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www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2007, **16**, 531–539

Fuel and fire characteristics in savanna–woodland of West Africa in relation to grazing and dominant grass type

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Abstract. Fuel characteristics, fire behaviour and temperature were studied in relation to grazing, dominant grass type and wind direction in West African savanna–woodland by lighting 32 prescribed early fires. Grazing significantly reduced the vegetation height, total fuel load, and dead and live fuel fractions whereas plots dominated by perennial grasses had higher values for vegetation height, total fuel load and the quantity of live fuel load. Although fire intensity remained insensitive ($P > 0.05$) to any of these factors, fuel consumption was significantly ($P = 0.021$) reduced by grazing, rate of spread was faster in head fire ($P = 0.012$), and flame length was shorter in head fire than back fire ($P = 0.044$). The average maximum temperature was higher ($P < 0.05$) on non-grazed plots, on plots dominated by annual grasses, on plots subjected to head fire, and at the soil surface. Lethal temperature residence time showed a nearly similar trend to fire temperature. Wind speed and total fuel load were best predictors of fire behaviour parameters (R^2 ranging from 0.557 to 0.862). It can be concluded that grazing could be used as a management tool to modify fire behaviour, back fire should be carried out during prescribed burning to lower fire severity, and the fire behaviour models can be employed to guide prescribed early fire in the study area.

Additional keywords: Burkina Faso, fire behaviour model, fuel load, fuel moisture, weather variables.

Introduction

Fire has been an important ecological component of African savanna ecosystems for millennia (Goldammer 1990; Scholes and Walker 1993; van Langevelde *et al*. 2003). In the Sudanian savanna–woodland alone, an area stretching from Senegal in the west to the Ethiopian highlands in the east at 6–13°N (Menaut *et al*. 1995), between 25 and 50% of the savanna woodland burns annually (Delmas *et al*. 1991), primarily owing to anthropogenic causes. In most protected Sudanian savanna–woodlands, prescribed early fire (burning taking place between October and December–January) has been adopted as an ecosystem 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; Sawadogo *et al*. 2005; Laris and Wardell 2006). It is generally believed that fires burning early in the dry season tend to be of lower intensity as the predominantly herbaceous fuel still holds higher moisture than later during the dry season (Liedloff *et al*. 2001).

Fire behaviour is defined as what the fire achieves, the dynamics of the fire event, the manner in which it occurs, and the factors that influence the release of heat energy (Trollope 1983). It is often characterised by fire intensity, rate of spread, flame height and fuel consumption (Trollope 1984). Fire intensity is the most important parameter because it determines the amount of heat released per time unit during conflagration and is thus a useful indicator of its impact on plants (Trollope 1984; Gambiza *et al*. 2005). It is influenced by a wide range of variables such as topography, fuel characteristics, vegetation structure, the season of burning, and weather conditions (Pyne *et al*. 1996). The species composition and spatial distribution of available fuel loading affect the ease of ignition as well as fire size and intensity whereas fuel moisture content increases the amount of heat necessary to reach the point of ignition (Cochrane 2003). In tropical savanna ecosystems, the fuel load is mainly composed of herbaceous vegetation that makes up 75–90% of total annual biomass (Garnier and Dajoz 2001) with high amounts of standing dead fuel, resulting in high combustibility and fire risk (Hennenberg *et al*. 2006). In terms of species composition, the herbaceous fuel is composed of both annuals and perennials in varying proportions, which in turn influence fire behaviour. The annual grasses dry earlier at the end of the rainy season and burn easily, whereas the perennial grasses hold a relatively high moisture content and burn more slowly. Weather conditions, including ambient air temperature, relative humidity, and wind direction and velocity affect fire behaviour (Trollope 1984; Trollope *et al*. 2002). Wind conditions have a dominant influence on fire behaviour; particularly, wind speed affects the rate of fire spread and flame

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height (Bilgili and Saglam 2003). Relative air humidity and air temperature affect fire behaviour indirectly through their effect on the moisture content of vegetation and litter (Bond and van Wilgen 1996).

Herbivores generally reduce fuel load by herbage removal and trampling and therefore lower the intensity and frequency of fires. For example, moderate level of grazing and prescribed burning early in the dry season are used for limiting the extent and severity of late fire in southern Africa (Frost *et al*. 1986; Shea *et al*. 1996). As fire and grazing regimes can be manipulated directly, they are potentially important ecosystem management tools (Frost *et al*. 1986; Liedloff *et al*. 2001). In West Africa, the management of savanna–woodland ecosystems entails application of prescribed early fire while precluding grazing by livestock (Bellefontaine *et al*. 2000). Recent studies, however, have shown that a moderate level of grazing has no detrimental effect on seedling and sapling recruitment of woody species (Zida *et al*. 2007) and on coppice growth (Sawadogo *et al*. 2002) as well as on herbaceous plant cover and phytomass (Savadogo *et al*. 2007). An understanding of the relationship between grazing and fire behaviour is essential to critically examine the current management prescription. Thus, the present study was performed to address the following questions:

1. Do fuel characteristics vary between grazed and non-grazed plots, as well as between plots dominated by annual or perennial grasses?
2. Do grazing treatment, dominant grass type and wind direction influence fire behaviour, maximum fire temperature and residence time of lethal temperatures?
3. Do fuel characteristics and weather data satisfactorily predict fire behaviour?

Materials and methods

Description of study site

The study was conducted in Tiogo State forest (12°13′N, 2°42′W) located at an altitude of 300 m above sea level in Burkina Faso, West Africa. The Tiogo State forest (called forêt classée) was delimited by the colonial French administration in 1940 and covers 30 000 ha. It is situated along the only permanent river in the country (Mouhoun, formerly known as Black Volta). Phytogeographically, it is situated in the Sudanian regional centre of endemism in the transition from the north to the south Sudanian Zone (White 1983). The unimodal rainy season lasts ~6 months, from May to October. The mean annual rainfall for the years 1992–2005 was 851 ± 49 mm (mean ± s.e.) with inter-annual variability. The number of rainy days per annum during this period was 67 ± 3 (mean ± s.e.). Mean daily minimum and maximum temperatures were 16 and 32°C in December–January (the coldest period) and 26 and 40°C in April (the hottest month). Most frequently encountered are Lixisols according to the FAO soil classification system (Driessen *et al*. 2001). The soils are mainly deep (>75 cm) silt–clay and are representative of large tracts of the Sudanian Zone in Burkina Faso (Pallo 1998).

The vegetation is a tree and bush savanna with a grass layer dominated by the annual grasses *Andropogon pseudapricus* Stapf. and *Loudetia togoensis* (Pilger) C. E. Hubbard as well as the perennial grasses *Andropogon gayanus* Kunth. and *Diheteropogon amplectens* W. D. Clayton (Sawadogo *et al*. 2005). In the study area, these two perennial grasses are the most important species owing to their fodder value and their use in local construction (roof-thatching and fences) and handicraft. The main forb species are *Cochlospermum planchonii* Hook. F., *Borreria stachydea* (DC.) Hutch. & Dalz., *Borreria radiata* DC. and *Wissadula amplissima* Linn. The woody vegetation component is dominated by species in the families Mimosaceae and Combretaceae. The most common woody species are *Acacia macrostachya* Reichenb. ex Benth., *Combretum nigricans* Lepr. ex Guill. & Perr. and *Combretum glutinosum* Perr. ex DC. The Tiogo State forest is subjected to annual early fire and grazing. The livestock-carrying capacity at Tiogo State forest was estimated at 1.4 Tropical Livestock Unit ha^{-1} (TLU ha^{-1}) (Sawadogo 1996) and the grazing pressure at the experimental site was about half of this capacity. The mean herbaceous biomass production during the period 1993–2003 was 3.47 ± 1.37 t dry matter ha^{-1} (mean ± s.e.) (Savadogo *et al*. 2007).

Experimental set-up and burnings

The present study is part of a larger factorial experiment with four replicates of 4.5 ha each established for studying the long-term ecological effects of grazing, prescribed fire and selective tree cutting on savanna–woodland ecosystems (Sawadogo *et al*. 2005). In the present study, we examined the effects of grazing (with or without), vegetation types (annual *v.* perennial grass), and wind direction (back fire *v.* head fire) on fire behaviour parameters. The experimental site was first split into two main plots: grazed plot (open for livestock grazing) and non-grazed plot (fenced at the start of the experiment in 1992 to exclude livestock). The grazing intensity in the grazed main plot was moderate; i.e. half the carrying capacity. A total of 32 plots (20 × 20 m) were used in the present study, of which 16 plots each were from grazed or non-grazed areas. The 16 plots were further grouped into 8 plots based on the dominant vegetation type (annual *v.* perennial grasses). Four of the 8 plots were subjected to back fire while the other four were subjected to head fire. The experimental layout is shown in Fig. 1. All plots were located on flat ground to eliminate the influence of slope on fire behaviour. Fire was ignited with a drip torch along one side of each plot at a time to rapidly establish a fire-line and to ensure linear ignition. To examine the influence of wind direction on fire behaviour, fire was ignited in an east-to-west direction (head fire) in half of the plots or in the opposite direction, west to east, in the other half (back fire). Each plot was surrounded by fire breaks and five to eight people were standing by to extinguish the fire once it reached the plot edge. All burns (32 fires) were conducted early in the morning (0500 to 0700 hours) or late in the afternoon (1700 to 1900 hours) for 5 consecutive days from 30 November to 4 December 2005. Such a schedule enabled us to reduce the variation in fuel moisture that could be caused by an extended period of burning.

Assessment of fuel characteristics

Fuel characteristics were described by the following variables: fuel load (kg m^{-2}) and composition, moisture content of the fuel (%), and vegetation cover (%) and height (cm). Fuel characteristics were assessed on two occasions, pre- and post-burning in

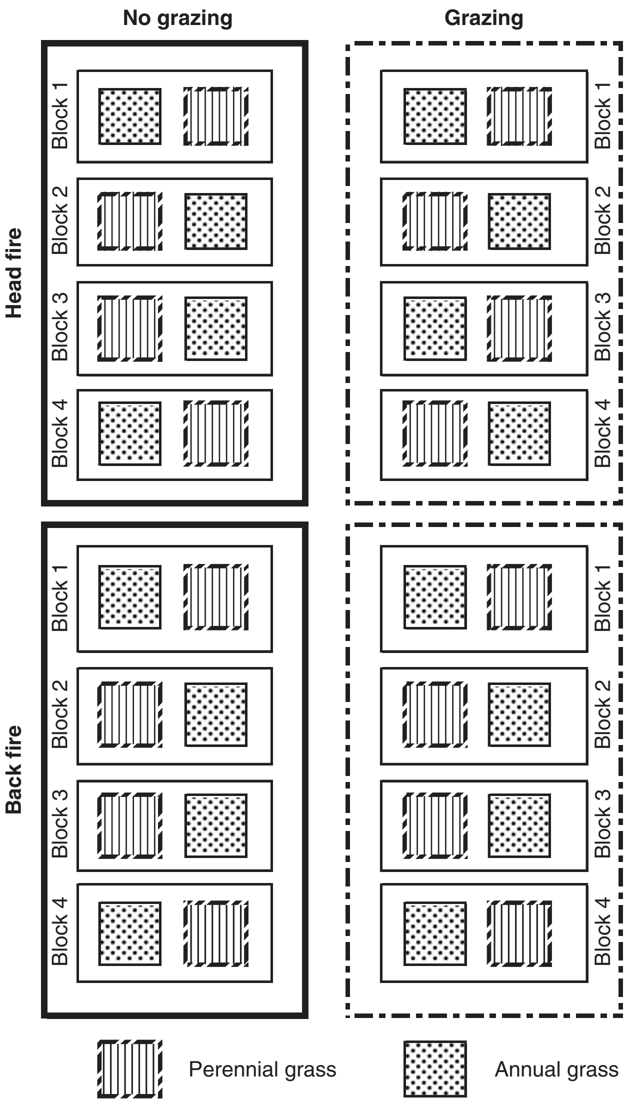

Fig. 1. Experimental set-up.

order to compute fuel consumption later on. To assess fuel loads, six quadrats of 1 × 1 m in each plot were established, which were further divided into four equal parts. Fuels were collected in two diagonal parts of each quadrat shortly before burning to determine the pre-burn fuel load, while fuels in the other two diagonal parts were collected after the fire was extinguished to determine the post-burn fuel load. Both the pre- and post-burning fuels were separated into litter (defined as dead and fallen tree and grass leaves), live fuel (green standing grass and herbs) and dead fuel (dead standing grass and stems), and immediately weighed. For moisture content determination, 32 samples of litter, dead and live fuels were bagged separately, sealed and then oven-dried at 80°C until constant dry weight was reached. Moisture content was then calculated on a dry weight basis. The height and cover of the vegetation were determined as the vertical distance (to the nearest 5 cm) from the ground to the tip of the shoot and using the point intercept sampling procedure (Levy and Madden 1933), respectively.

Weather data

During the experimental fires, open wind speed, air temperature and relative humidity were recorded every minute on each plot using an *in situ* automatic weather station placed at 1.8 m above ground. For recording wind speed and air temperature, a handheld anemometer with integrated temperature reader (Model Silva ALBA Windwatch, Horw, Switzerland) was used while a digital thermo-hygrometer (Model S-631 07 Termometerfabriken, Eskilstuna, Sweden) was used for recording the relative humidity. The recorded values were averaged over the period of fire propagation for each plot.

Fire behaviour parameters

The fire behaviour was characterised by the following parameters: fuel consumption, rate of spread, fire intensity, and flame height. The fuel consumption was computed as the difference between the pre- and post-burn fuel loads. The rate of spread was determined by recording the time the fire front took to arrive at the pre-placed, 5 m apart poles on either side of the burning plot. A reading on the progression of the fire was recorded for every 5-m distance to estimate the mean rate of spread during head fire and back fire. Fire intensity was estimated using Byram's (1959) equation:

$$I = H \times w \times r$$

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}), r = rate of spread (m s^{-1}). The heat value (H) developed for grass fuel of head (16 890 kJ kg^{-1}) and back fires (17 781 kJ kg^{-1}) (Trollope 1983) were adopted to calculate the fire intensities. Flame height of the moving fires was measured vertically from the ground. The pre-placed poles along the sides of the plots at an interval of 5 m were used to measure the mean flame height. The occasional higher flashes when the foliage of a tree or shrub burst into flames were not considered. Each fire was photographed with the painted poles in sight. These photographs were later used to verify the height of the flames.

Fire temperature and residence time

To examine whether maximum temperature and residence time show spatial variation (vertical position) with elevation below or above the surface of the plot, we simultaneously registered fire temperatures at 10, 5, and 2 cm below ground, at the surface (0 cm) and at 20, 50, 150, 300, and 500 cm above the surface of each plot using MiniCube data loggers with 10 thermo elements type-K (Model VC, Environmental Measuring Systems, Brno, Czech Republic). Each probe was made of a 30-m length of double-stranded wire (high temperature thermocouple cable type HH-KI-24-SIE) by removing 1 cm of insulation and twisting the bare ends together. The probes were connected to the loggers programmed to record data every 5 s and to store the average of two measurements every 10 s. For each burnt plot, the maximum temperature at each probe position from 10 cm below ground to 500 cm above ground was considered during data analysis. The series of temperature measurements at each probe position were used to calculate residence time above 60°C, defined as the time taken by maximum fire temperature to stay above 60°C, as temperature above 60°C is considered lethal for plant tissues (Daniell *et al*. 1969).

Statistical analyses

The effects of grazing treatments (G_i), vegetation type (V_j), wind direction (W_k), probe location (P_l) and their interactions, with m replicates (m varies from 1 to 4), on pre-burn fuel characteristics (see model 1 below), fire behaviour parameters (see model 2 below) and maximum fire temperature and residence time above 60°C (see model 3 below) were subjected to analysis of variance using the following linear models:

$$Y_{ijm} = \mu + G_i + V_j + G_iV_j + e_{ijm} \quad (1)$$

$$Y_{ijkm} = \mu + G_i + V_j + W_k + G_iV_j + G_iW_k + V_jW_k + G_iV_jW_k + e_{ijkm} \quad (2)$$

$$Y_{ijklm} = \mu + G_i + V_j + W_k + P_l + G_iV_j + G_iW_k + G_iP_l + V_jW_k + V_jP_l + W_kP_l + G_iV_jW_k + G_iV_jP_l + G_iW_kP_l + V_jW_kP_l + G_iV_jW_kP_l + e_{ijklm} \quad (3)$$

In these models Y_{ijm}, Y_{ijkm} and Y_{ijklm} were the response variables, μ was the overall mean, and e_{ijm}, e_{ijkm} and e_{ijklm} were the error terms. Data were checked for normality and homoscedasticity before running ANOVA, and no assumptions were violated. We also examined the plot of standardised residual *v.* fitted values and found no special structure, suggesting independence of the residuals. Multiple comparisons were made with Tukey's test to detect differences between probe locations at the 5% level of significance. Correlation analyses were also performed to examine the relationship between fire behaviour parameters and fuel characteristics and weather data. Fire behaviour prediction models were derived by stepwise multiple regressions (backward elimination with 5% significance level) using both fuel characteristics and weather data as predictors. The magnitude of grazing effect was determined by a statistic called partial eta squared (η_p^2), and the effect was considered as small, moderate or large if the value of this statistic was 0.01, 0.06 or 0.14, respectively (Cohen 1988).

Results

Fuel characteristics

Pre-burn fuel characteristics were differentially affected by the grazing treatment, the vegetation type and their interaction. Vegetation height ($F_{1,28} = 11.70$, $P = 0.002$), total fuel load ($F_{1,28} = 25.04$, $P < 0.0001$), dead fuel load ($F_{1,28} = 13.38$, $P = 0.001$) and live fuel load ($F_{1,28} = 13.59$, $P = 0.001$) were significantly reduced on grazed plots compared with non-grazed plots (Table 1). The magnitude of grazing effect was large for these fuel characteristics ($\eta_p^2 = 0.472$, 0.327, 0.323 and 0.295 for total fuel consumption, live fuel load, dead fuel load and plant height, respectively). At all levels of grazing treatments, plots dominated by perennial grasses had significantly higher values for vegetation height ($F_{1,28} = 79.42$, $P < 0.0001$), total fuel load ($F_{1,28} = 16.76$, $P < 0.0001$), and live fuel load ($F_{1,28} = 54.54$, $P < 0.0001$) than plots dominated by annual grasses. The interaction effect of grazing treatment and vegetation type was significant for the quantity of litter fuel ($F_{1,28} = 12.35$, $P = 0.002$) and live fuel fractions ($F_{1,28} = 13.19$, $P = 0.001$). The amount of litter fuel fraction was higher on non-grazed than on grazed plots that were dominated by annual grasses whereas it was nearly the same in both grazed and non-grazed plots that were dominated

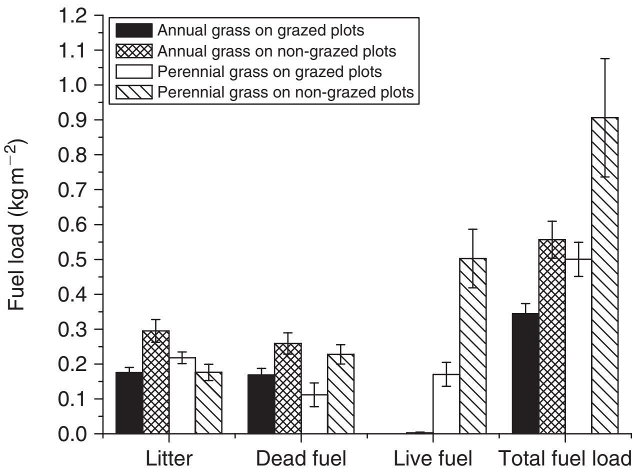

Fig. 2. Aboveground fuel load before burning (mean ± standard error).

Table 1. Main effects of grazing and vegetation type on pre-burn fuel characteristics (mean ± standard error)

Characteristics	Grazing treatment		Vegetation type	
	Grazing	No grazing	Annual	Perennial
Vegetation height (cm)	122.71 ± 16.25[A]	170.21 ± 21.21	84.58 ± 4.28[A]	208.33 ± 16.14
Vegetation cover (%)	92.06 ± 5.86	82.31 ± 5.16	82.13 ± 7.17	92.25 ± 3.05
Litter fuel load (kg m^{-2})	0.20 ± 0.01	0.24 ± 0.025	0.24 ± 0.02	0.20 ± 0.01
Dead fuel load (kg m^{-2})	0.14 ± 0.02[A]	0.24 ± 0.02	0.21 ± 0.02	0.17 ± 0.03
Live fuel load (kg m^{-2})	0.09 ± 0.028[A]	0.25 ± 0.08	0.00 ± 0.00[A]	0.34 ± 0.06
Total fuel load (kg m^{-2})	0.42 ± 0.034[A]	0.73 ± 0.07	0.45 ± 0.04[A]	0.70 ± 0.07
Litter moisture content (%)	4.69 ± 2.27	3.99 ± 2.46	4.24 ± 2.17	4.44 ± 2.55
Dead fuel moisture content (%)	6.95 ± 2.93	3.68 ± 1.76	2.60 ± 1.00	8.02 ± 3.17
Live fuel moisture content (%)	19.95 ± 6.14	27.48 ± 6.64	0.00 ± 0.00[A]	43.26 ± 3.94

[A]Significant, $P < 0.05$.

by perennial grasses (Fig. 2). The live fuel fraction was lower on grazed than on non-grazed plots when perennial grasses dominated, whereas it was at a similar (and much lower) level when annual grasses dominated (Fig. 2). Among the different fuel characteristics, vegetation cover and moisture content of litter and dead fuel fractions were insensitive to grazing treatment, vegetation type or both (Table 1).

Weather and fire behaviour parameters

During the 32 experimental fires over 5 days, the average air temperature, relative air humidity and wind speed were $34.43 \pm 1.22°C$, $54.56 \pm 0.72\%$ and $0.53 \pm 0.10\ m\ s^{-1}$ (mean ± s.e.), respectively. Generally, fires were burnt under a relatively narrow range of weather conditions. The vegetation type had no effect ($P > 0.05$) on any of the fire behaviour parameters, but the effects of grazing treatment and wind direction were significant for some fire behaviour parameters. The amount of fuel consumed during burning was significantly lower on grazed than non-grazed plots ($F_{1,24} = 6.11$, $P = 0.021$), and the magnitude of grazing effect was large ($\eta_p^2 = 0.203$). The rate of spread ($F_{1,24} = 7.43$, $P = 0.012$) and flame height ($F_{1,24} = 4.52$, $P = 0.044$) were significantly shorter for back fire than head fire, but fire intensity remained similar in both grazed and non-grazed plots, in plots dominated by annual or perennial grasses or in plots subjected to head fire or back fire (Fig. 3).

Fuel consumption during head fire showed significant correlations with vegetation height, dead fuel load, live fuel load and total fuel load, whereas the rate of spread and fire intensity showed negative correlation with relative air humidity but positive correlation with wind speed (Table 2*a*). During back fire, fuel consumption was significantly correlated with total fuel load and the different fuel load fractions; flame height correlated significantly with litter fuel load; fire intensity was negatively correlated with vegetation height, whereas the rate of spread showed significant negative correlations with vegetation height, live fuel load and total fuel load (Table 2*b*). The most pertinent fire behaviour prediction models are presented in Table 3. Wind speed and total fuel load explained 56 and 73% of the variations in rate of spread and fire intensity during head fire respectively. The total fuel load alone explained 86% of the variation in fuel consumption during head fire. Fire intensity and the rate of spread during back fire could be predicted using wind speed, vegetation cover and height, which explained 81 and 63% of the variations in fire intensity and rate of spread, respectively (Table 3). The total fuel load described 71% of the variation in fuel consumption during back fire.

Fire temperature and residence time

The average maximum fire temperature varied significantly between grazing treatment ($F_{1,216} = 33.01$, $P < 0.0001$), vegetation type ($F_{1,216} = 10.77$, $P = 0.001$), wind direction ($F_{1,216} = 6.37$, $P = 0.012$) and probe position ($F_{8,216} = 34.67$, $P < 0.0001$). It was higher on non-grazed than grazed plots, on plots dominated by annual rather than perennial grasses, and on plots subjected to head fire rather than back fire (Table 4). The magnitude of grazing effect on maximum temperature was nearly moderate ($\eta_p^2 = 0.133$). It was also significantly higher at the soil surface (0 cm) than either at 20, 50, 150, 300 or 500 cm above the soil surface or at 2, 5 or 10 cm below the soil surface (Fig. 4). Generally, fire temperature in the sub-surface (ranging

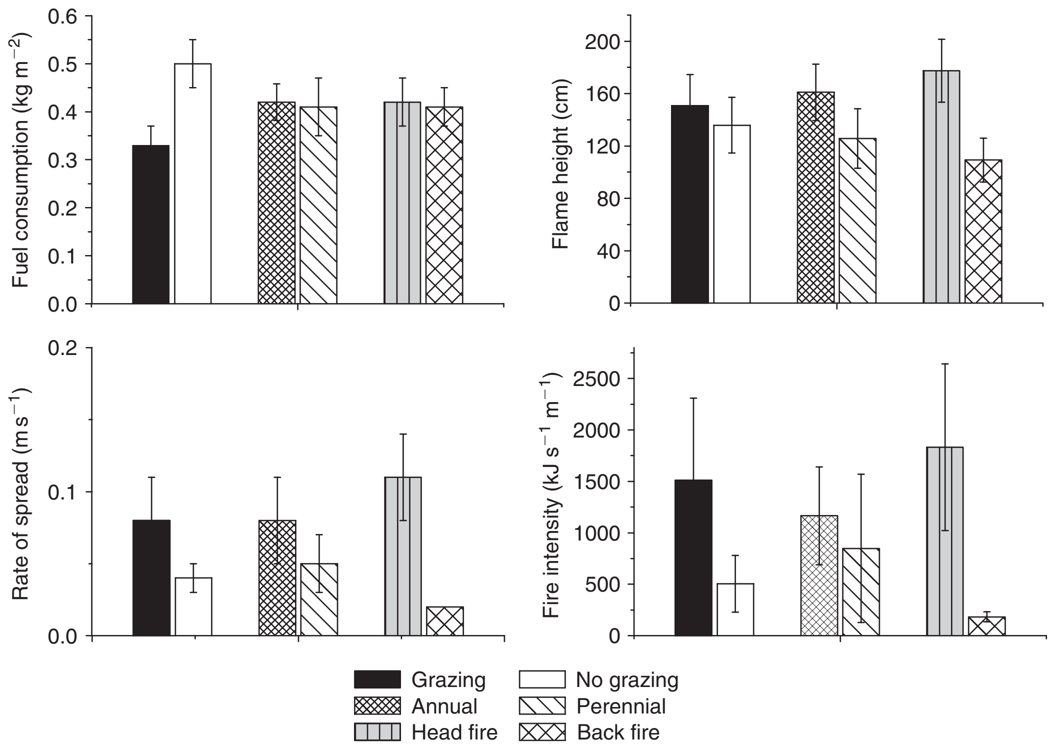

Fig. 3. Main effects of grazing, vegetation type and wind direction on fire behaviour parameters (mean ± standard error).

Table 2. Correlations between fire behaviour parameters and fuel characteristics and weather variables, (*a*) head fire, (*b*) back fire
Ht, mean vegetation height (cm); VC, vegetation cover (%); FL_l, litter fuel loading ($kg\,m^{-2}$); FL_d, dead fuel loading ($kg\,m^{-2}$); FL_f, fresh fuel loading ($kg\,m^{-2}$); TFL, total fuel loading ($kg\,m^{-2}$); MC_l, moisture content of litter (%); MC_d, moisture content of dead fuel (%); MC_f, moisture content of live fuel (%); *w*, fuel consumption ($kg\,m^{-2}$); T, air temperature (°C); RH, relative air humidity (%); W, wind speed ($m\,s^{-1}$); FH, flame height (cm); *r*, rate of fire spread ($m\,s^{-1}$); *I*, fire intensity ($kJ\,s^{-1}\,m^{-1}$)

	Ht	VC	FL_l	FL_d	FL_f	TFL	MC_l	MC_d	MC_f	T	RH	W
(*a*) Head fire												
w	0.48[A]	−0.14	0.32	0.90[A]	0.56[A]	0.93[A]	−0.27	−0.08	−0.19	0.16	0.08	−0.01
FH	−0.19	0.37	0.20	−0.15	−0.37	0.27	0.21	0.06	0.15	0.21	−0.23	0.08
r	−0.29	−0.43	0.02	−0.22	−0.32	−0.33	0.12	0.03	0.08	0.45	−0.62[A]	0.71[A]
I	−0.31	−0.38	0.19	−0.08	−0.35	−0.22	0.12	0.04	0.09	0.43	−0.63[A]	0.82[A]
(*b*) Back fire												
w	0.29	−0.14	0.64[A]	0.49[A]	0.27	0.84[A]	0.17	0.10	0.12	−0.03	0.11	−0.42
FH	−0.20	0.16	0.60[A]	0.37	−0.41	0.16	0.23	0.13	0.16	−0.33	0.00	0.03
r	−0.70[A]	−0.19	0.14	0.17	−0.73[A]	−0.48[A]	0.25	0.14	0.18	0.35	−0.41	0.30
I	−0.49[A]	−0.15	0.40	0.26	−0.49[A]	−0.08	0.23	0.13	0.16	0.23	−0.42	0.19

[A]Significant correlation, $P < 0.05$.

Table 3. Regression equations for predicting rate of fire spread (*r*), fuel consumption (*w*) and fire intensity (*I*) in savanna woodland
The predictors were wind speed (W), total fuel load (TFL), vegetation cover (VC), and vegetation height (Ht). s.e.e. = standard error of estimation. R^2 = coefficient of determination

	Variable	s.e.e.	R^2	F	*P*
Head fire	$r = 0.1042 + 0.1301\text{W} - 0.1418\text{TFL}$	0.0879	0.557	8.16	0.005
	$w = 0.0877 + 0.7006\,\text{TFL}$	0.0600	0.862	87.62	<0.0001
	$\text{Log}(I) = 1.84 + 1.81\,\text{W} - 1.22\,\text{TFL}$	0.8148	0.731	17.63	<0.0001
Back fire	$r = 0.0454 + 0.0023\,\text{W} + 0.0002\,\text{VC} - 0.00009\,\text{Ht}$	0.0062	0.631	6.85	0.006
	$w = 0.1294 + 0.6436\,\text{TFL}$	0.0652	0.705	33.42	<0.0001
	$\text{Log}(I) = 1.52 + 1.40\,\text{W} - 0.00405\,\text{Ht} + 0.00037\,\text{VC}$	0.4756	0.807	16.72	<0.0001

Table 4. Main effects of grazing, vegetation type and wind direction on maximum fire temperature and residence time above 60°C (mean ± standard error). Significant *P*-value are marked in bold type

Main factors	Max. temperature (°C)	Residence time (minutes)
Grazing	126.57 ± 12.74	0.72 ± 0.11
No grazing	200.16 ± 15.54	1.02 ± 0.10
P	**<0.0001**	**0.028**
Annual grass-dominated	189.53 ± 16.38	0.88 ± 0.09
Perennial grass-dominated	137.21 ± 12.03	0.86 ± 0.12
P	**0.001**	0.843
Head fire	174.65 ± 14.74	0.77 ± 0.10
Back fire	152.08 ± 14.26	0.97 ± 0.11
P	**0.012**	0.147

from 34.61 ± 1.28 to 88.91 ± 16.34°C) tended to be lower than that above the soil surface (ranging from 108.99 ± 16.41 to 289.21 ± 36.59°C).

There were also significant interaction effects of vegetation type × probe position ($F_{8,216} = 5.97$, $P < 0.0001$), wind direction × probe position ($F_{8,216} = 2.37$, $P = 0.018$) and vegetation type × grazing treatment × wind direction ($F_{1,216} = 4.55$, $P = 0.034$) on maximum fire temperature. The average maximum temperatures at 0-cm and 20-cm probe positions were 511.39 ± 41.29°C and 401.16 ± 50.02°C, respectively, on plots dominated by annual grasses, which were nearly twice the maximum temperature recorded on plots dominated by perennial grasses (298.00 ± 51.97°C at 0-cm and 177.26 ± 36.89°C at 20-cm probe position). The average maximum temperatures during head fire were substantially higher at 50-cm (269.36 ± 41.10°C), 150-cm (180.65 ± 31.23°C) and 500-cm (164.41 ± 47.91°C)

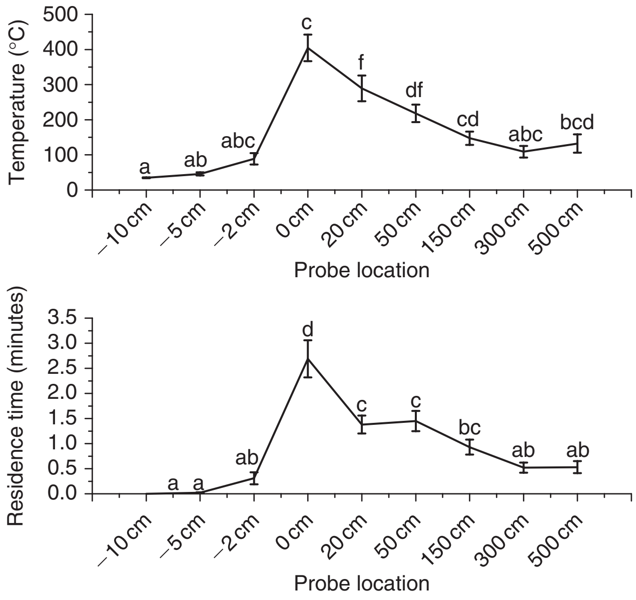

Fig. 4. Main effects of probe location on maximum fire temperature and residence time above 60°C (mean ± standard error). Means with different letters are significantly different based on Tukey's Honestly Significant Difference test.

probe positions than during back fire (166.92 ± 23.23°C, 114.49 ± 18.71°C and 100.12 ± 19.55°C at 50, 150 and 500 cm). During head fire, the average maximum temperature was higher on plots dominated by annual grasses (172.55 ± 27.76°C) than by perennial grasses (91.57 ± 17.82°C), both subjected to grazing, whereas the variation was insignificant for non-grazed plots. During back fire, the maximum fire temperature was still higher on plots dominated by annual (211.41 ± 36.80°C) rather than by perennial grasses (142.12 ± 18.78°C) that were not subjected to grazing treatment.

The residence time above 60°C also varied significantly with respect to grazing treatment ($F_{1,216} = 4.89$, $P = 0.028$) and probe position ($F_{8,216} = 20.90$, $P < 0.0001$). The residence time was shorter on grazed than non-grazed plots at all levels of probe position (Table 4) although the magnitude of grazing effect was nearly small ($\eta_p^2 = 0.022$). The residence time was longer at the soil surface (0 cm) than either above or below the surface at all levels of grazing treatment, vegetation type and wind direction (Fig. 4). The residence time was also longer at the first two probe positions above the soil surface than those below the surface. Further below the surface (−10 cm), the residence time was nil as the temperature did not reach 60°C at this position (Fig. 4). The residence time was insensitive to vegetation type and wind direction.

Discussion

Grazing affected the quantity of pre-burn fuel load and the vegetation structure significantly. This effect is related to herbage removal and trampling pressure (static load) exerted by the animals, which are the best known grazing disturbance factors affecting vegetation structure and dynamics in savannas (Frost *et al*. 1986; Rietkerk *et al*. 2000). The effect of grazing on fuel load also interacts with vegetation type. By preferentially grazing on high-quality plant species, such as annual grasses and forbs, livestock enhances the dominance of perennial grass that can tolerate grazing pressure while reducing the quantity of annual grass fuels. The fact that moderate grazing reduces annual grass fuel load suggests that this grazing system could be advantageous in reducing the severity of fire as evidenced from significantly lower fuel consumption by fire on grazed than non-grazed plots. Furthermore, the incomplete consumption of fuel is beneficial for livestock, which can graze on the remaining grass during the dry season.

Despite significant effects on total fuel load, both grazing treatment and vegetation type did not affect the rate of spread and fire intensity. Most savanna–woodlands have a mosaic architecture with bush clumps and open areas (Menaut *et al*. 1995), which creates spatial heterogeneity in fuel load that has potential to influence fire behaviour (Whelan 1995). In addition, the free-grazing strategies of mixed herds (cattle, sheep and goats) adopted in the experiment create spatial differences in terms of grazing intensity, stocking rate and feeding behaviour that in turn might not sufficiently decrease the horizontal and vertical fuel continuity on the plots. Fire intensity and rate of spread are also closely related to wind speed, thus appeared to be faster during head than back fire in the present study. Apparently both wind direction and speed have a strong effect on fire behaviour in the Sudanian savanna–woodland, as documented previously in other vegetation communities (Cheney *et al*. 1993; Trollope *et al*. 2002; Bilgili and Saglam 2003). The positive effect of wind speed is attributed to enhanced supply of oxygen to the fire (Trollope *et al*. 2004), which stimulates the heat transfer by conduction or radiation, which in turn results in pre-heating of the fuel ahead of a fire front. Wind direction and speed also affected rate of spread due to tilting of the flames towards the fuel ahead of the fire. Generally, increased wind speed results in an exponential increase in rate of spread during head fire compared with back fire (e.g. Govender *et al*. 2006). The rate of spread and fire intensity were negatively correlated with relative air humidity. As high relative humidity results in increased moisture content of fuel, the amount of heat necessary to reach the point of ignition will increase, thereby leading to reduced combustibility. Fire behaviour parameters during head and back fire were not significantly correlated with ambient air temperature, most likely owing to the narrow range of air temperatures during fire. The ranges of fire behaviour variables found in the present study were comparable with those reported from the savanna–woodland ecosystems of southern Africa (Shea *et al*. 1996; Gambiza *et al*. 2005).

The fire behaviour models are statistically significant and conceptually meaningful and logical, thus can serve as a guide for predicting fire behaviour in the study area. It should, however, be noted that some of the correlation and regression results seemed inconsistent; for example, total fuel load and fuel consumption during burning were positively correlated whereas the rate of spread and total fuel load weren't, as found for the negative relationship between fire intensity and total fuel load. This is indeed not surprising because the fire intensity and rate of spread are influenced by the moisture conditions and temperature of fuels at the time of fire occurrence, as the rate of combustion of moist, cold fuels is slower than that of dry, hot fuels (DeBano *et al*. 1998). This is further supported by the large quantity of live perennial fuel load with high moisture content observed during prescribed early fire during our study (Table 1). As a whole, the predictor variables can be measured relatively easily on site; thus making these models practically useful for monitoring annual fire. Although very little work has been done on predicting fire behaviour in West African savanna ecosystems, our result is comparable with studies made in other savanna or grassland ecosystems (e.g. Trollope *et al*. 2002).

By removing biomass and creating patchiness in the fuel, livestock grazing significantly reduced fire temperature and residence time of temperatures above 60°C. Also, plots dominated by annual grasses were hotter than those dominated by perennial grasses, which can be explained by the level of desiccation during prescribed early burning. The moisture content of live fuel in perennial grass-dominated plots was substantially higher than that in annual grass-dominated plots. The overall temperature was higher in head fire than in back fire; however, the majority of back fires were hotter than the head fires at the surface (0 cm), which is consistent with findings by Trollope *et al*. (2002). Fire temperature and residence time also varied significantly with respect to probe location, with the highest values recorded at the soil surface (0 cm). Generally, fire temperatures and residence times above the soil surface were higher than below the soil surface with a decreasing tendency with increasing soil depth. Our result is in agreement with previous reports from comparable ecosystem types (Silva *et al*. 1990; Auld and O'Connell 1991; Miranda *et al.* 1993; Bradstock and Auld 1995). It is generally believed that fire temperature decreases with increasing soil depth in a negatively exponential manner (De Luis *et al*. 2004), which is related to the thermal conductivity across the soil profile (Valette *et al*. 1994).

The findings from the present study have an important implication to the current savanna–woodland management that entails application of early fire, exclusion of grazing by livestock and harvesting 50% of the merchantable volume. As a moderate level of grazing by livestock reduced herbaceous fuel load, fire temperature and lethal temperature residence time, it can be used as a potential management tool to modify fire behaviour in the savanna–woodlands. Recent studies on our experimental sites have also provided additional evidence that the effect of moderate grazing on species richness, abundance and recruitment of both herbaceous and woody species is marginal or insignificant (Savadogo 2007; Zida 2007). Therefore, the current management practice that prohibits grazing in savanna–woodland reserves may need revision so that the future management strategy should integrate wood production and livestock husbandry, as the latter is the main source of livelihood for local people. When applying early fire as a management regime, back fire is recommended, as it was found to reduce fire propagation and intensity.

Conclusions

A moderate level of grazing by livestock reduced herbaceous fuel load, fire temperature and lethal temperature residence time, thus decreasing fire severity in the savanna–woodlands of West Africa. The dominant grass type influenced the moisture content of the fuel, which in turn reduced the fire temperature and created spatial heterogeneity in fire behaviour. Wind direction affected fire temperature, residence time, flame height and rate of spread. The empirical fire behaviour models are reasonably good, thus could serve as a tool to guide prescribed burning in the study area. However, larger experiments with broader weather and fuel conditions as well as greater geographical spread are required to further improve the model and to make it 'global' for the region.

Acknowledgements

The Swedish International Development Cooperation Agency (Sida) financially supported the study. We are greatly indebted to Meda Modeste, Bama Théophile and the local fire crew. Without their dedication and support, the field work couldn't have been completed. Anonymous reviewers are highly appreciated for providing valuable and constructive comments on the manuscript.

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Manuscript received 30 January 2007, accepted 22 June 2007