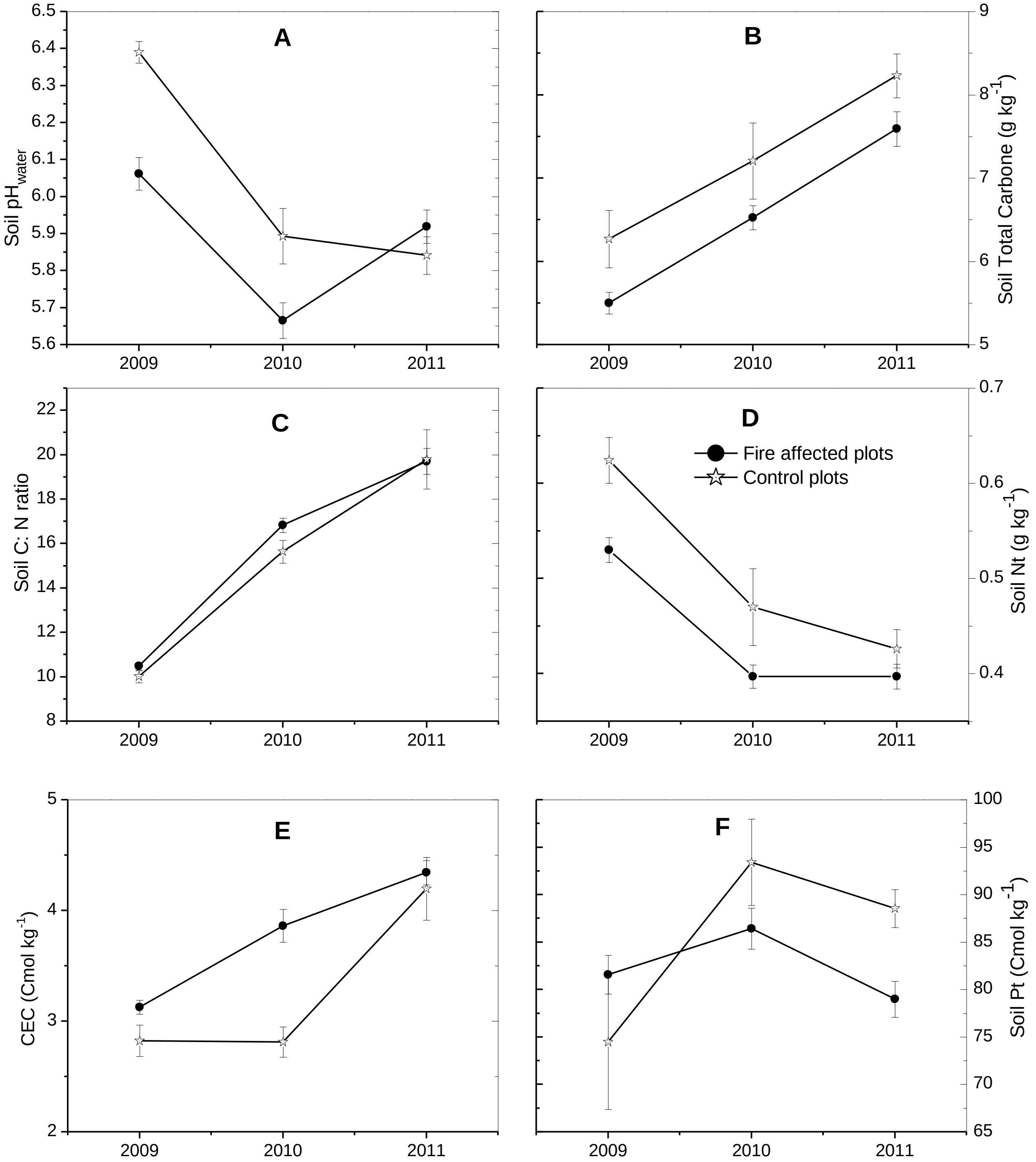

Figure 4. Inter-annual variation in soil chemical properties at the site of Dindéresso in the Sudanian savanna-woodland of Burkina Faso. Capped lines represent standard error.

the second year before increasing slightly during the final year of sampling (Figure 4). Soil organic C, C/N; CEC increased steeply during the study period. Soil Pt fluctuated during the three years with a highest value in 2010. However, soil Nt decreased from the first to the last year (Figure 4). Some of the treatments interacted significantly with the within-subject factor, that is, year. There were significant interaction effects of year and soil conditions (pre- and post-fire environment) on total pH, Pt and CEC (Table 1A).

Time series analysis of the soil parameters on fire protected plots indicated that soil pH and C/N ratio varied significantly with regards to the depth of soil sampling (Table 1B). The pH values varied from 6.18 ± 0.06 to

Table 1. Summary of repeated measures ANOVA for testing the significance of the between-and within-subject effects on chemical properties in a Sudanian savannah-woodland. The factors studies were fuel treatment (Treatment), soil depht (Depht), pre-and post-fire environment (Test.).

Source		**pH water**		**Total C**		**C/N**		**Pt**		**Nt**		**CEC**	
	(A) Fire affected plots												
	df	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Between subject factors													
Treatment	2	2.558	0.091	0.292	0.749	0.171	0.843	0.359	0.701	0.370	0.693	0.813	0.452
Depht	2	131.04	**0.000**	11.80	**0.000**	3.270	**0.050**	1.398	0.260	21.878	**0.000**	0.825	**0.007**
Test	1	21.829	**0.000**	0.043	0.836	8.959	**0.005**	8.588	**0.006**	7.643	**0.009**	67.859	**0.000**
Treatment x Depht	4	0.086	0.986	0.642	0.636	0.559	0.694	0.052	0.995	0.730	0.578	0.757	0.560
Treatment x Test	2	0.696	0.505	1.931	0.160	0.198	0.821	0.193	0.825	0.961	0.392	0.601	0.554
Depth x Test	2	0.082	0.922	0.869	0.428	0.171	0.843	0.291	0.749	0.070	0.933	0.110	0.896
Treatment x Depht x Test	4	0.051	0.995	0.370	0.828	0.439	0.779	0.245	0.911	0.313	0.867	0.094	0.984
Error	36												
Year	2	40.01	**0.000**	31.91	**0.000**	178.72	0.527	2.371	0.101	34.815	0.527	77.304	**0.000**
Year x Treatment	4	0.730	0.574	0.057	0.994	0.347	0.845	0.259	0.903	0.445	0.775	1.620	0.178
Year x Depth	4	0.056	0.994	0.637	0.638	2.068	0.094	0.023	0.999	0.235	0.918	0.695	0.598
Year x Test	2	0.785	**0.001**	0.878	0.420	1.327	0.272	3.454	**0.037**	1.160	0.319	31.14	**0.000**
Year x Treatment x Depth	8	0.112	0.999	0.097	0.999	0.887	0.532	0.122	0.998	0.202	0.990	0.345	0.945
Year xTreatment xTest	4	0.441	0.778	0.840	0.505	2.052	0.096	0.268	0.897	0.370	0.829	1.368	0.253
Year x Depth xTest	4	0.888	0.476	0.218	0.928	0.072	0.990	0.198	0.938	0.134	0.970	0.390	0.815
Year x Treatment xDepth x Test	8	0.163	0.995	0.423	0.904	1.692	0.115	0.079	1.000	0.271	0.973	0.505	0.849
Error	72												
(B) Control plots													
Between subject factors													
Depth	2	10.715	**0.010**	0.141	0.871	6.193	**0.035**	0.031	0.969	0.901	0.455	0.197	0.827
Error	6												
Within subject factors													
Year	2	84.817	**0.000**	14.364	**0.001**	39.048	**0.000**	6.304	**0.013**	13.340	**0.001**	27.192	**0.000**
Year x Deph	4	4.621	**0.017**	1.556	0.249	2.101	0.144	0.101	0.980	0.456	0.767	0.007	1.000
Error	12												

Note that the degrees of freedom of the within-subject factor for testing abundance were Huynh-Feldt adjusted as deemed necessary.

6.00 ± 0.11 and 6.31 ± 0.12 for the 0-5 cm; 5-10 cm and 10-15 cm layers, respectively whereas the C/N ratio increased from 13.87 ± 1.04 to 15.25 ± 1.47 and 16.31 ± 2.13 Cmol/kg, respectively. Further, there was an inter-annual variation in pH, Soil organic C, C/N, Pt, Nt and CEC as well as an

Table 2. The main effects of fuel load treatment, depth of soil sampling and pre-/post-fire environment on soil chemical parameters over three years of prescribed early fire application in the Sudanian savanna -woodlands in Burkina Faso. For each factor, means denoted by the same letter are not significantly different (p <0.05).

Soil properties	Fuel load treatment			Depth of soil sampling			Pre-/Post-fire sampling	
	RF	NF	IF	A[0-5 cm]	B[5-10 cm]	C[10-15 cm]	PRE	POST
pHwater	5.93 ± 0.05^{a}	5.84 ± 0.05^{a}	5.87 ± 0.05^{a}	6.21 ± 0.047^{a}	5.84 ± 0.04^{b}	5.6 ± 0.04^{c}	6 ± 0.04^{a}	5.81 ± 0.04^{b}
Organic C (g/kg)	6.46 ± 0.19^{a}	6.55 ± 0.20^{a}	6.61 ± 0.21^{a}	7.1 ± 0.20^{a}	6.45 ± 0.2^{b}	6.11 ± 0.20^{b}	6.60 ± 0.18^{a}	6.50 ± 0.15^{a}
Nt (g/kg)	0.43 ± 0.02^{a}	0.45 ± 0.02^{a}	0.44 ± 0.01^{a}	0.50 ± 0.02^{a}	0.43 ± 0.01^{b}	0.40 ± 0.01^{b}	0.50 ± 0.001^{a}	0.40 ± 0.01^{b}
C / N	15.86 ± 0.72^{a}	15.64 ± 0.7^{a}	15.5 ± 0.6^{a}	14.75 ± 0.52^{a}	16.02 ± 0.72^{a}	16.25 ± 0.71^{a}	14.900 ± 0.5^{a}	16.44 ± 0.6^{b}
Pt (mg/kg)	82 ± 2.10^{a}	81.56 ± 1.50^{a}	83.52 ± 25^{a}	82.7 ± 2.4^{a}	80.1 ± 2^{a}	84.2 ± 1.85^{a}	85.3 ± 2^{a}	79.34 ± 1.4^{b}
CEC (Cmol/kg)	3.74 ± 0.15^{a}	3.7 ± 0.13^{a}	3.88 ± 0.11^{a}	4.34 ± 0.15^{a}	3.64 ± 0.13^{b}	3.35 ± 0.1^{b}	3.8 ± 0.1^{a}	3.75 ± 0.12^{b}

RF: Reduced fuel load; NF: Normal fuel load; IF: Increased fuel load; CT: Control.

Table 3. Inter-annual variation in properties in fire protected plots in the Sudanian savanna - woodlands in Burkina Faso.

Soil properties	Year-2009	Year-2010	Year-2011
pHwater	6.4 ± 0.03	5.9 ± 0.07	5.84 ± 0.05
Organic C (g/kg)	6.3 ± 0.35	7.21 ± 0.46	8.23 ± 0.26
Nt (g/kg)	0.62 ± 0.02	0.47 ± 0.04	0.43 ± 0.02
C/N	10.004 ± 0.3	15.63 ± 0.51	19.7 ± 1.34
Pt (mg/kg)	74.45 ± 7.07	93.40 ± 4.56	88.52 ± 2
CEC (Cmol/kg)	2.82 ± 0.14	2.81 ± 0.14	4.196 ± 0.1

interaction between year and depth of sampling. Soil pH and Nt decreased during the course of the study period while C, C/N, Pt, and CEC increased from the first to the third year (Table 3).

DISCUSSION

Fire behavior

There was an inter-annual variation in the pre-burn fuel load, which could be explained by the variability in the amount and distribution of rainfall observed during the course of the study. In the NF, without any manipulation of biomass, the total fuel load varied to 0.48 ± 0.23; 1.40 ± 0.70; 0.4±0.12 t/ha for 2009; 2010; 2011 respectively (Figure 3). Therefore, the wettest year seems to induce an important production of fuel (Figure 2). This trend concurs with Govender et al. (2006) that observed increase in fuel load increased with rainfall in a range of only two consecutive years.

Despite the variation in fuel load, only the first year of study (2009) presented significant variations in fire intensity. This parameter increased significantly in increased fuel load plot. The biomasses obtained from the different plots were low compared to other studies. We obtained biomasses ranging from 0.75 to 1.56 t/ha, whereas on sites protected from fires and animal grazing. Previous studies reported phytomass ranging from 2.5 to 4 t/ha for *Andropogon gayanus* fallow and *Andropogon ascinodis*/*Loudetia togoensis* savanna, respectively (Sow et al., 2013). As the protected forest of Dindéresso lies close to an urban area, it is subject to frequent grass biomass removal, namely for animal feeding and for handicraft. This may explain the low biomass obtained. The highest measured temperature reached 657±36°C. Similar temperatures were also obtained at 0 cm on the soil surface by previous studies (Savadogo et al., 2012). The temperature decreased between 24°C and 40°C at 10 cm from soil surface (Dayamba et al., 2010; Savadogo et al., 2012). In this study, the temperature was measured only in the flaming front. This temperature emitted from the combustion of biomass is transferred to the mineral soil layers (DeBano et al., 1999). Many studies have reported that overall fire temperature increases with fuel load (Hély and Alleaume, 2006) and that fire behavior is determined by fuel physical properties and weather parameters. For instance, the positive effect of wind speed has been attributed to an enhanced supply of oxygen to the fire (Trollope et al., 2004), which stimulates heat transfer by conduction or radiation, resulting in pre-heating of the fuel ahead of the fire front (Savadogo et al., 2007b). Wind direction and speed are known to affect the rate of fire spread due to tilting of the flames towards the fuel ahead of the fire (Sow et al., 2013). In the present study, fires were burnt under a relatively narrow range of weather conditions. Therefore, no such effect was observed. However, an interannual variation in fire intensity was observed due to the annual variation of rainfall that affects the amount of fuel. The cutting of the fuel and its homogeneous distribution on the ground before setting the fire could explain the observed lack of difference in rate of spread. Indeed the main characteristic of fuel that influences the spread of fire is the continuity of the fuel bed, that is, how unbroken the fuel bed is (Cheney and Sullivan, 2008). Indeed, this practice results in better distribution and less spatial heterogeneity in the fuel bed on the ground surface, promoting combustion that is more continuous and progresses with constant speed.

Textural and soil chemical properties changes induced by fires

The results show that, generally, burning has no effect on the particle size distribution, which is supported by Oswald et al. (1999), who reported that burning does not cause dramatic changes in soil texture. The main components contributing to soil texture (sand, silt, and clay) have high temperature thresholds and are not usually affected by fire (DeBano and Neary 2005), because most fires do not cause sufficient soil heating to produce significant changes in soil physical properties. This is particularly true for low intensity prescribed fires in savanna because elevated soil temperatures are usually brief and not depth penetrating (Savadogo et al., 2007a).

Contrary to expectations, the fuel load treatment during early fire did not significantly modify the chemical characteristics of the burnt soil, such as pH, Soil organic C, C/N, total nitrogen, total phosphorus and CEC. This, can primarily be explained by the fact that, despite the variation in the quantity of fuel (normal, increased or reduced), the measured temperatures were statistically similar. The values of soil pH, Soil organic C, Nt, CEC were significantly dependent on the depth of soil sampling. The increase in chemical elements on the soil superficial horizon can be explained by nutrient enrichment due to ash deposition. Indeed, in the post-fire environment, some of the nutrients accumulated in the aboveground biomass and litter are deposited as ash, which contains various amounts of available nutrients depending on the fire severity (Gimeno-Garcia et al., 2000). Black ashes are known to be rich in organic matter, containing more than 90%, whereas grey ashes contain about 12 to 55% (Gimeno-Garcia et al., 2000). Moreover, dead roots and twigs could provide an additional source of carbon to the soil (Knicker et al., 2005). However, the fire did not induce significant changes in the amount of total carbon. These results are in agreement with the previous studies (Jensen, 2001). Further, analysis of the results showed that the values of pH, total nitrogen and total phosphorus decreased significantly after the passage of fire, unlike in previous studies (Aref et al., 2011). An increase in pH has been commonly explained by the presence of ash and accumulation of potassium, sodium hydroxide, magnesium, calcium carbonate, as well as the destruction of certain groups of acids in the organic matter (Schafer and Mack, 2010). However, Giovannini et al. (1990) consider that the pH value is related to the combustion temperature; higher temperatures (> 460°C) during the fire induce increase in pH whereas lower temperatures (<220°C) result in decrease of pH. The amounts of nitrogen were also reduced after fire, most likely due to rapid loss by volatilization. Indeed, nitrogen is readily lost by volatilization at 200°C in the form of gas and ash (Christensen, 1994), while at 500°C, more than half of the nitrogen is lost to the atmosphere (Knicker et al., 2005). Phosphorus may also be lost by volatilization (Prieto-Fernandez, 2004). Further, the results indicated a significant inter-annual variation of pH, CEC and Pt. Since the impact of fire depends on the environmental conditions during burning, the inter-annual variation in fuel load and the rainfall variation over the three years of study may explain the observed variation in the effects of fire on the soil parameters.

Conclusions

Fire is a widespread process in the earth system and plays a key role in ecosystem composition distribution and function. The aim of this study is to evaluate the modification induced in soil physicochemical properties by repeated and prescribed burning for different fuel load treatment. The result of this study showed some variations with depth of soil sampling and superficial layers have got the highest nutritive elements. This could be attributed to the release of nutrients accumulated in the aboveground biomass and litter after deposition as ashes, which contain different amounts of nutrients depending on the severity of fires. Furthermore, there was no effect of fuel load treatment on the soil properties. The biomass is not abundant in these savannah regions. Therefore, fire apply early does not affect directly and in the short term, the chemical and physical properties of the soil. However, a long-term study should be carried out in order to be able to identify the possible long-term impact on soil physicochemical properties.

The findings from the present study have an important implication for current savanna–woodland management: early fire seems to be a good management option from a soil perspective, striking a balance between total fire protection (which is utopian) and the occurrence of intense late fire. However, studies on the late season burns need to be thorough and globally on environment could be more damaging. Nevertheless, the application of annual early fire should continue with due consideration of the timing of burning, weather conditions and other possible factors related to fuel properties that influence fire intensity.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

Funding for this study was provided by International Foundation for Science (Grant Agreement No. C/4816-1). The author appreciates Amoro Ouattara and Pascal T. Simporé for their help during the soil sampling and analysis. Thanks are also due to Dr Zacharia Gnankambary and Dr Jacques Gignoux for reviewing the early version of the manuscript. They are grateful to Dr John Blackwell and Sees–editing Ltd for linguistic improvements.

REFERENCES

Afnor (1981). Détermination du pH. (Association française de normalisation) NF ISO 103 90. In AFNOR Qualité des sols, Paris, 339-348.

Archibald S, Staver AC, Levin SA (2012). Evolution of human-driven fire regimes in Africa. Proceedings of the National Academy of Sciences of the United States of America 109(3)L847-852.

Aref IM, Atta HA, Ghamade AR (2011). Effect of forest fires on tree diversity and some soil properties. International Journal of Agriculture and Biology 13(5):659-664.

Badia D, Marti C, Aguirre AJ, Aznar JM, Gonzalez-Pérez JM, De la Rosa JM, Leon J, Ibarra P, Echeverria T (2014). Wildfire effects on nutrients and organic carbon of a Rendzic Phaeozem in NE Spain: Changes at cm-scale topsoil. Catena 113:267-275.

Bellefontaine R, Gaston A, Petrucci Y (2000). Management of natural forests of dry tropical zones. (Conservation guide 32) Food and Agriculture Organization of the United Nations (FAO). Rome, Italy, 318p.

Byram GM (1959). Combustion of forest fuels. In ‘Forest Fire: Control and Use’. (Ed. KP Davis) (McGraw-Hill: New York).

Certini G (2005). Effects of fire on properties of forest soils: A review. Oecologia 143(1):1-10.

Cheney P, Sullivan A (2008). Grassfires, fuel, weather and fire behaviour. 2^{nd} edn. (CSIRO Publishing: Melbourne).

Christensen NL (1994). The effect of fire on physical and chemical properties of soil in Mediterranean-climate shrublands. in J. M. Moreno and W. C. Oechel, editors. The role of fire in Mediterranean-type ecosystems. Springer-Verlag, New York, New York, USA, pp. 79-95.

Davis CS (2002). Statistical methods for the analysis of repeated measurements. Springer, London.

Dayamba SD, Savadogo P, Zida D, Sawadogo L, Tiveau D, Oden PC (2010). Fire temperature and residence time during dry season burning in a Sudanian savanna-woodland of West Africa with implication for seed germination. Journal of Forestry Research 21(4):445-450.

DeBano LF, Neary DG (2005). Effects of fire on soil. In ‘Wildland Fire in Ecosystems: Effects of Fire on Soil and Water’. (Eds DG Neary, KC Ryan, LF DeBano) USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42:4:21-92(Ogden, UT).

DeBano LF, Neary DG, Ffolliott P (1999). Fire's effects on ecosystems. John Wiley. JohnWiley & Sons, NewYork, NY.

Delmas RA, Loudjani P, Podaire A, Menaut JC (1991). Biomass burning in Africa: an assessment of annually burned biomass. In: Levine, S.J. (Ed.), Global Biomass Burning. Atmospheric, Climatic and Biospheric Implications. The MIT Press, Cambridge, Massachusetts, pp. 126-132.

Doamba SW, Savadogo P, Nacro HB (2014). Effects of burning on soil macrofauna in a savanna-woodland under different experimental fuel load treatment. Applied Soil Ecology 81:31-44.

Driessen P, Deckers J, Spaargaren O (2001). Lecture notes on the major soils of the world. FAO World Soil Resources Reports-94. Food and Agriculture Organization of the United Nations, Rome.

Feller C (1979). Une méthode de fractionnement granulométrique de la matière organique des sols: Application aux sols tropicaux, à textures grossières, très pauvres en humus. Cah. ORSTOM, sér. Pédol 17, 339-346.

Fontès J, Guinko S (1995). Carte de la végétation et de l'occupation du sol du Burkina Faso. Ministère de la Coopération Française, France.

Frost P, Medina E, Menaut JC, Solbrig OT, Swift M, Walker B (1986). Responses of Savannas to Stress and Disturbance: A Proposal for a Collaborative Programme of Research. Biology International, Special Issue, No. 10. (International Union of Biological Sciences: Paris).

Gimeno-Garcia E, Andreu V, Rubio JL (2000). Changes in organic matter, nitrogen, phosphorus and cations as a result of fire and water erosion in a Mediterranean landscape. European Journal of Soil Science 51(2)201-210.

Giovannini G, Lucchesi S, Giachetti M (1990). Effect of heating on some chemical parameters related to soil fertility and plant growth. Soil Science 149(3):344-350.

Govender N, Trollope WSW, Van Wilgen BW (2006). The effect of fire season, fire frequency, rainfall and management on fire intensity in savanna vegetation in South Africa. Journal of Applied Ecology 43(4):748-758.

Hély C, Alleaume S (2006). Fire regimes in dryland landscapes. In: D’odorico, P., Porporato, A. (Eds.), Dryland Ecohydrology. Springer, pp. 283-301.

Hewitt JE, Thrush SE, Cummings VJ (2001). Assessing environmental impacts: Effects of spatial and temporal variability at likely impact scales. Ecological Applications 11(5):1502-1516.

Jensen M, Michelsen A, Gashaw M (2001). Responses in plant, soil inorganic and microbial nutrient pools to experimental fire, ash and biomass addition in a woodland savanna. Oecologia 128(1):85-93.

Knicker H, Gonzalez-Vila FJ, Polvillo O, Gonzalez JA, Almendros G (2005). Fire-induced transformation of C- and N-forms in different organic soil fractions from a Dystric Cambisol under a Mediterranean pine forest (*Pinus pinaster*). Soil Biology and Biochemistry 37(4):701-718.

Kugbe J, Fosu M, Tamene LD, Denich M, Vlek PLG (2012). Annual vegetation burns across the northern savanna region of Ghana: period of occurrence, area burns, nutrient losses and emissions. Nutrient Cycling in Agroecosystems 93(3):265-284.

Metson AJ (1956). Methods of chemical analysis for soil survey samples. New Zealand Soil Bureau Bulletin No. 12.

Midgley JJ, Lawes MJ, Chamaille-Jammes S (2010). Savanna woody plant dynamics: The role of fire and herbivory, separately and synergistically. Australian Journal of Botany 58(1):1-11.

N'Dri AB, Gignoux J, Barot S, Konaté S, Dembélé A, Werner PA (2014). The dynamics of hollowing in annually burnt Savanna trees and its effect on adult tree mortality. Plant Ecology 215(1):27-37.

N'Dri AB, Soro TD, Gignoux J, Dosso K, Koné M, N'Dri JK, Koné NA, Barot, S (2018). Season affects fire behavior in annually burned humid Savanna of West Africa, Fire Ecology 14(2):5

Olsen SR, Dean LA (1965). Phosphorus. Methods of soil analysis. Ed. C.A.Black. American Society of Agronomy, Madison, Wisconsin.

Oswald BP, Davenport D, Neuenschwander LF (1999). Effects of slash pile burning on the physical and chemical soil properties of Vassar soils. Journal of Sustainable Forestry 8(1):75-86.

Pricope NG, Binford MW (2012). A spatio-temporal analysis of fire recurrence and extent for semi-arid savanna ecosystems in southern Africa using moderate-resolution satellite imagery. Journal of Environmental Management 100:72-85.

Prieto-Fernandez A, Carballas M, Carballas T (2004). Inorganic and organic N pools in soils burned or heated: Immediate alteration and evolution after forest wildfires. Geoderma 121(3-4):291-306.

Savadogo P, Santi S, Dayamba SD, Nacro HB, Sawadogo L (2012). Seasonal variation of fires temperature and influence on soil respiration, root biomass and soil water properties in a Sudanian savanna-woodland, West Africa. Autralian Journal of Soil Research 50(3):195-206.

Savadogo P, Sawadogo L, Tiveau D (2007a). Effect of grazing intensity and prescribed fire on soil physical and hydrological properties and pasture yield in the savanna woodland of Burkina Faso. Agriculture ecosystem and environment 118(1-4):80-92.

Savadogo P, Tigabu M, Sawadogo L, Oden PC (2009). Examination of multiple disturbances effects on herbaceous vegetation communities in the Sudanian savanna-woodland of West Africa. Flora-Morphology, Distribution and Functional Ecology of Plants 204(6):409-422.

Savadogo P, Tiveau D, Sawadogo L, Tigabu M (2008). Herbaceous species responses to long term effects of prescribe fire, grazing and selective cutting tree in the savanna-woodland of west Africa. Perspectives in Plant Ecology, Evolution and Systematics 10(3):179-195.

Savadogo P, Zida D, Sawadogo L, Tiveau D, Tigabu M, Oden PC (2007b). Fuel and fire characteristics in savanna-woodland of West Africa in relation to grazing and dominant grass type. International Journal of Wildland Fire 16(5):531-539.

Schafer JL, Mack MC (2010). Short-term effects of fire on soil and plant nutrients. Plant Soil 334(1-2):433-447.

Snyman HA (2003). Short-term response of rangeland following an unplanned fire in terms of soil characteristics in a semi-arid climate of South Africa. Journal of Arid Environments 55(1):160-180.

Sow M Hély, Mbow C, Sambou B (2013). Fuel and fire behavior analysis for early-season prescribed fire planning in Sudanian and Sahelian savannas. Journal of Arid Environments 89:84-93.

Stoof CR, Wesseling JG, Ritsema CJ (2010). Effects of fire and ash on soil water retention. Geoderma 159(3-4):276-285.

Trollope WSW, de Ronde C, Geldenhuys C.J (2004). Fire behaviour. In 'Wildland Fire Management Handbook for Sub-Saharian Africa. (Ed. JG Goldammer) pp. 27-59. Global Fire Monitoring Centre: Freiburg, Germany.

Trollope WSW, Trollope LA, Hartnett DC (2002). Fire behaviour: A key factor in the ecology of african grasslands and savannas. Millpress, Rotterdam.

Trollope WSW, Potgieter ALF (1985). Fire behaviour in the Krugger National Park. Journal of the Grassland Society of South Africa 2(2): 17-22.

Van Straaten O, Doamba SWMF, Corre MD, Veldkamp E (2019). Impacts of burning on soil trace gas fluxes in two wooded savanna sites in Burkina Faso, Journal of Arid Environments 165:132-140

Verma S, Jayakumar S (2012). Impact of forest fire on physical, chemical and biological properties of soil: A review. Proceedings of the International Academy of Ecology and Environmental Sciences 2:168-176.

Walinga I, Van Vark W, Houba VJG, Van der lee JJ (1989). Plant analysis procedures. Department Soil Science Plant Nutrition. Wageningen Agricultural University. Syllabus, part 7. pp 197-200.

Walkley A, Black IA (1934). An examination of the Degtjareff method for determining soil organic mater and a proposed modification of the chromic acid titration method. Soil Science 37(1):29-38.

Whelan RJ (1995). The ecology of fire. Cambridge University Press, Cambridge.