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Fire spread control for management purpose: Fuel moisture critical threshold in annually burned dry savanna of west Africa

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ABSTRACT

Fire serves as management tool in protected areas in savanna ecosystems, particularly for biodiversity conservation and tourism purposes. However, selecting the appropriate burning periods that align with management objectives remains a major challenge for managers. For fire spreading, taking into account soil and fuel moisture levels, which vary throughout the season, is essential. This study aimed to identify the moisture content controlling fire spread and to determine its critical threshold. Through monthly experimental burnings on 90 plots in Comoé National Park's savanna ecosystems, we measured soil and fuel moisture contents throughout a complete dry season spanning from October 2023 to March 2024. The results showed that soil moisture (p < 0.001) and fuel moisture (p < 0.001) decreased as the season progressed. Regarding fire spread, the rate of spread increased when soil moisture (p < 0.001) and fuel moisture (p < 0.001) decreased. On the other hand, the distance traveled by flames that was indicating continuous fire spread, was exclusively influenced by fuel moisture content (p < 0.001). Fire spreading risk mapping revealed the fuel moisture critical threshold of 30.35 ± 2.35% from December. Above this threshold, fuel moisture limits fire spread by its dominant influence. But below it, the probability of continuous fire spread was high and almost certain, because fuel moisture ceases to be a limiting factor. This quantitative threshold provides park managers with an objective tool for timing prescribed burns according to specific fire management objectives.

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INTRODUCTION

In the ecological functioning of savannas, fire is a key factor that shapes savanna structure, composition and dynamics globally (Sankaran *et al.*, 2005; Laris *et al.*, 2020). It maintains the grass-tree balance by regulating the vegetation distribution and structure, preventing woody encroachment, and creating habitat heterogeneity (McLauchlan *et al.*, 2020). However, its use varies according to the location and period in which it is lit, which should depend on the desired objective (Afelu *et al.*, 2025). Burnings can occur for a variety of causes, including economic, social, or landscape management (Eriksen, 2007; Lopez-Moreino *et al.*, 2009). Thus, in rural areas of Africa, fires are mainly used for land preparation in agriculture, pastoralism, hunting, firebreaks, charcoal burning, or customary reasons (Kouassi *et al.*, 2020; Amoako and Gambiza, 2022; Soro *et al.*, 2025). Considered as a primary determinant of savanna ecology and distribution (Bond *et al.*, 2005; Li *et al.*, 2023), fires are also part of protected area management policies in savanna zones where they play a crucial role in maintaining the dynamic equilibrium between plant components (Yao *et al.*, 2010). Thus, early fires that are less severe and burn at lower intensities, are typically recommended for protected area management to reduce tree mortality while maintaining open habitats (Savadogo *et al.*, 2007). Controlled burning enhances wildlife viewing by keeping landscapes open, generating tourism revenue that supports conservation efforts, while also facilitating surveillance patrols through reduced vegetation density.

Despite regular burnings, woody encroachment continues across many regions of the world and particularly in African savannas (Gautier, 1990; Heubes *et al.*, 2011). This trend threatens savanna conservation values, as these ecosystems support disproportionate megafauna diversity globally (Fritz, 1997; Gray and Bond, 2013). An increase in woody encroachment would negatively impact the conservation and observation of savanna fauna, reducing the number of visitors and therefore, the economy of these protected areas (Gray and Bond, 2013). Like many other countries, this phenomenon of woody encroachment is also observed in Côte d'Ivoire. This occurs in the Lamto scientific reserve located in the Guinean (humid) savanna zone despite annual burnings, several sub-adults resisting to fire (N'Dri *et al.*, 2022). Furthermore, although located in the Sudanian savanna zone (dry savanna), the Comoé National Park (CNP) is also subject to that phenomenon. These patterns indicate that fire is not always destructive in savanna, especially if it occurs at the right time taking into account the area conditions. This justifies the use of fire as a management tool in CNP, a UNESCO World Heritage Site and Biosphere Reserve, and underscores the importance of updating of its fire management strategy to safeguard this protected area of high national and global importance.

The Ivorian Office of Parks and Reserves (OIPR) faces challenges updating CNP's fire management strategy due to the lack of experimental data to determine the optimal burning periods for the different sectors of the park. In this context, this work was undertaken to address the lack of scientific data to decide on appropriate burning periods according to area and management objectives. This requires the monitoring, throughout the dry season, of parameters likely to influence fire behavior, including fuel characteristics, soil moisture, climatic parameters, among others (Savadogo *et al.*, 2007; Rissi *et al.*, 2017; Laris *et al.*, 2020; Wilson and Yebra, 2023). While climate parameters have an indirect link to fire activity (Soro *et al.*, 2021), it is well known that soil and fuel have a direct link, especially through seasonal moisture contents (N'Dri *et al.*, 2018; Yurkonis *et al.*, 2019). Thus, moisture contents are key elements that vary depending on the season and can have a direct influence on fire spread (Govender *et al.*, 2006).

We hypothesized that moisture content (soil or fuel) exhibits threshold effects on fire spread, with a critical value below which continuous spread becomes highly probable regardless of other factors. Therefore, the objective is to identify the moisture content that controls fire spread and its critical threshold. To achieve this objective, the following questions were addressed:

1. How do soil and fuel moisture contents vary throughout the dry season?
2. Which moisture content controls fire spread?
3. What is the critical moisture threshold for continuous fire spread?

MATERIALS AND METHODS

Study area

The study was carried out in Comoé National Park (CNP) extending from 8°30' to 9°37' N and from 3°7' to 4°25' W, in the northeast of Côte d'Ivoire (West Africa). Located at approximately 570 km from Abidjan, it extends over five prefectures including Bouna, Nassian and Téhini (in the Bounkani region), Dabakala (in the Hambol region) and Kong (in the Tchologo region). This park is subdivided into five management sectors whose command offices are located in the five prefectures (i.e Bouna, Dabakala, Kong, Nassian and Téhini sectors). The study covered all these sectors with sites in each (Fig. 1).

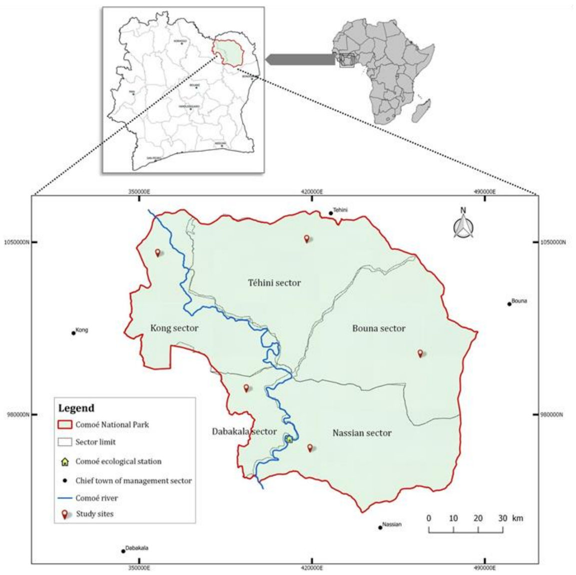

Fig. 1. Location of study area and experimental sites

Covering an area of 1,148,756 hectares, the CNP is the largest protected area in Côte d'Ivoire and one of the largest of West African parks, listed as a Biosphere Reserve (in 1982) and a UNESCO World Heritage Site since 1983. Thus, it is a biodiversity conservation site highly recognized for its ecological, cultural, and social values. This protected area is crossed by one of Ivorian's main rivers, the Comoé, from which it takes its name.

The CNP experiences a subhumid tropical (transitional Sudanian) climate (Guillaumet and Adjanohoun, 1971). As in all of West Africa, the climate of this northeastern part of Côte d'Ivoire is influenced by the migration of the Inter-Tropical Convergence Zone (ITCZ), the confluence zone between the northern continental trade wind (Harmattan) and the southern oceanic trade wind (Monsoon), leading to alternation between dry and wet seasons. The dry season can last up to six or eight months, from October. Rainfall is unimodal and the maximum is recorded between August and September (Tie *et al.*, 2007). Average annual rainfall is around 800 mm. However, the annual water deficit due to dry season can reach 700 to 800 mm. The coldest month is January (with an average daily minimum of 15°C) and the warmest month is March (with an average daily maximum of 37°C).

The vegetation of CNP belongs to Sudanian and sub-Sudanian savanna zones, which are dry savannas that are annually burned. The park is also located in one of the three main fire hotspots of Côte d'Ivoire (Soro *et al.*, 2021). More than 80% of its surface area is dominated by savannas (Poilecot, 1989). Representing approximately 72% of the park, shrub and woody savannas are the most abundant. Their woody cover varies between 5 and 40%, but can reach up to 80% (Lauginie, 2007). Thus, for the maintenance of this ecosystem, which plays a fundamental role in the survival of herbivorous wildlife and for ecotourism, regular burnings are necessary during the dry seasons.

Experimental set-up

Experimental burnings and data collection were carried out monthly throughout the dry season from October 2023 to March 2024. The site selection was based on three criteria: savanna type, accessibility and the possibility of making replicates for statistical reasons. In all five sectors of CNP (Bouna, Dabakala, Kong, Nassian and Téhini), the experimental design (Fig. 2) was installed in shrub savanna, as the park is dominated by this savanna type. In each sector, the design included a block of 190m x 30m, replicated on three sites. On each site, six plots of 20m x 10m were installed. They were separated from each other by 10m and surrounded by 10m of firebreak to protect them from accidental fires. To minimize the influence of slope, sites were located on flat ground. Among the six plots of each site, one was sampled and burned each month. Thus, three plots were burned per sector and fifteen for all five sectors per month. On the whole, the experiments were conducted on eighteen plots per sector and 90 for the five sectors of the park, during the six months of the dry season.

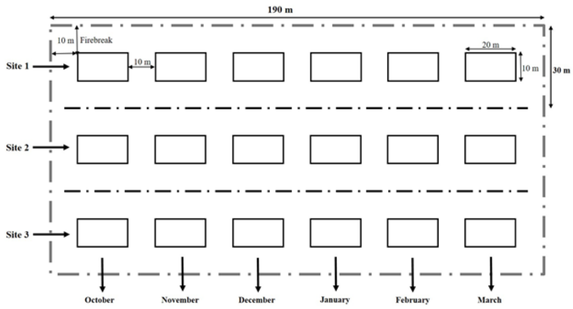

Fig. 2. Experimental set-up of controlled burnings

Data collection

Soil moisture

To assess soil moisture content, five soil samples per plot were randomly taken using an auger up to 5 cm depth, as grass (main fuel) roots are generally superficial, and fire impact is negligible below 5 cm (Miranda *et al.*, 1993). Each month, before burning, fifteen samples were collected from the three sites per sector and 75 in total for all the five sectors of the park. Over the six months of the study period, a total of 450 soil samples were collected overall. Using laboratory electronic scale (precision = 0.01g), samples were immediately weighed *in situ* for fresh masses, while dry masses were determined after oven drying until constant mass.

Fuel moisture

Fuel was mainly composed of grass (live fuel) and litter (dead fuel). Before burning, fuel was collected in five 1 m² quadrats (Fig. 3A) randomly installed on each plot within which measurements were made (Fig. 3B). In each quadrat, grass was first cut to ground level, tied, and immediately weighed to obtain the fresh mass (kg), using digital hanging scale (precision = 0.01kg)). The litter was then collected in a bag and also weighed on site with laboratory electronic scale (precision = 0.01g). These samples were oven-dried to a constant mass and reweighed to determine the dry mass. Each month, fifteen samples were collected per sector and 75 for all five sectors. A total of 450 fuel samples were collected as part of this study.

Fig. 3. Fire experiments in the Comoé National Park A: Set up of a 1m² quadrat; B : Measurements on a plot; C : Spreading fire; D : A plot of 20m x 10m after burning

Soil and fuel moisture contents were calculated using the following formula:

$$M_c = \frac{W_m - D_m}{W_m} \times 100$$

Where M_c is the moisture content (%), W_m is the fresh mass (kg), and D_m is the dry mass (kg).

Fire rate of spread

On each 20m x 10m plot, fire was always lit on one of the widths. While fire was spreading (Fig. 3C), the travel time of the flames was recorded at 5m intervals along the lengths, using stopwatches. Thus, four time records were made on each length, that's to say eight measurements per plot. Each month, 24 measurements were therefore recorded per sector and 120 measurements for the entire park. Overall, 720 measurements were recorded over the entire study period. After plot burning (Fig. 3D), the distance traveled by flames before going out was assessed.

Finally, the fire rate of spread (m/s) was deduced from the travel times and distances as follows:

$$R = \frac{d}{t}$$

Where R = rate of spread (m/s), d = distance traveled by flames (m), and t = flame travel time (s).

From the distance traveled by the flames, the probability of continuous spread was calculated:

$$p_{fire} = \frac{d_{ij}}{d_f}$$

Where p_{fire} is the fire spreading probability, d_{ij} is the distance traveled by flames (m) in sector i for month j, and d_f is the full distance to travel (m), i.e the length of a plot.

Data processing and statistical analysis

The statistical tests were performed using the version 4.4.0 of R software (R Core Team, 2024) at 5% threshold. Data normality was assessed using Shapiro-Wilk test, and homoscedasticity using Bartlett's test. When variances were homogeneous, the one-way Anova test was applied for mean comparisons according to months or sectors. Then, pairwise comparisons were performed using the Tukey HSD test. Contrariwise, the non-parametric Kruskal-Wallis test was used for comparison of means, the variances not being homogeneous. Subsequently, the Wilcoxon rank sum test was applied for pairwise comparisons. To illustrate the influence on fire spread, linear regressions were performed showing the variation of the fire rate of spread and the distance traveled by flames according to moisture contents. Using 'ggplot2' package (Wickham, 2016), regression charts were established by 'Loess' method expressing fire rate of spread according to soil and fuel moisture contents. Finally, the Excel software was used for spreading risk mapping that plots the fire spreading probability according to fuel moisture throughout dry season.

RESULTS

Soil and fuel moisture contents in sectors

In all park sectors, both soil and fuel moisture contents showed significant variations depending on months ($p < 0.001$). Indeed, a decrease in these moisture contents was observed as dry season progressed (Fig. 4). In the case of soil moisture, the variation was regular in the Bouna and Nassian sectors, excluding value of March. Thus, soil moisture decreased from 16.26 ± 3.71% (in October) to 0.71 ± 0.21% (in February) in Bouna sector and from 18.10 ± 2.96% (in October) to 2.04 ± 0.64% (in February) in Nassian sector. In the other three sectors, the variation in soil moisture was more or less irregular, probably due to variations in local conditions. However, in all sectors soil moisture was high at the beginning of dry season (October-November) and at the end in March (Fig. 4A).

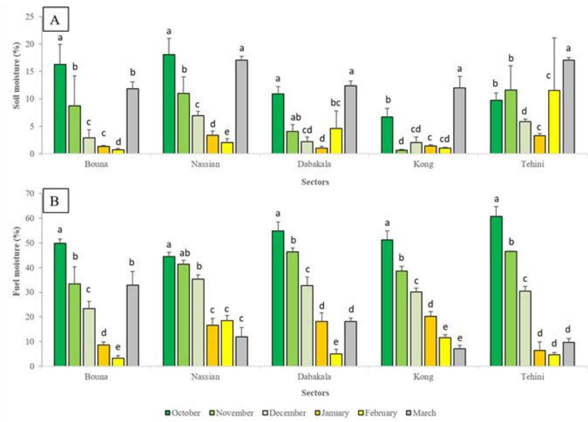

Fig. 4. Variation of soil (A) and fuel (B) moisture contents in sectors throughout dry season

In each sector, values with the same letter were not significantly different.

The decline in fuel moisture contents was fairly regular throughout the dry season in all sectors, except Bouna and Dabakala where a significant increase was observed at the end of the season in March (Fig. 4B). The rain occurred before March's sampling was probably more abundant in these two sectors. Fuel moisture ranged from 49.79 ± 1.78% (in October) to 3.19 ± 1.20% (in February) in Bouna sector, from 54.85 ± 3.66% (in October) to 4.96 ± 1.16% (in February) in Dabakala, and from

60.79 ± 2.87% (in October) to 4.58 ± 1.20% (in February) in Tehini. In the two other sectors, the decline in fuel moisture was continuous until the end of dry season. In fact, it ranged from 44.48 ± 1.68% (October) to 11.91 ± 3.85% (March) in Nassian and from 51.24 ± 3.91% (October) to 7.01 ± 1.50% (March) in Kong.

Fire spread in sectors

Fire rate of spread in sectors

Fire rate of spread showed a significant variation according to months in all sectors, namely Bouna ($F = 4.71$; $p = 0.013$), Nassian ($\chi^2 = 13.94$; $p = 0.016$), Dabakala ($\chi^2 = 14.29$; $p = 0.013$), Kong ($\chi^2 = 15.54$; $p = 0.008$) and Téhini ($\chi^2 = 12.84$; $p = 0.025$). Indeed, the rate of spread increased each month until reaching a peak in January for Nassian (0.161 ± 0.042 $m.s^{-1}$), Dabakala (0.096 ± 0.034 $m.s^{-1}$) and Téhini (0.132 ± 0.071 $m.s^{-1}$) sectors or in February for Bouna (0.178 ± 0.035 $m.s^{-1}$) and Kong (0.388 ± 0.191 $m.s^{-1}$) sectors, before decreasing at the end of dry season (Fig. 5). Furthermore, fire rate of spread was found to be dependent on fuel moisture in all sectors: Bouna ($F = 13.10$; $p = 0.002$), Nassian ($F = 6.10$; $p = 0.025$), Dabakala ($F = 8.66$; $p = 0.009$), Kong ($F = 5.39$; $p = 0.034$) and Téhini ($F = 9.71$; $p = 0.007$). The less humid the fuel, the faster the fire.

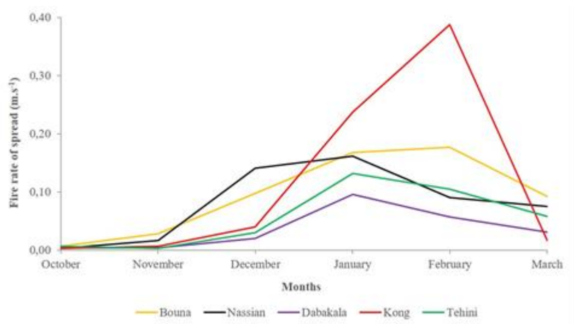

Fig. 5. Fire rate of spread according to months in sectors

Distance traveled by flames in sectors

The distance traveled by flames varied significantly according to months in Nassian ($\chi^2 = 14.78$; $p = 0.011$), Kong ($\chi^2 = 13.01$; $p = 0.023$), and Dabakala ($\chi^2 = 16.16$; $p = 0.006$) sectors. Indeed, flames only traveled short distances at the beginning of the season in October (0.67 ± 0.17 m, 1.00 ± 0.25 m, and 2.62 ± 1.37 m in the Nassian, Kong, and Dabakala sectors, respectively). These distances gradually increased until reaching the maximum from December when, in those three sectors, fire was spreading along the entire length of experimental plots (20 m) without going out. On the other hand, in Bouna and Tehini sectors, the distances traveled by flames did not show any significant variation depending on months. This is explained by the fact that these distances were maximal, and therefore constant from November onwards (Fig. 6).

The distance traveled by flames was influenced by fuel moisture content in all sectors of the park, namely Tehini ($F = 9.21$; $p = 0.007$), Nassian ($F = 13.58$; $p = 0.002$), Bouna ($F = 6.98$; $p = 0.018$), Dabakala ($F = 34.27$; $p < 0.001$) and Kong ($F = 11.85$; $p = 0.003$). Indeed, fire traveled the shortest distance when fuel moisture was the highest, especially at the beginning of dry season in October (Fig. 6). This distance increased in the following months whereas fuel moisture was decreasing. However, once the distance traveled by flames reached the maximum (20 m corresponding to the entire length of a plot), no decrease in fuel moisture was influencing it. On the other hand, a further increase in fuel moisture immediately caused a decrease in the distance traveled by flames. This was the case in Kong sector in March. These results suggest the existence of sector-specific fuel moisture thresholds. Thus, from the moment the entire length of the plots (20 m) was traveled by flames in each sector, fuel moisture was 46.55 ± 0.20% in Tehini (Fig. 6A), 35.36 ± 1.60% in Nassian (Fig. 6B), 33.31 ± 7.00% in Bouna (Fig. 6C), 32.62 ± 3.46% in Dabakala (Fig. 6D), and 30.05 ± 1.67% in Kong (Fig. 6E). Below these thresholds, fuel moisture was no longer a limiting factor for fire spread in the concerned sector.

Particularly, both the distance traveled by the flames ($F = 5.63$; $p = 0.03$) and fire rate of spread ($F = 6.39$;

p= 0.022) were influenced by soil moisture in Nassian sector solely. Flames were slower and traveled a short distance when soil was wetter, especially at the beginning of dry season. This result could be explained by the fact that Nassian is located in the southern part of the park, and is therefore a little wetter. It is probably why the highest soil moisture was observed in this sector (18.10 ± 2.96%).

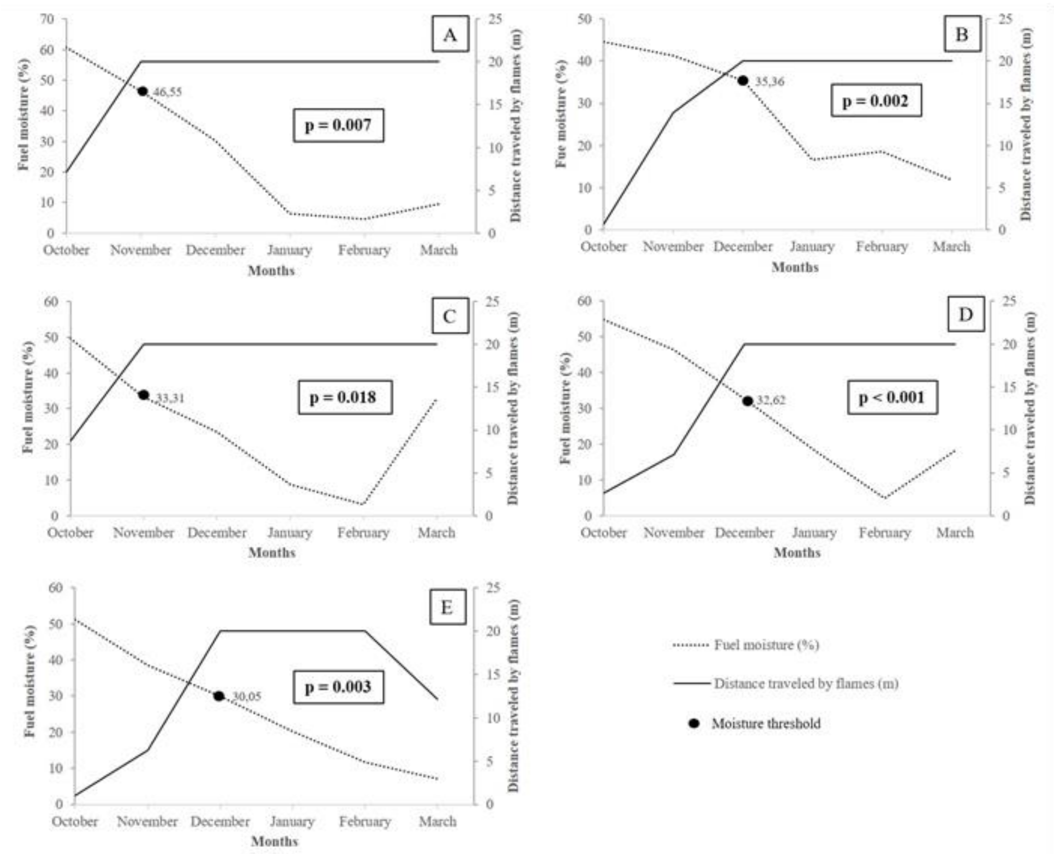

Fig. 6. Variation of the distance traveled by flames according to fuel moisture in sectors A: Téhini; B: Nassian; C: Bouna; D: Dabakala; E: Kong

Average soil and fuel moisture contents in the park

The average soil moisture content of the entire park varied significantly according to months (χ^2 = 198; p < 0.001). Indeed, soil moisture was decreasing along dry season (Fig. 7A), particularly from October (12.33 ± 2.18%) to January (2.07 ± 0.36%). The same was true for the average fuel moisture content depending on months (χ^2 = 333.86; p < 0.001), decreasing from 52.23 ± 2.78% in October to 8.58 ± 1.29% in February (Fig. 7B). However, both soil moisture and fuel moisture increased at the end of the season in March. This is explained by the sampling of this month occurring the day after rainfall occurrence in all sectors of the park, as previously stated. Indeed, significant correlations were observed between soil moisture and the moisture contents of total fuel load (r = 0.26; p < 0.001), grass (r = 0.19; p < 0.001) and litter (r = 0.58; p < 0.001). This means that the more it rains, the wetter the soil and the wetter the fuel. However, although the correlations are statistically significant, the correlation coefficients that attest those relations are low, with the exception of that between soil moisture and litter moisture.

Importantly, overall, the average moisture content of the total fuel (grass + litter) did not vary significantly between sectors for a given month. That's to say for the same month, fuel moisture content did not differ from one sector to another within the park. These results demonstrate a certain homogeneity between the shrub savanna sites that hosted experiments in the different sectors, reinforcing the findings.

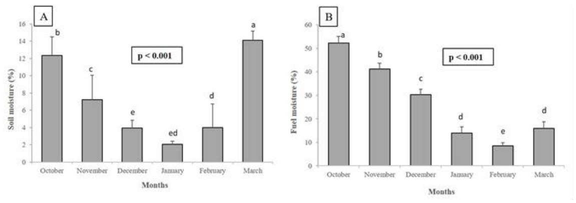

Fig. 7. Average soil (A) and fuel (B) moisture contents according to months in dry season

Fire spread in the park

Average fire rate of spread

The average fire rate of spread showed significant variation according to months ($\chi^2 = 60.42$; $p < 0.001$). Indeed, early burnings were slow at the beginning of dry season (0.005 ± 0.002 m.s^{-1} in October). As in sectors, the rate of spread went increasingly the following months until reaching the peak in February (0.164 ± 0.066 m.s^{-1}) which was not significantly different from the value of January (0.159 ± 0.052 m.s^{-1}). At the end of dry season in March, a decrease in the average fire rate of spread was observed (Fig. 8).

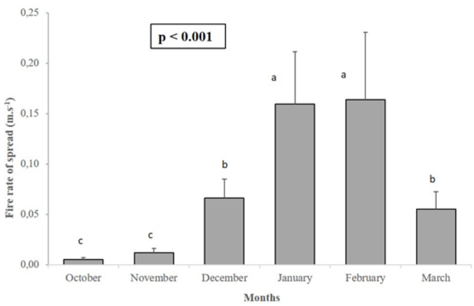

Fig. 8. Average fire rate of spread according to months in dry season

Moreover, the decrease in average fire rate of spread at the end of dry season could be explained by average soil and fuel moisture contents, which increased significantly in March. Indeed, fire rate of spread was significantly influenced by soil (F = 11.78; $p < 0.001$) and fuel (F = 20.79; $p < 0.001$) moisture contents. During burnings, flames were faster when the soil (Fig. 9A) and fuel (Fig. 9B) were less humid. These overall results confirm the influence of moisture contents on fire behavior, already observed in the different sectors. Obviously, the Fig. 9 reveals that above 10% soil moisture and 30% fuel moisture, almost all the points were within the 95% confidence interval (see gray area around the curves). This means that soil and fuel moisture contents significantly influence the fire rate of spread only above the indicated thresholds (10% and 30% for soil and fuel, respectively). However, below these thresholds, the most points were outside the confidence interval. This expresses an absence of influence or a weak influence of moisture contents. Thus, the results suggest that fuel and soil moisture contents influence the capacity of the park's sectors to burn at a given period, depending on their desiccation level.

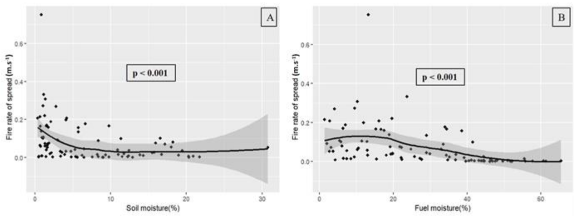

Fig. 9. Regression of average fire rate of spread according to soil (A) and fuel moisture (B)

Average distance traveled by flames

Regardless of their rate of spread, the distance traveled by flames before going out can provide an overall idea on fuel flammability and the possibility of ignition. Globally, the average distance traveled by flames differed according to months overall ($\chi^2 = 52.91$; $p < 0.001$). It was low in October (4.04 ± 2.81 m) where flames did not travel a quarter of plot length (20 m) before going out, and this, in almost all sectors. Results showed that the distance traveled by flames depended solely on fuel moisture (F = 51.38; $p < 0.001$). On the other hand, soil humidity did not show a significant influence on this distance. Probably because average soil moisture contents were below 10% for most months, since the Fig. 9 showed that below this threshold, soil moisture does not significantly influence fire spread. Therefore, among these two moisture contents, the study reveals that it is fuel moisture that most controls fire spread in dry savannas of the CNP.

During the first three months of dry season (October, November and December), the average distance traveled by flames was increasing as fuel moisture decreased (Fig. 10). From December onwards, when this distance reached the 20m length of the plots at once in all sectors, illustrating the possibility of continuous fire spread, fuel moisture was 30.35 ± 2.35% on average. Thus, this moisture content constitutes the critical threshold below which continuous fire spread was possible. Above it, continuous fire spread was compromised. Between December and February, the distance traveled by flames remained maximum regardless of the decline in fuel moisture. At the end of dry season, when this moisture increased following the resumption of rains, the distance traveled by flames experienced a slight decrease in March (Fig. 10). This decrease would be particularly linked to the increase in the moisture content of litter covering the ground, itself quite humid, conditioning fuel flammability and thus, fire spread.

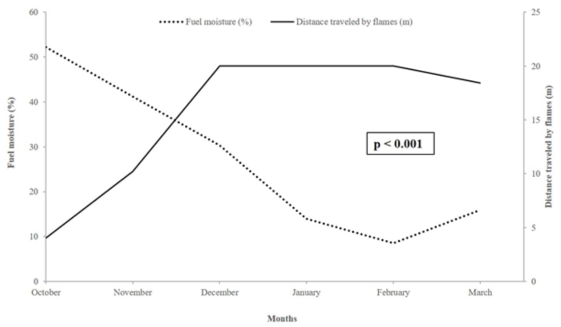

Fig. 10. Evolution of the distance traveled by flames according to fuel moisture throughout dry season

Critical threshold of fuel moisture and fire spreading probability

The mapping of continuous fire spread risk highlighted fuel moisture thresholds and fire spreading probability in relation to burning periods during dry season (Fig. 11). Three intervals can be distinguished on the map. Firstly, below the critical threshold of 30% fuel moisture, the probability of continuous fire spread was high and almost certain. This level of risk was observed from December. Secondly, between 30 and 45% fuel moisture, the probability of continuous fire spread was low, medium, or high. Low risk was observed between October and November, with medium and high risks occurring in November or often in March. Finally, above 45% fuel moisture, the probability of continuous fire spread was exclusively low. This implies a low risk exclusively observed in October, and rarely in November.

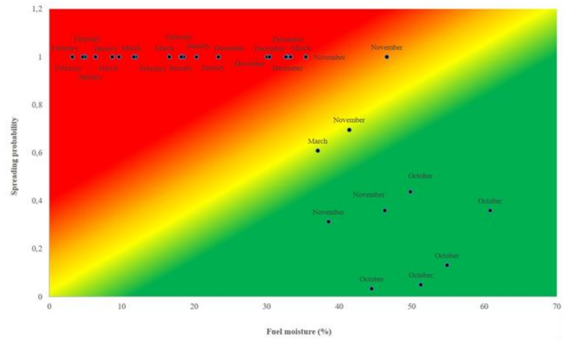

Fig. 11. Mapping of fire spreading risk in dry season according to fuel moisture

DISCUSSION

Moisture contents according to season

The monitoring of soil and fuel moisture contents throughout dry season helps understanding their evolution and their influence on fire spread. The moisture contents were decreasing as the dry season progressed. The high soil and fuel moisture values observed at the beginning of dry season can be explained by the climate of this area. Indeed, with unimodal rainfall (Tie *et al.*, 2007), August and September experience the maximum rainfall of wet season there. Accordingly, soil and fuel are still quite wet in October and November, corresponding to the beginning the dry season. This explains why previous studies recorded low fire occurrence during this period (Soro *et al.*, 2020).

After decline along the season, the sudden increase in moisture contents observed in March was due to rainfall occurring on the eve of the sampling in that month, while measurements were planned on predefined dates each month. This rainfall led to a direct increase in soil moisture and an indirect increase in fuel moisture, their effects on moisture contents being recognized, contributing to the limitation of fire frequency (Archibald *et al.*, 2009; Wilson and Yebra, 2023). The positive and significant correlation between soil and litter moisture contents confirmed that soil moisture has a greater impact on litter moisture as the primary component of fuel that covers the soil. Since most fires are surface fires (Werner, 2010), its role in fire spread becomes decisive. This certainly explains why it has an influence on fire behavior (Rissi *et al.*, 2017).

Fire rate of spread according to season and moisture contents

Fire behavior strongly depends on its spread. Since the beginning of dry season, fire spread increased each month, peaking in January and February according to sectors. Thus, those peaks reveal when fires are the fastest and could therefore be uncontrollable, even if they are initially carried out under controlled conditions as part of park management or scientific experiments. This probably explains the fact that Brou *et al.* (2025) observed experimental fires that crossed firebreaks in this same park and during the same months (January and February). While fire occurrence generally peaked in December in the Northeast (N'Datchoh *et al.*, 2015; Soro *et al.*, 2021), this study records the peak of rates of spread in January and February. Indeed, these months correspond to the peak of dry season in the area. Biomass burning is made more favorable by faster winds and low air relative humidity levels, this area being under the influence of the Harmattan. This affects fuel state, making it increasingly dry, due to decline in moisture. Moreover, fire spread was influenced by fuel moisture content. In this dry savanna where experiments occurred, this confirms that fire behavior is also influenced seasonality through the state of fuel, as elsewhere in humid savanna (N'Dri *et al.*, 2018) or grassland (Yurkonis *et al.*, 2019).

However, the higher rate of spread recorded in February, particularly in Kong sector, suggests the influence of other factors such as fuel load. Indeed, at the beginning of dry season (October) when fuel moisture contents were high (> 40%), fuel loads were most abundant for each sector, but fire rate of spread remained low all over the sectors. On the other hand, although fuel moisture contents were low (<20%) in all sectors in February, Kong sector experienced the highest fire rate of spread. Importantly, because its fuel load was the most abundant for this month. If the influence of fuel moisture (Williams *et al.*, 1998; Govender *et al.*, 2006) and that of fuel load (N'Dri *et al.*, 2012; Rissi *et al.*, 2017) are recognized on fire behavior, our results suggest the existence of a fuel moisture threshold below which the influence of fuel load becomes dominant. This threshold would be between 20 and 40%, based on observations.

Furthermore, it was revealed that above the critical thresholds of 10% soil moisture and 30% fuel moisture, soil and fuel moisture contents influenced the average fire rate of spread. Below these thresholds however, they did not limit fire spread. In the last case, the influence of other factors such as fuel load, air relative humidity or wind speed (Savadogo *et al.*, 2007; Archibald *et al.*, 2009) would become dominant on fire spread.

Distance traveled by flames according to season and moisture contents

The distance traveled by flames was crucial in determining the critical fuel moisture threshold. Over all, the fact that fire traveled the entire length of a plot without extinguishing on its own was considered continuous spread. This meant that, without natural barrier such as watercourse or green firebreak (Curran *et al.*, 2018), fire would spread throughout the area.

The distance traveled by flames was exclusively influenced by fuel moisture content. This means that this distance varied regardless of soil moisture content. These results can be explained by the levels of soil moisture in this dry savanna. Indeed, all soil moisture contents were below 10%. As previously stated, soil moisture below this threshold did not influence fire spread. This influence may be indirect. For instance, if the spread and frequency of fires are influenced by rainfall through moisture contents (Soro *et al.*, 2021; Wilson and Yebra, 2023), rains act more quickly on soil moisture, which is able to influence them in return (Koné *et al.*, 2022). Once high, soil moisture positively influences fuel moisture which, in turn, negatively influences fire spread as observed in March. The more humid the soil, the more humid the fuel and the less the fire spreads. Using the variation of average distance traveled by flames, 30% fuel moisture was identified again as the critical threshold below which continuous fire spread was possible, the influence of fuel moisture being negligible. On the other hand, above this threshold, continuous fire spread was limited by fuel moisture influence, which would dominate that of fuel load (Govender *et al.*, 2006) and other factors.

While the distance traveled by flames increased gradually to reach the maximum from December in all sectors, Bouna and Téhini sectors experienced this maximum since November. Further, early in October, fire was traveling almost half the length of plots in these two sectors. Moreover, from the first experiments at the beginning of dry season (October), these last two sectors were the only ones where burning covered the entire length (20 m) of at least one plot. Although all experiments occurred in a park located in the same climatic zone, these results could be due to the particular location of Bouna and Téhini sectors in the eastern part. As a result, they are more exposed to the winds and the drying front from the Intertropical Convergence Zone (ITCZ), of which the Northeast of the country is a gateway. Seasonal changes induced by this ITCZ controlling biomass burning in the West African zone in general (Swap *et al.*, 2002; N'Datchoh *et al.*, 2015).

Even if continuous fire spread was observed very early in Tehini and Bouna sectors, their specific fuel moisture thresholds were high, comparatively to the other sectors. This indicates that fuel moisture is not the only factor that explains fire spread. In fact, fire behavior in a given area is influenced by a number of factors, including fuel characteristics, climatic parameters, and topography (N'Dri *et al.*, 2018; Yurkonis *et al.*, 2019; Laris *et al.*, 2020; Wilson and Yebra, 2023). However, some factors may have a dominant influence at a given time, such as seasonal fuel moisture (Govender *et al.*, 2006).

Critical moisture thresholds and fire spread risk

To sum up, the mapping of continuous fire spread risk provides an overview on fuel moisture thresholds and their spreading probabilities. This map identified three main intervals in fuel moisture. The first one includes values below the critical threshold of 30%. Within this interval, continuous fire spread was certain. This level of risk was observed from December. This means that a fire started at this time can spread continuously without difficulty. Well-done or severe burnings may be recommended for this period, particularly for areas whose objective is ecotourism in protected areas of savanna ecosystems (Gray and Bond, 2013). However, maximum vigilance is required, as fires can easily become uncontrollable and even cross firebreaks (Brou *et al.*, 2025). At this time, fire behavior is mostly controlled by air relative humidity and wind speed (Laris *et al.*, 2020).

The second interval runs from 30 to 45% fuel moisture, wherein the continuous fire spread is mitigate, as the probability can be low, medium, or high. While, low risk was observed between October and November, medium and high risks was experienced in November or often in March. During this period, both fuel moisture and climate factors control fire behavior, which is generally influenced by a combination of factors (N'Dri *et al.*, 2018; Yurkonis *et al.*, 2019). The level of risk would depend on the importance of other factors. Moderate burning may be recommended.

Finally, the third interval includes all values above 45% fuel moisture. Observed in October, and rarely in November, the probability of continuous fire spread was exclusively low, indicating a lower risk. Thus, since fuel moisture is high, its influence becomes dominant and limits fire spread (Govender *et al.*, 2006). Early ignitions during this period would cause incomplete burnings and contribute to an increase in woody plant density at long term (Heubes *et al.*, 2011; N'Dri *et al.*, 2022).

CNP's managers, which is high importance protected area for biodiversity conservation, now have data-based insights at their disposal to update their fire ignition plans, choosing the appropriate burning periods according to areas and management objectives. Nevertheless, some limitations of this study should be acknowledged. First, our study was conducted during a single dry season, limiting temporal generalizability. Second, we focused on shrub savanna. Results may differ in other savanna types.

CONCLUSION

Protected areas in savanna ecosystems need fire as a management tool. Therefore, the choice of appropriate burning period and the control of fire spread become essential for targeted management. This study dealt with fire spreading control for management purpose in dry savanna ecosystems. The monthly monitoring of fuel and soil moisture contents showed a decline over dry season. Between the two types of moisture, the findings revealed that fuel moisture content was the determining factor that controls fire spread during biomass burning in savannas of the CNP. However, its influence worked above a certain threshold. This study provides the first quantitative determination of fuel moisture thresholds for fire management in Ivorian savannas for the first time. Using fire spreading probability, the map of fire spreading risk according to fuel moisture content helped identifying the critical threshold above which fuel moisture controls fire spread, and below which it doesn't have significant effect. In the last case, continuous fire spread was possible. Thus, scientific data-based findings are provided to CNP managers to update their fire management strategy as requested. Furthermore, these insights may be useful for all managers of protected areas and other areas of interest in savanna ecosystems for targeted burning according to management objectives. The monitoring of fuel moisture will be necessary as the critical threshold may vary according to savanna type and local climate conditions.

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