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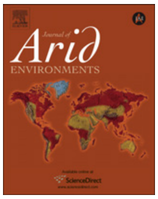

Fuel and fire behavior analysis for early-season prescribed fire planning in Sudanian and Sahelian savannas

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ABSTRACT

Early dry-season prescribed fires can reduce fuel loads and thus prevent or mitigate the severity of late, high-intensity fires that spread widely in savanna ecosystems and damage woody plants. However, due to the lack of scientific knowledge regarding fuel characteristics and fire behavior in West African savannas, this practice can have effects that are diametrically opposed to those desired and may threaten the environment. There are three crucial parameters that must be considered when planning early-season prescribed fires: the ignition probability, the rate of spread of a fire and the amount of fuel consumed. In this study, 231 early-season prescribed fires were conducted in three savanna ecosystems in Senegal in order to characterize these three fundamental parameters.

Logistic regression analyses revealed that fuel moisture content and relative humidity are good predictors of ignition probability. Multiple linear regressions were used to investigate the relationships between fire rate of spread, fuel consumption or fire intensity and fuel and weather conditions. Readily usable nomographs for forest managers were created based on those relationships that proved to be significant. Kruskal–Wallis tests performed to compare the observed rates of fire propagation with those predicted using BehavePlus showed no statistically significant difference between them.

1. Introduction

Savanna fires play a major role in structuring ecosystem patterns in tropical areas (Heinl et al., 2007). The frequency of these fires influences the biogeography and vegetation composition of these regions, as well as land use and land cover trends (Alleaume et al., 2005; Laris and Wardell, 2006). Each year, 2.5 gigatonnes (Gt) of dry matter burn in African savannas (van der Werf et al., 2010) causing substantial losses of natural resources. Fauna and soil properties are especially severely affected (Savadogo et al., 2007a; Vasconcelos et al., 2009). Fire affects the physical features of the soil while reducing its nutrient content and causing it to adopt a poor aggregate structure with non-optimal infiltration rates (Savadogo et al., 2007a). In addition, fire increases gas emissions into the atmosphere (Furley et al., 2008).

The environmental impacts of these fires such as the removal of trees and the changes they cause to the physiognomy of vegetation, and floristic composition (Mbow et al., 2003) prompted Africa's colonial administrations to ban the intentional setting of fires. The earliest state policies on fire in West Africa were thus radically anti-fire (Laris and Wardell, 2006). Gradually, these restrictive policies were abandoned. Hence, in Burkina Faso, two laws were passed in 1950 authorizing the use of fire for clearing farmland and regenerating rangelands in specified vegetation zones (GGAOF, 1954, 1955). In 1955, the governor of French Sudan (Mali and Senegal) issued a law reversing an existing ban on fire and promoting early-season burning (Laris and Wardell, 2006).

These regulatory reversals were driven by a wish to use fire for land management. In Senegal, savanna fires are usually human-made, such as management fires used by forest agents, agricultural fires, and pastoral fires. However, these fires can become uncontrolled and quite destructive. Field data obtained by Senegal's Forestry Service indicate that the total burned area was 172,913 ha in 2007–2008 and 184,419 ha in 2008–2009 (DEFCCS, 2009). However, these figures are much lower than

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estimates based on remote sensing methods, which are 952, 900 ha for 2007–2008 and 727, 600 ha for 2008–2009 (CSE, 2009). Burned area detected by remote sensing was higher than that detected by direct ground-based observation. This is due to the ability of remote sensing to observe larger areas. The substantial difference between the two sets of statistics indicates that it will be necessary to develop more effective systems for evaluating the extent of fires and their undesirable impacts.

Late-season fires that cover large areas of land present many challenges in terms of ecosystem conservation, including serious losses of biodiversity and ecosystem services, high greenhouse gas emissions, and severe soil erosion. The lack of equipment and qualified human resources for firefighting in Senegal makes the issue even more pressing. The Senegalese Forestry Service has adopted fire breaks as a means of forest protection. These cleared paths are typically 10 m or more wide and are completely cleared of vegetation to prevent the spread of fires. In 2009, the Forestry Service had planned to create 2000 km of fire breaks (DEFCCS, 2009). However, this goal was not reached because of the cost of their initial construction and expensive annual maintenance. Due to these costs, and as a measure to mitigate late-season fire damages, the Forestry Service has implemented early-season prescribed fires every year since the early 1960s (Wardell et al., 2004). Early-season fires of this kind were established over 1,013,224 ha at the beginning of the 2007–2008 fire season (DEFCCS, 2009). In national parks and reserves, prescribed early-season fires are started and managed by forest service agents. Outside these areas, they are initiated by villagers under the supervision of forestry service agents.

However, early-season fires are controversial. The Forestry Service states that prescribed early-season fires should be initiated between the second half of November and the end of December (Wardell et al., 2004). Such rigid timeframe-based planning is probably obsolete, given the observed spatial and temporal variability in rainfall patterns. In order to ensure that early-season prescribed fires are effective, it is necessary to unambiguously identify the optimal period for their initiation based on the fuel status of the targeted area, i.e. in the quantity (load) and quality (moisture, distribution, size, composition) of the fuel. These variables depend directly on rainfall and vegetation phenology. In general, fire management requires good planning that clearly states when burning should be conducted, what should burn, and to what extent (Mbow et al., 2004).

In general, fire ignition risks are dependent on fuel conditions and the presence of anthropogenic ignition sources, whereas the risk of a fire spreading is dependent on the fuel load and arrangement as well as the wind and the slope of the land. These factors vary substantially over time and between regions. While several studies on fuel and fire characteristics in Southern Africa have been performed (Archibald et al., 2009, 2010; Hély et al., 2007; Mbatha and Ward, 2010), there is comparatively little scientific data of this sort for West Africa (Savadogo et al., 2007a,b) and so there is a need for more detailed information on the relevant physical and chemical factors in this region (Hély and Alleaume, 2006). The objectives of the present study were threefold: (1) to characterize fuel types in the savanna ecosystems of Senegal; (2) to predict ignition probabilities for early-season fires based on fuel availability and weather patterns; (3) to determine whether fire behavior predictions for this region generated using BehavePlus (Andrews, 2008, 2009) matched observed fire intensities and rates of propagation. To answer these questions, we performed field measurements of fuel characteristics and experiments on fire behavior by testing prescribed burns in plots.

2. Material and methods

2.1. Study area

The study area encompasses three sites that are representative of the main Senegalese savanna ecosystems and livelihoods along a gradient in tree cover increasing from north to south: the Sahel, the north-Sudanian savanna and the south-Sudanian savanna (Fig. 1).

The first site was located in the northern part of Senegal in the semi-arid area near Barkedji village, whose inhabitants are primarily employed in pastoral occupations. The climate is classified as dry tropical with one rainy season (summer monsoon and squall lines), extending from July to September, with rainfall ranging from 200 to 400 mm in the north. The relative humidity can reach a minimum of 10% in the northern part in May, as a consequence of high temperatures and high evaporating power of the region's hot and dry harmattan wind. In the early stages of the dry season, the harmattan winds first reach the northeast of Senegal where they remain for several weeks before moving to the southern continental regions (Sagna, 2005). Conversely, the relative humidity can exceed 75% throughout this area when the summer monsoon starts in July. The annual mean of the maximum temperatures for the region is above 35 °C. The representative ecosystem category for the study area is an herbaceous savanna (Fig. 2) characterized by annual grasses (*Eragrostis gangetica*, *Eragrostis tremula*, *Schoenefeldia gracilis*, *Zornia glochidiata*, *Dactyloctenium aegyptium*, *Aristida mutabilis*, *Aristida funiculata*, *Cenchrus biflorus*, *Chloris virgata* and *Polycarpaea linearifolia*) and sparse woody vegetation (*Balanites aegyptiaca*, *Boscia senegalensis* and *Adenium obesum*).

The second site was located in the center of the sub-humid area around Maka village, whose inhabitants are primarily employed in agroforestry and pastoral activities. Rainfall in this region ranges from 700 to 800 mm and the relative humidity ranges from 34 to 79 %. The average annual temperature is ca. 29 °C. The central and southern regions are dominated by leached tropical ferruginous soils that are richer in clay and therefore less porous than the northern soils of the first site (Tappan et al., 2004). The representative ecosystem is a shrub savanna (Fig. 2) with grass cover dominated by *Andropogon pseudapricus*, *Pennisetum pedicellatum*, *Spermacoce chaetocephala* and *Spermacoce stachydea*. Woody vegetation covers a greater proportion of this region than is the case for the first site and is dominated by *Combretum glutinosum*, *Guiera senegalensis*, *Sterculia setigera*, *Pterocarpus erinaceus* and *Cordyla pinnata*.

The third site was located in the southern part of the country in a sub-humid area near Dioulacolon village. Most of the economic activity in this region pertains to agriculture, forest resource extraction and cattle breeding. The rainfall and relative humidity range from 800 to 1200 mm and 37–89%, respectively. The annual mean temperature is ca. 28 °C. The site is situated in a shrub-tree savanna ecosystem (Fig. 2) with a grass layer dominated by *A. pseudapricus*, *Andropogon gayanus*, *Ctenium villosum* and *Indigofera leptoclada*, while the dominant woody species are *C. glutinosum*, *Combretum nigricans*, *Strychnos spinosa*, *Crossopteryx febrifuga*, *Terminalia macroptera*, and *Bombax costatum*.

2.2. Experimental design for fuel sampling and fire behavior

The canopy cover percentage and tree density were assessed in three plots of 50 × 50 m at the first site and 30 × 30 m plots at the other two sites using the method outlined by Mahamane and Saadou (2008) based on physiognomy and floristic composition.

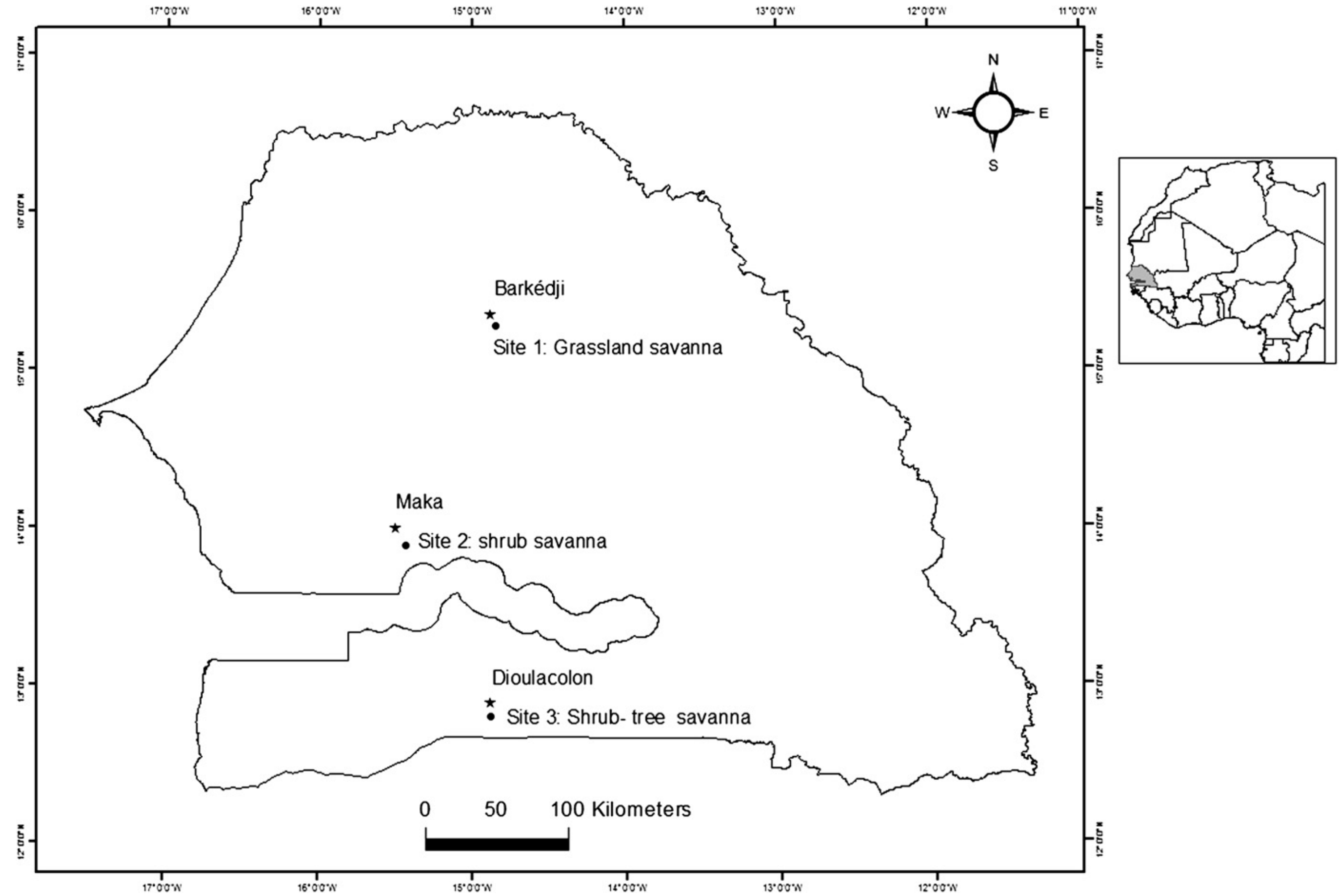

Fig. 1. Location of the three sites in Senegal.

In tropical savanna ecosystems, the fuel consists primarily of herbaceous vegetation (Hély et al., 2003a; Savadogo et al., 2007a; Stocks et al., 1996; Trollope and Trollope, 2002). We therefore measured the herbaceous load and cover at 77 plots for each site, with each plot being sampled just before the ignition attempt. At the end of the 2010 rainy season (October 6 – November 23), we conducted 231 prescribed fires (77 per site) in a 10 × 10 m plot. Each plot was delimited by a 1.5 m wide fire break (Fig. 3) to ensure control of the fires' spread. Before each ignition attempt, the dominant species in the plot was identified or a specimen was collected for subsequent identification. The fuel bed depth (grass height in centimeters) was measured using a graduated metallic pole and the grass cover (as a percentage) was estimated by visual inspection of the plot. To estimate the fuel load, the herbaceous vegetation was clipped at ground level in a 1-m^2 quadrat. The dead (yellow) and living (green) herbaceous matter loads for each plot were computed separately, as required for BehavePlus fire propagation simulations (Andrews, 2009). Samples of dead and living grass subsamples were immediately weighed in the field and then oven dried at 60 °C until a constant dry weight was achieved. The fuel moisture content (FMC, in %) for each material was then calculated by comparing the wet and dry weights for each pre-burn grass subsample according to Equation (1) (Chuvieco et al., 2009; Dauriac, 2004):

$$\mathrm{FMC} = 100*(\mathrm{FW} - \mathrm{DW})/\mathrm{DW} \tag{1}$$

where FW is the sample's fresh weight measured in the field and DW is its oven-dried weight.

2.3. Weather conditions and fire behavior

The air temperature, relative humidity, and wind speed were recorded using a portable weather station (pro WMR100 Oregon Scientific) placed 1.90 m above the ground. Measurements of these meteorological parameters were performed just before each fire ignition.

Line-source ignition using a torch was applied on the upwind side of each plot in order to ensure rapid equilibration (Hély et al., 2003a) and thus ensure that the observed fire behavior would be comparable to the output of BehavePlus simulations. Before each ignition, two metallic poles separated by 4 m were set up inside the plot along a line parallel to the direction of fire propagation, with each pole being at 1 m away from the plot boundary. The fire's rate of spread was calculated based on the time required for the flame front to cover the distance between the two poles, which was recorded using a stopwatch. Any biomass remaining after the fire had died down was collected in order to determine the fire's fuel consumption.

The three main variables describing fire behavior are the rate of spread (ROS in ms^{-1}), fuel consumption (FC in g m^{-2}) and fire intensity (FI in kWm^{-1}) (Hély and Alleaume, 2006; Savadogo et al., 2007b). The ROS was calculated by dividing the distance between the poles (maximum 8 m) by the duration (in seconds) it took the fire to cover that distance. The FC was calculated as the difference between the pre- and post-burning fuel loads, while the FI was calculated using Equation (2) as proposed by Byram (1959):

$$I = H*\mathrm{FC}*\mathrm{ROS} \tag{2}$$

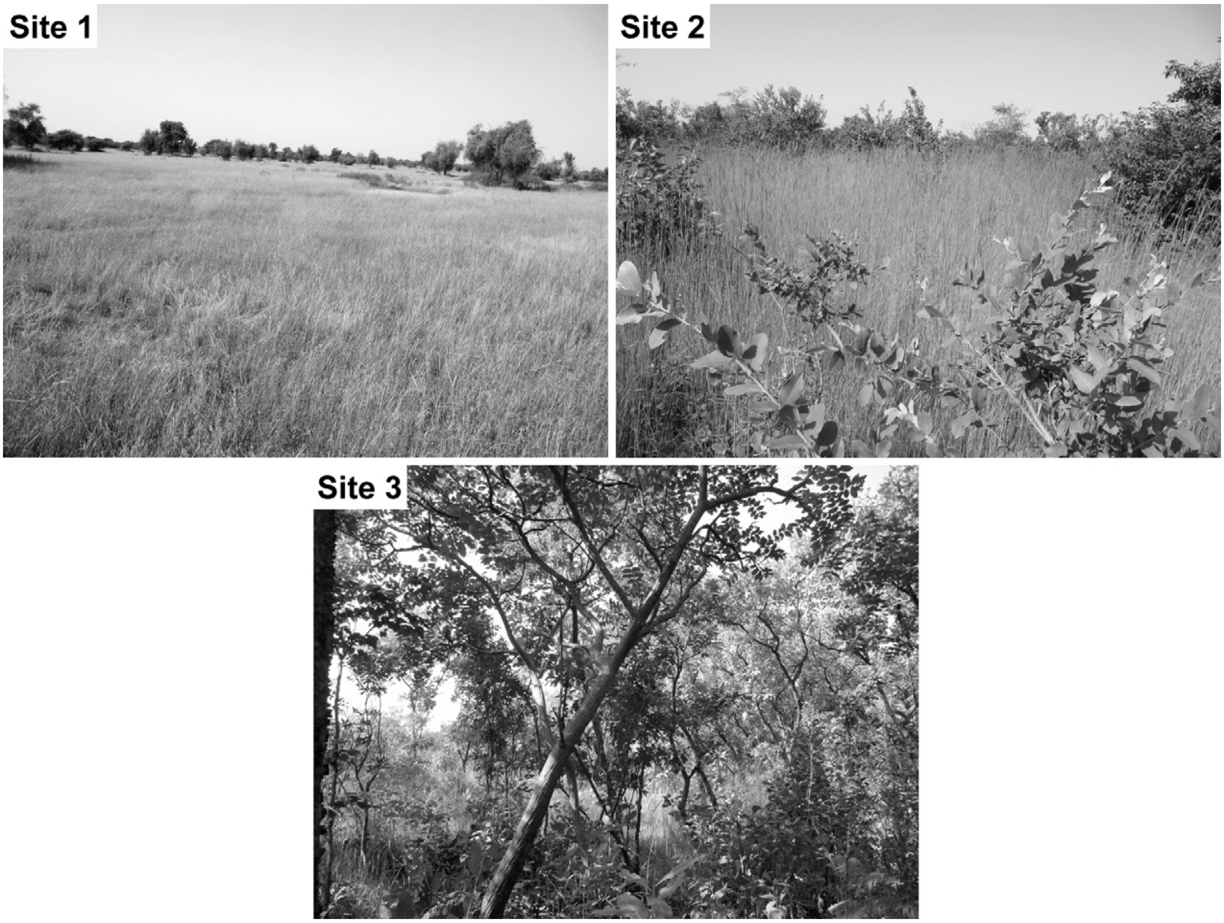

Fig. 2. Horizontal and vertical fuel arrangements typical of the three sites: Site 1: Grassland savanna ± shrub; Site 2: Shrub savanna; Site 3: Shrub savanna ± trees.

with H being the heat of combustion (16,890 kJ kg^{-1} for fuel grass in the head fire zone (Trollope et al., 1996).

2.4. BehavePlus simulations

The BehavePlus prediction system (Andrews, 2008, 2009) was selected because it allows the user to predict the behavior of surface fires based on stand fuel characteristics in conjunction with 53 predefined fuel models or new user-developed models. It was straightforward to design fuel models for the Senegalese savanna based on our field measurements (Table 1) because almost all of the required BehavePlus inputs relating to fuel characteristics, topography, and weather conditions were available (see the corresponding Tables in the Appendix). We used 75% of the field survey data to calibrate the fuel models based on the linear relationship between the observed and simulated ROS and FI. Once calibrated, we validated these settings using the remaining 25% of the data set. In all simulations, a slope of 0% was assumed (i.e. it was assumed that the fire propagated over flat land) in order to properly represent the topography of the studied regional landscapes (Collectif, 2007).

2.5. Statistical analysis

The statistical software environment R (R Development Core Team, 2007) was used to compare fuel and weather characteristics across sites using analysis of variance (ANOVA) on ranks followed by Tukey's HSD (Honestly Significant Difference) comparison tests to identify significant differences between sites in cases where the ANOVA results rejected the null hypothesis. The use of a ranking procedure was necessary because the residuals of the raw data did not meet normality conditions. We then used a logistic regression model with the backward stepwise procedure to predict ignition probabilities. The logistic regression model had the general form Equation (3):

$$P(i) = \frac{1}{1 + e^{-(b0 + b1x1 + \ldots + bkxk)}} \tag{3}$$

where $P(i)$ is the probability of fire ignition, $x1$ to xk are independent variables driving variation in that probability, and $b0$ to bk are model parameters estimated from the data set. A training sample set comprising 75% of the total binary field data (ignition/no ignition) was extracted and the Hosmer and Lemeshow goodness-of-fit test was used to fit the model to this data set (at the standard 5% significance level). The Wald test was used to evaluate the statistical significance of each parameter in the model. The model was then validated against the remaining 25% of the full data set. The observed and predicted ignition probabilities were compared using the kappa test (Monserud and Leemans, 1992).

Finally, a multiple linear regression model with the backward stepwise procedure was used to investigate the relationship between ROS and the fuel and weather variables. We also verified that residuals in this case satisfied the normality and homoscedasticity conditions (Scherrer, 2007).

Comparisons between the observed data and the BehavePlus predictions of ROS and FI were performed using the Kruskal–Wallis test with $\alpha = 0.05$. The nomographs used for future predictions

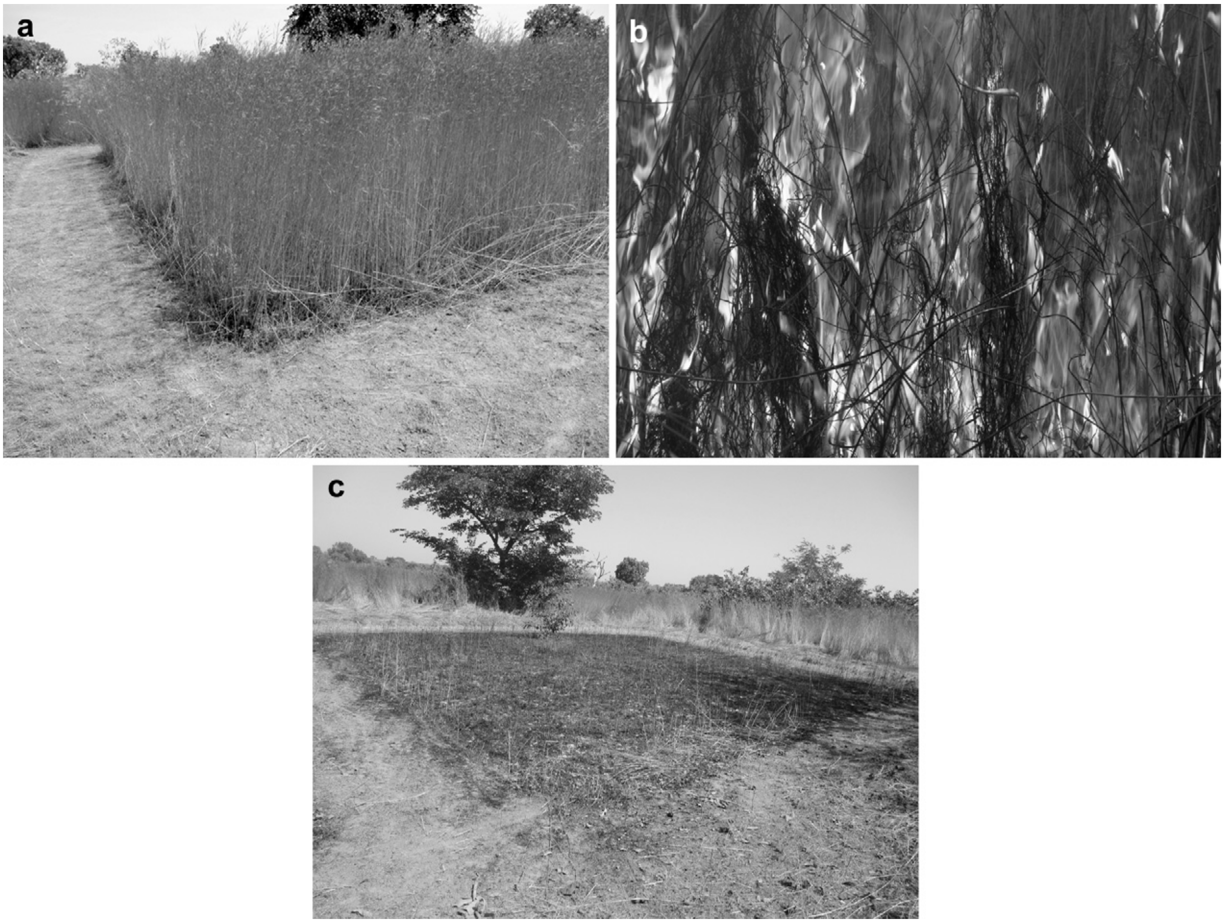

Fig. 3. Prescribed fire experimental protocol: (a) pre-fire setting with fire breaks; (b) measuring fire behavior components during the flaming combustion phase, including the rate of spread and flame characteristics; (c) post-fire conditions from which fuel consumption was measured.

(Burgan and Rothermel, 1984; Hély et al., 2003b) were established by combining the outputs of the logistic and linear regression models.

3. Results

3.1. Fuel characterization

The first site differed qualitatively from the others in terms of the floristic composition of the grass cover. Three species of annual grasses (*C. virgata*: 51%, *E. gangetica*: 23%, and *Z. glochidiata*: 19%) accounted for 93% of the grass cover in the first site, whereas *A. pseudapricus* accounted for over 95% in the others. While the only fuels in each site were herbaceous dead fine fuels (Table 1), there were significant differences between the sites in terms of fuel load – notably, the third site contained four times more fuel than the first. During the 32-day data collection period, the average fuel moisture content (FMC) varied between 135 ± 63% and 83 ± 31%, decreasing steadily over time at all three sites. From the 26th day of collection onwards, the grass vegetation was almost wholly cured (100% yellow and dead) in the first site, while the cured proportion ranged from 76% to 80% in sites 2 and 3, respectively. The fuel bed consisted exclusively of grass and was densest and deepest at the third site. At the first site, it was similarly dense but very shallow, while at the second site it was deep but loose (Table 1).

There was a gradual increase in tree density from the first to the third site (from 120 stems/ha to 300 stems/ha, respectively). *B. aegyptiaca* was the most abundant woody species in the first site, *C. glutinosum*, *G. senegalensis*, *Acacia ataxacantha*, *S. setigera* and *C. pinnata* were dominant at the second, and *T. macroptera*, *C. glutinosum*, and *Combretum collinum* were the most prevalent at the third. The tree cover increased by a factor of five ongoing from the

Table 1
Fuel characteristics in the three studied sites (mean ± standard deviation).

Sites	Vegetation type	Live fuel load ($g\ m^{-2}$) ***	Dead fuel load ($g\ m^{-2}$)***	FMC (% of dry matter)***	Grass height (m) ***	Grass cover (%) ***	Tree cover (%) ***	Canopy base height (m) ***	Vertical continuum between tree base height and grass	Connecting between canopies
1	Herbaceous savanna ± shrub	38 ± 28 c	94 ± 35 c	83 ± 31 c	0.38 ± 0.05 b	81 ± 7 b	11 ± 1 c	0.80 ± 0.2 c	No	No
2	Shrub savanna	367 ± 71 a	233 ± 45 b	189 ± 90 a	1.61 ± 0.2 a	61 ± 7 c	29 ± 0.8 b	1 ± 0.3 b	Yes	No
3	Shrub savanna ± trees	156 ± 80 b	397 ± 91 a	135 ± 63 b	1.7 ± 0.03 a	92 ± 6 a	50 ± 1 a	1.5 ± 0.5 a	Yes	No

FMC for Fuel Moisture Content.
*** for $P < 0.001$ from the ANOVA on ranks.
Note: Different letters in the same column indicate significant differences at $P < 0.05$ (Tukey HSD test).

first to the third site (Table 1). The tree crowns were discontinuous at all studied sites, but the average grass height reached the canopy base at the second and third sites.

3.2. *Probability of ignition*

Of the 231 ignition attempts, 154 were successful. The fuel moisture content (FMC) values for plots in which ignition succeeded varied between 133% and 6% and the relative humidity (RH) in these plots was between 79 and 12%. On average, the first successful ignitions occurred at 120% FMC, corresponding to the 12th day after the last rain in the first site 1. At the second and third sites, the first successful ignitions occurred on the 31st and 29th days, respectively.

The logistic regression model established based on data from all three sites showed that the FMC and RH both significantly affect the probability of ignition in all cases. The Hosmer and Lemeshow test indicated that the model fit the data from the training sample data set adequately (98%). The concordance between observed and predicted ignition was very high (95%), with an excellent kappa coefficient of 0.89. Based on the output of the logistic regression model, a nomograph was created to predict probabilities of ignition (Fig. 4).

3.3. *Weather conditions and fire behavior*

Among the meteorological parameters, wind speed was the most variable parameter between the three study sites. Tukey's HSD test indicated a significantly higher average wind speed at the first site compared to the other two.

Wind speed and grass cover correlated positively with ROS, whereas FMC, RH and fuel load correlated negatively with ROS (Table 2). The observed ROS values ranged from 0.03 ± 0.01 to 0.13 ± 0.08 ms^{-1} and the multiple linear regression showed that independent variables explained 74% of this variance. Notably, there were significant differences between the ROS values for the first two sites. Based on these data, two nomographs for predicting ROS were created (Fig. 5). The first is for use in the beginning of the dry season when live grasses are still present, while the second one is designed for the part of the dry season when the grasses have lost most of their water content and the grass cover has become heterogeneous.

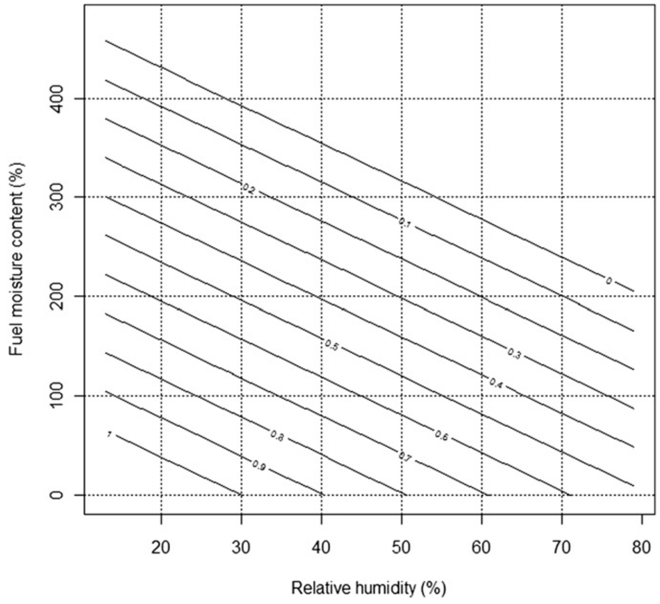

Fig. 4. Nomograph for predicting ignition probability based on fuel moisture content and relative humidity measured during field survey. Guide for interpreting the nomograph: if the relative humidity is 50% and the fuel moisture content is 200%, then the probability of ignition is approximately 30%.

Table 2
Results of the backward stepwise linear multiple regression between the rate of spread (ROS) and five explanatory variables. The Shapiro test confirmed the residual normality, while the homogeneity of variances was visually checked.

Variables	Coefficient	s.e.	*t* value	d.f.	*P* value
Constant	2.102444	1.406128	1.495	149	0.1373
FMC	−0.045818	0.008747	−5.238	149	6.48e-07***
Dead fuel load	−0.005648	0.001943	−2.907	149	0.0043**
Grass cover	0.090322	0.017703	5.102	149	1.18e-06***
Relative humidity	−0.101643	0.024312	−4.181	149	5.35e-05***
Wind speed	1.579081	0.210134	7.515	149	8.70e-12***

$R^2 = 0.74$, *p*-value: <0.001.
Shapiro test: $W = 0.9845$, *p*-value = 0.1337.
** for $P < 0.01$; *** for $P < 0.001$.

Fuel load, wind speed and grass cover all significantly affected FI but the stepwise linear multiple regression model found (not shown) was not as powerful ($r^2 = 0.54$) as for ROS. The average estimated FI for the second site was 73 kWm^{-1}, three and five times lower than the estimated values for the first and the third sites, respectively.

Dead and live fuel loads determined 90% of the variation in fuel consumption, with the proportion of dry matter correlating positively with the FC as might be expected. Conversely, fresh matter correlated negatively with the FC. Fig. 6 illustrates the predicted FC values based on both significant explanatory variables.

3.4. *BehavePlus simulations*

The very satisfactory agreement ($r^2 = 0.81$) between the observed and predicted ROS values for all three sites together concealed important differences between the sites. In fact, the predicted values for the first site were almost always underestimates, while those for the second and the third sites generally overestimated the ROS for speeds below 0.05 ms^{-1} and underestimated it for higher values. Simple linear regressions performed to evaluate the relationship between observed and predicted ROS values yielded coefficients of determination (r^2) greater than 0.60 (Fig. 7). The Kruskal–Wallis test used to compare the observed and predicted ROS revealed no statistically significant difference between the two ($p\text{-value}_{\text{site 1}} = 0.1367$, $p\text{-value}_{\text{site 2}} = 0.2335$ and $p\text{-value}_{\text{site 3}} = 0.3543$).

The FI range predicted using BehavePlus was between 2 and 919 kWm^{-1}, with a mean of 245 kWm^{-1}. The correspondence between observed and predicted FI was only good and linear when FI values from all sites were pooled ($r^2 = 0.59$) or when only values from the third site were analyzed (Kruskal–Wallis test, *p*-value = 0.1652).

4. Discussion

Biophysical vegetation characteristics such as water content and spatial arrangement are critical parameters when evaluating fire risks (Burgan and Rothermel, 1984; Chuvieco et al., 2004, 2010; Trollope and Trollope, 2002). The savannas examined in this work lay along a north-south gradient in terms of fuel desiccation, following the course of the summer monsoon rains. The vegetation structure ranged from open savanna in the north to more closed savanna ecosystems on moving south. Near-continuous grass cover was present at all study sites (Table 1). These annual plants produce fine fuels exclusively and constituted an ideal fuel bed for surface

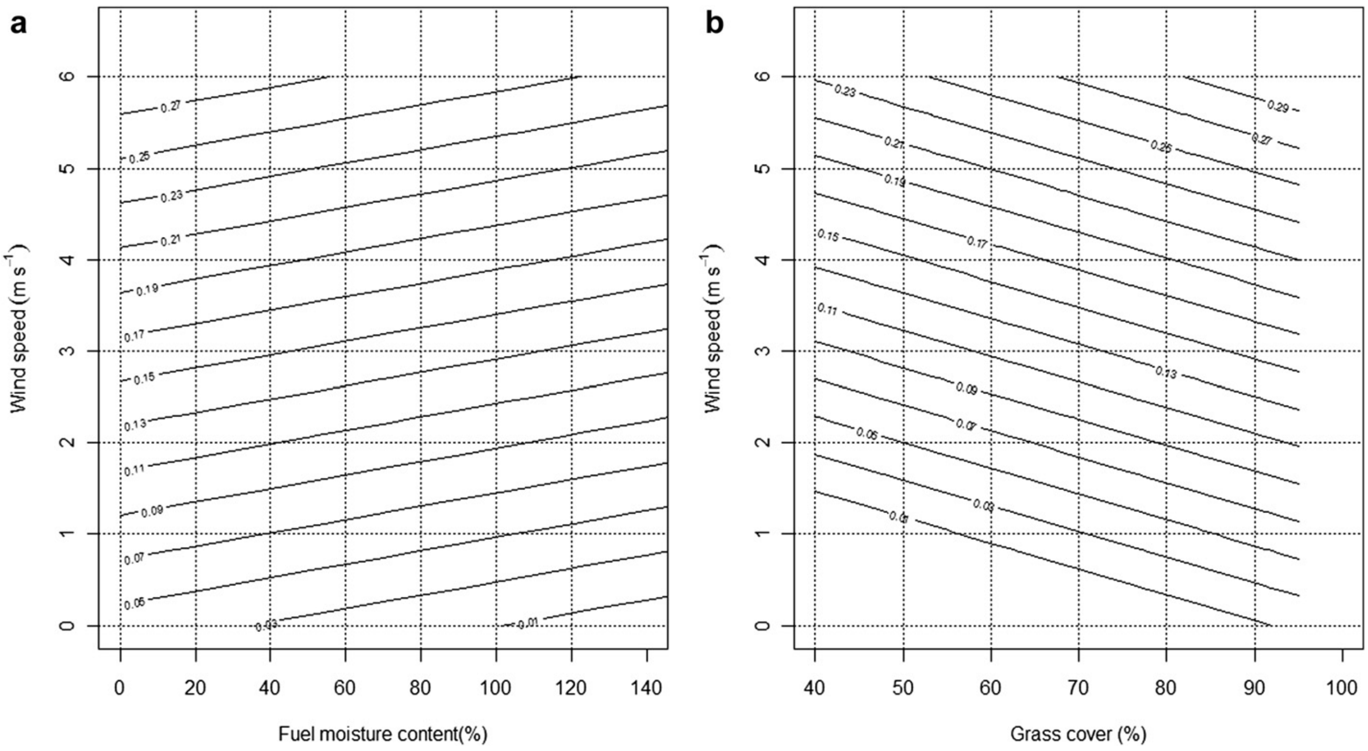

Fig. 5. Nomographs for predicting rate of spread: version (a) is adequate at the beginning of the dry season while version (b) is suitable for cases when the grass is completely dry and the grass cover is heterogeneous (which will affect the rate of fire spread).

fires. There was a vertical connection between the tree crowns and the grass at the second and third sites, which could have facilitated the burning of woody plants in an intense fire. However, the absence of connections between canopies would prevent such crown fires from spreading. If ongoing global changes in the climate or human activity favor canopy closure, the fire regime in southern sites could shift significantly toward more intense fires with a probable change from low severity surface fires to more severe crown-intermittent fires.

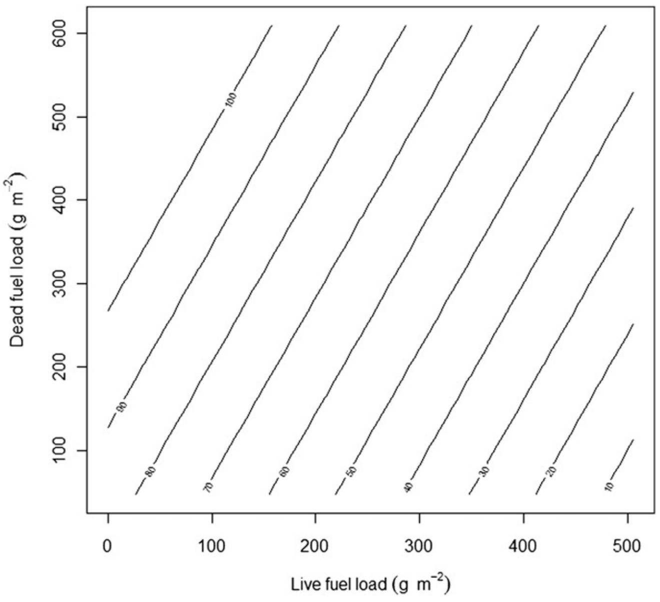

Fig. 6. Nomograph for predicting fuel consumption using live and dead fuel loads from the studied sites.

Despite the morphological differences between the studied savannas, the mechanisms that induced fire ignition were similar due to the homogeneous grassy composition of the fuel bed. The woody cover, which is known to slow the loss of the grass water content (Akpo et al., 2003), combined with the seasonal lag of few days marking the beginning of the dry season may partly explain the observed differences in terms of water content loss between the first site and the other two. Partly because of this difference in water content loss rate, fire risks become significant at very early stages in the northern open savannas of the Sahel. This is exacerbated by the combined effects of rapid loss of FMC due to the low woody cover in this region, the high temperatures, and the region's very porous soils, which have low water holding capacity. Together, these factors create environmental conditions that are suitable for early-season fires within two weeks of the last rainfall in the Sahel region.

Despite the wide area covered by savanna ecosystems in Africa, relatively little work has been conducted on predicting fire behavior in these savannas (Savadogo et al., 2007b; Stocks et al., 1996; Trollope and Trollope, 2002; Trollope et al., 2004). Most of the studies cited above concern southern African savannas and focused on the ecology of fire or the various causes of burning. The results obtained in this work for Sudanian savannas (at the second and third sites) are in agreement with those from a previous study conducted in West African woodland savannas (Savadogo et al., 2007b). While some authors (Hély et al., 2003a; van Wilgen and Scholes, 1997) have reported that a minimum fuel load of approximately 200–250 gm^{-2} is required to support fire in the southern African savannas, our results indicate that fire propagation is possible with a fuel load that is less than half this value (94 gm^{-2} on average), which is similar to the findings of Savadogo et al. (2007b) for other West African savannas. We attribute this result to both the importance of the high grass cover (which does not necessarily correlated with the fine fuel load; $r = 0.34$) and the fast

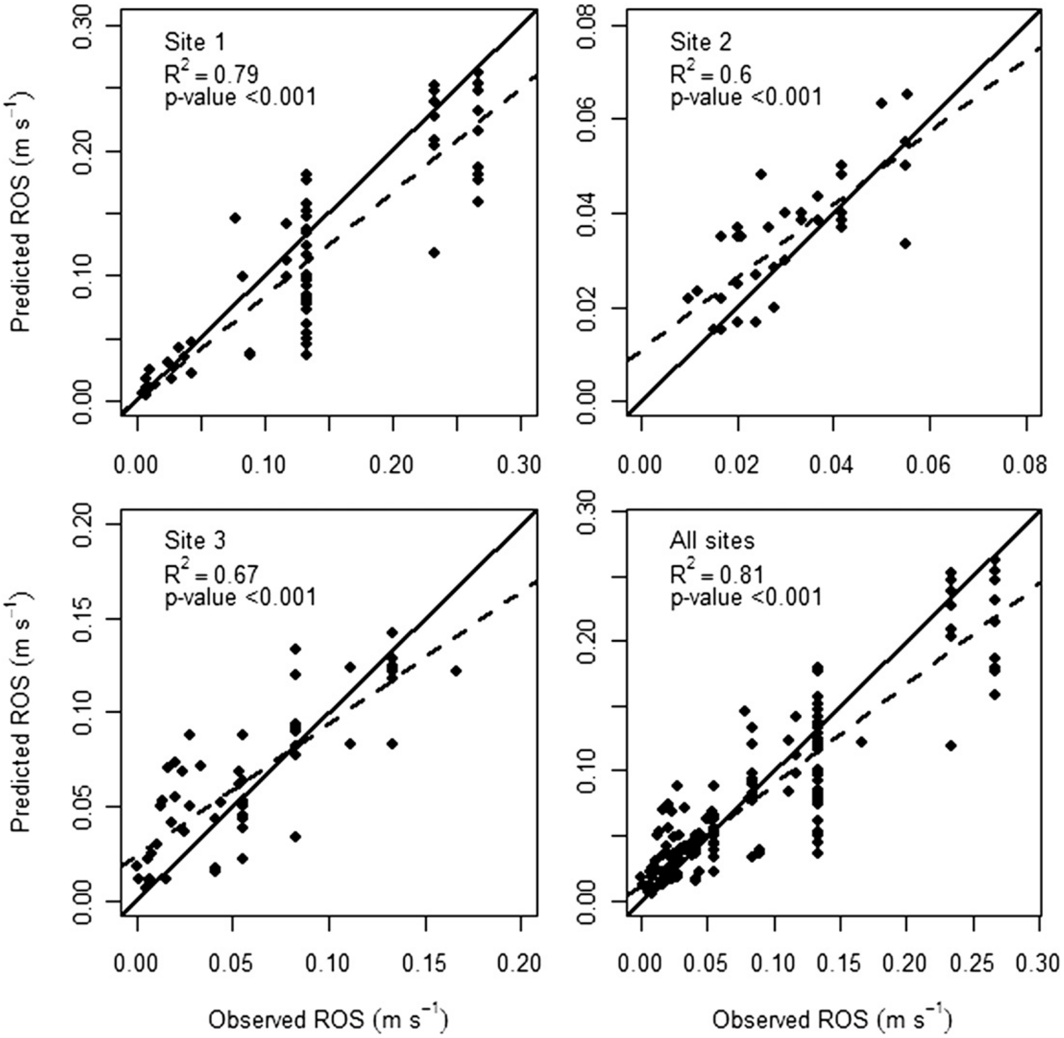

Fig. 7. Observed rates of spread plotted against predicted values obtained from BehavePlus simulations. The dashed line is the linear regression, whereas the plain line shows the first bisector line that is representative of full agreement.

wind speeds, which were not reduced by the region's low tree density and which significantly affected ROS, especially in the first site located in the Sahel. Several studies (Gambiza et al., 2005; Stocks et al., 1996) conducted in southern African savannas found ROS ranges comparable to those observed in this work, again with slightly lower fuel loads than those suggested at the continental scale. The negative relationship between ROS and fuel load is probably indirectly due to the compactness of herbaceous fine fuels as well as to the curing percentage – the presence of green material may have interfered with fire propagation.

The average observed FI values in this work were lower than those reported by Savadogo et al. (2007b) in the framework of early-season prescribed fires (ca 600 $\mathrm{kWm^{-1}}$ versus 233 $\mathrm{kWm^{-1}}$ in the present study). This may be due to the fact that we conducted most of our prescribed fires between mid-October and mid-November while Savadogo et al. (2007b) conducted theirs over a very short period later in the dry season (between November 30th and December 4th). At this later stage, more extensive fuel desiccation would be expected, yielding increased fire intensity with efficient combustion and maximum combustion completeness. Conversely, the earlier fires conducted in this work were initiated at a point when the fuel moisture content would still have been relatively high and variable.

Reliable predictions of fire ROS and the proportion of fuel consumption are both helpful for forestry management. Indeed, the practice of early-season prescribed fires aims to reduce fuel loads in order to minimize the impact of late-season fires (Wardell et al., 2004). The high concordance between the BehavePlus simulations and the observed ROS values indicate that this model and the related nomographs are promising tools for predicting early-season fire behavior. However, they still need further development because although we can partially attribute the predictions slightly underestimated the ROS at low moisture contents and slightly overestimated the ROS for very high (>83% of dry weight) live fuel moisture contents. The first of these problems is probably due to the minimum live fuel moisture value of 30% for the BehavePlus system; considerably lower values were observed in the field. However, we have not yet established an explanation for the slight overestimation of ROS when the live fuel moisture content is very high (>83% of dry weight). The BehavePlus FI predictions were not satisfactory for the first two sites but those for the third site were encouraging.

In African savanna ecosystems, the use of locally developed fuel models is recommended when working with BehavePlus because fuel biomass differences depend on the primary production and thus on annual rainfall (Hély et al., 2003a, 2007). This is even more important in open savannas where the low tree density provides only light twig and leaf litter loads relative to the dominant grass production. Grass curing changes the fuel composition, which is initially dominated by live fuel that is hard to burn but later consists primarily of readily-ignited dead fuel. The comparisons between observed and predicted fire behavior variables drawn up in this work are reliable because we calibrated our fuel models against field data and validated the fire behavior simulations against independent fire measurements.

The goal of using prescribed burns in fire research is to approach as closely as possible the normal conditions of fire in the field. However, this objective is not always achieved. Indeed, Laris and Wardell (2006) highlight several limitations of the methods used to establish experimental prescribed fires in much fire research. They note that experimental conditions are often far from ideal, the burn timing dates are sometimes inadequate and the homogeneity of the plots limits their application in heterogeneous areas. These methodological problems could limit the practical relevance of the results obtained. Overall, the methodological approaches used in several recent studies are similar to those used here. However, there are important differences in terms of the sizing of the studied plots. While the plots examined in such studies are generally square, their size differs between studies even when they focus on similar savanna ecosystems. For example, one previous work dealt with 20 × 20 m plots in a savanna woodland in West Africa (Savadogo et al., 2007b), another considered 50 × 50 m plots in a savanna woodland in Southern African (Gambiza et al., 2005), and another still investigated 120 m × 120 m in plots southern African dambos that are representative of edaphic grassy savanna (Hély et al., 2003a). Usually, the plot size is set according to the nature of the grass cover in order to obtain homogeneous plots. As was done in the previous studies, we took care in this work to select sites that were representative of the landscape on a sub-regional scale in terms of vegetation structure, composition and fuels (for both the herbaceous and woody layers). Our sites were therefore both representative of the regional vegetation structure and homogeneous inside their own fire-break boundaries. Such pre-sampling attention may justify the concordance between the observed and predicted results and bodes well for the future practical applications of these results in Senegal.

5. Conclusion

This study, which was primarily based on field experiments, constitutes a first step toward addressing the lack of accurate scientific knowledge on planning early-season prescribed fires. The results show that fuels in the studied Senegalese savannas consisted exclusively of herbaceous biomass although their characteristics were site-specific. Moreover, it was found that the optimal period for early-season prescribed burns always begins after the final rainfall since before this, the fuels will be too wet to sustain ignition. It is thus necessary to consider parameters relating to both fuel characteristics and weather conditions when planning early season prescribed fires. Our results also indicated that the mechanisms of ignition were similar in all three savanna ecosystems. Probabilities of ignition were influenced by the fuel moisture content and relative humidity. The fires' rate of spread was determined by several fuel parameters and weather conditions, while fuel consumption was solely influenced by the dead and live fuel loads. The agreement between the BehavePlus predictions and fire behavior observations was very good at the regional scale, and tools derived from this model could be valuable for planning prescribed fires according to the desired fire behavior. Finally, we predicted the risks of fire initiation and aspects of fire behavior using statistical methods and simulations. Although these methods can already be useful for forest managers, research in this area should continue in order to increase their usefulness and predictive accuracy. Our findings also indicate a strong need to study tree mortality in order to compare the effects of early and late-fires on woody vegetation.

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Appendix

Table 1
(in the Appendix): Weather conditions during the experimental burns.

Sites	Air temperature (°C)			Relative humidity (%)			Wind speed (ms^{-1})		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
1	31	37.82	48	12	25.37	53	0.7	2.81	6
2	33	37.32	42	14	21.32	37	Calm	0.98	1.9
3	30	33.32	38	26	39.55	56	Calm	1.37	3
All sites	30	36.16	48	12	29.68	56	Calm	2	6

Table 2
Definition of the Senegalese fuel model to be input in the BehavePlus system. This fuel model was adapted from the BehavePlus "short grass and tall grass models" based on fuel estimates from field measurements.

Input variables	Input value	Units
1-h SA/V	4921	m^2/m^3
Live herbaceous SA/V	4921	m^2/m^3
Live woody SA/V	4921	m^2/m^3
Dead fuel moisture of extinction	100	%
Dead fuel heat content	16,890	kJ/kg
Live fuel heat content	16,890	kJ/kg
Canopy bulk density	0.016	kg/m^3
10-h moisture	1	%
100-h moisture	1	%
Live woody moisture	30	%
Foliar moisture	100	%
Slope steepness	0	%

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