



Development of a local prescribed burning plan in the miombo woodlands for agricultural systems in Huambo province (Angola)

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ABSTRACT

Fire regimes strongly influence vegetation dynamics, agricultural systems and land management across the Miombo Woodlands of Central Angola. However, locally adapted evidence to guide prescribed burning within integrated agricultural and forest landscapes remains limited. This study aimed to support the development of a local prescribed burning plan for agricultural systems in the Miombo Woodlands of Huambo Province by assessing fuel characteristics, stand structure and fire behaviour in a *Pinus spp.* plantation embedded within a broader agro-forestry context. The research contributes to operational fire management strategies applicable to both plantation forestry and surrounding agricultural mosaics. Eight systematically distributed sampling points were established, where dendrometric measurements, floristic composition and fuel loads were quantified using the planar intercept method. Fuel moisture content was determined through oven-drying procedures, and experimental prescribed burns were conducted in two 25×25 m² plots to evaluate flame height, rate of spread and burn depth under controlled conditions. These parameters were analysed to determine safe operational thresholds for low-intensity burns compatible with local agricultural land-use systems. Results showed rapid desiccation of grasses such as *Hyparrhenia rufa* and *Brachiaria mutica*, confirming their role as primary surface fuels across agricultural-forest interfaces, while woody species, including *Pinus patula*, retained moisture for longer, moderating fire intensity. The stand exhibited a clear two-tiered structure, with tall, thick-barked *Pinus patula* in the pole stage and a heterogeneous understory contributing fine fuels relevant to fire propagation in mixed land-use systems. Maximum flame heights remained below 1.4 m, and fire behaviour was consistent with low-severity surface burns, with no evidence of crown involvement. The findings demonstrate that appropriately timed, low-intensity prescribed burns can reduce 40–70% of surface and fine woody fuels without compromising overstorey integrity. These results support the feasibility of integrating locally adapted prescribed burning into sustainable fire management strategies for agricultural systems and plantation landscapes within the Miombo Woodlands of Huambo Province, Angola.

Keywords: Agricultural systems, combustible load, ecological assessment, fire behavior, fuel moisture, local fire management, Miombo Woodlands, *Pinus patula*.

Elaboração de um plano local de queimadas controladas nas florestas de Miombo para sistemas agrícolas na província do Huambo (Angola)

RESUMO

Os regimes de incêndio influenciam fortemente a dinâmica da vegetação, os sistemas agrícolas e a gestão da terra nas florestas de Miombo da região central de Angola. No entanto, continuam a ser escassos os dados adaptados às condições locais que possam orientar a queima controlada em paisagens agrícolas e florestais integradas. Este estudo teve como objetivo apoiar o desenvolvimento de um plano local de queimadas controladas para sistemas agrícolas nas florestas de Miombo da província do Huambo, através da avaliação

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das características do combustível, da estrutura do povoamento e do comportamento do fogo numa plantação de *Pinus spp.* inserida num contexto agroflorestal mais amplo. A investigação contribui para estratégias operacionais de gestão de incêndios aplicáveis tanto à silvicultura de plantação como aos mosaicos agrícolas circundantes. Foram estabelecidos oito pontos de amostragem distribuídos sistematicamente, onde as medições dendrométricas, a composição florística e as cargas de combustível foram quantificadas utilizando o método de intercepção planar. O teor de humidade do combustível foi determinado através de procedimentos de secagem em estufa, e foram realizadas queimadas controladas experimentais em duas parcelas de 25×25 m² para avaliar a altura da chama, a taxa de propagação e a profundidade da queima em condições controladas. Estes parâmetros foram analisados para determinar limiares operacionais seguros para queimadas de baixa intensidade compatíveis com os sistemas locais de uso do solo agrícola. Os resultados revelaram uma rápida dessecação de gramíneas como a *Hyparrhenia rufa* e a *Brachiaria mutica*, confirmando o seu papel como combustíveis de superfície primários nas zonas de transição entre a agricultura e a floresta, enquanto as espécies lenhosas, incluindo o *Pinus patula*, retiveram a humidade por mais tempo, moderando a intensidade do incêndio. A povoação apresentava uma estrutura clara de dois níveis, com *Pinus patula* de porte alto e casca espessa na fase de árvores jovens e um sub-bosque heterogêneo que contribuía com combustíveis finos relevantes para a propagação do fogo em sistemas de uso misto do solo. As alturas máximas das chamas mantiveram-se abaixo de 1,4 m, e o comportamento do fogo foi consistente com queimadas superficiais de baixa gravidade, sem indícios de envolvimento da copa. Os resultados demonstram que queimadas controladas de baixa intensidade, realizadas no momento adequado, podem reduzir 40–70% dos combustíveis de superfície e lenhosos finos sem comprometer a integridade do estrato superior. Estes resultados apoiam a viabilidade de integrar queimadas controladas adaptadas localmente em estratégias sustentáveis de gestão de incêndios para sistemas agrícolas e paisagens de plantações nas Florestas de Miombo da Província de Huambo, em Angola.

Palavras-chave: Sistemas agrícolas, carga combustível, avaliação ecológica, comportamento do fogo, humidade do combustível, gestão local do fogo, Florestas de Miombo, *Pinus patula*.

1. Introduction

Fire regimes have long shaped ecological processes and rural livelihoods across tropical and subtropical landscapes, influencing vegetation structure, nutrient dynamics and land management practices (Quissindo et al., 2026; Amankwah et al., 2025; Buramuge et al., 2023; Quissindo et al., 2021). By addressing sustainable fire management and landscape resilience, this study contributes to the objectives of Sustainable Development Goal 15 (Life on Land) of the United Nations, which promotes the conservation and sustainable use of terrestrial ecosystems (Sangha, 2023). Uncontrolled wildfires and unmanaged burns, however, pose substantial risks to both production forestry and native ecosystems in many parts of sub-Saharan Africa, including Angola, where satellite observations indicate a persistently high frequency of fire events in Miombo zone during the dry season (Quissindo et al., 2026; Catarino et al., 2020). These fire occurrences are often linked to traditional land use practices and a lack of evidence-based management strategies to control fuel loads in forested landscapes of Miombo woodlands, a tropical forests biome of Southern Africa described by White (1983).

In plantation forestry, stands dominated by *Pinus spp.* are widely recognised for their high accumulation of surface and ladder fuels and their susceptibility to high severity fire behaviour compared with native forests (Lindenmayer et al., 2023; Bartlett, 2012). Such fuels increase the likelihood of wildfire ignition and rapid spread, especially under dry season conditions typical of tropical highland climates. Prescribed burning, the deliberate application of fire under controlled conditions, is increasingly advocated as a cost-effective component of Integrated Fire Management (IFM), with potential benefits including surface fuel reduction, hazard mitigation, and maintenance of ecological processes (Oliveras et al., 2025). Within tropical plantation systems, controlled low intensity burns can reduce fuel loads while limiting impacts on stand structure and soil properties relative to untreated areas (Catarino et al., 2020; Bartlett, 2012).

Recent research in West and Central Africa highlights the ecological and socio-economic complexities of fire, with local practices affecting fire frequency, fuel accumulation, and land cover (Archibald et al., 2017). Empirical studies on prescribed burning in African plantations remain scarce, and locally adapted prescriptions for smallholder or experimental forestry are largely absent, reflecting the temperate and high-income bias noted in global reviews (Nieman et al., 2021; Archibald et al., 2017).

Some recent studies highlight the importance of sustainable land and forest management in tropical, subtropical and local contexts. Work on forest conservation in Ghana and Australia emphasises the need to contextualise technical interventions within socio-ecological frameworks (Amankwah et al., 2025; Buramuge et al., 2023; Sangha, 2023), a principle directly relevant to Fire Management (FM) in plantations, where

ecological and local land use factors must be considered.

Against this backdrop, this study focuses on the *Pinus spp.* plantation in the Miombo agricultural zone of Huambo province (Angola), where significant fuel accumulation and recurrent fire events threaten stand health and landscape stability. This research aims to generate robust, locally grounded evidence to inform the development of an operational and local prescribed burning plan that can be integrated into broader IFM strategies for similar tropical plantation contexts.

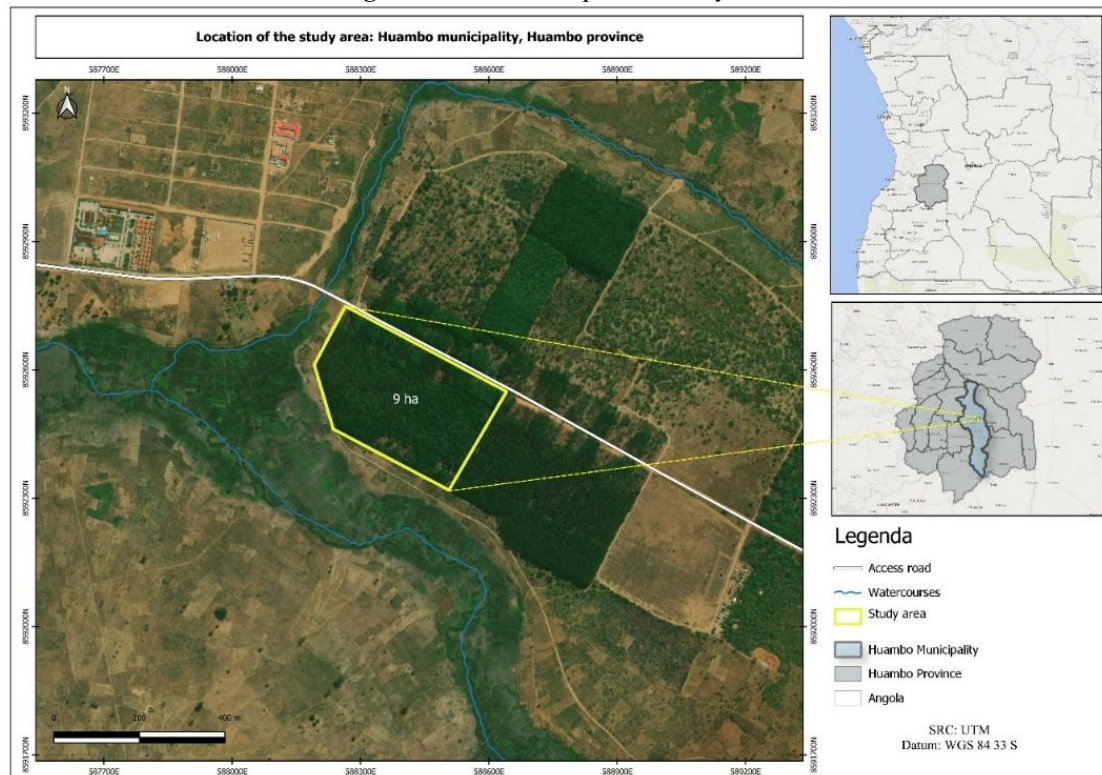
We hypothesise that appropriately timed, low-intensity prescribed burns removing approximately 40–70 % of surface and fine woody fuels will (a) substantially reduce key fire behaviour indicators (including rate of spread, flame length, and fire line intensity) to levels consistent with controllable surface fires, and (b) have minimal short-term impacts on stand structure and native understorey diversity. This hypothesis is supported by evidence from plantation and savanna systems (particularly in the Miombo zone), demonstrating that fuel-reduction treatments can moderate wildfire behaviour without compromising stand health (Amankwah et al., 2025; Buramuge et al., 2023; Nieman et al., 2021; Archibald et al., 2017).

2. Methodology

2.1 Study area

The study was conducted at the Chianga Agricultural Experimental Station, located approximately 13 km east – northeast of the city of Huambo (Figure 1). The study area is approximately delimited by the parallels $12^{\circ} 14'$ and $12^{\circ} 16'$ south latitude and the meridians $15^{\circ} 48'$ and $15^{\circ} 52'$ east longitude of Greenwich, and is characterized by generally flat relief.

Figure 1. Location map of the study area



Source: Authors (2026)

With elevations ranging between 1,650 and 1,740 m, the Chianga area receives a mean annual precipitation of approximately 1,380 mm, distributed across two distinct seasons: the rainy season, extending from October to April, during which about 96% of the annual precipitation occurs, and the dry season (locally known as “*cacimbo*”), spanning from May to September, during which rainfall is virtually absent (Kiala & Simpson, 2023).

The study area is classified as Cwb under the Köppen system, representing a mesothermal humid climate with a dry winter and mild, extended summer (Mateus et al., 2024). Mean annual temperature is approximately 19 °C, with low seasonal variability, and the warmest conditions occurring at the onset of the rainy season, particularly in October (20.6 °C) (Kiala & Simpson, 2023). The rainy season lasts about seven months, from late September to April, and mean annual precipitation is around 1,400 mm, with peak rainfall in March (Mateus et al., 2024; Kiala & Simpson, 2023).

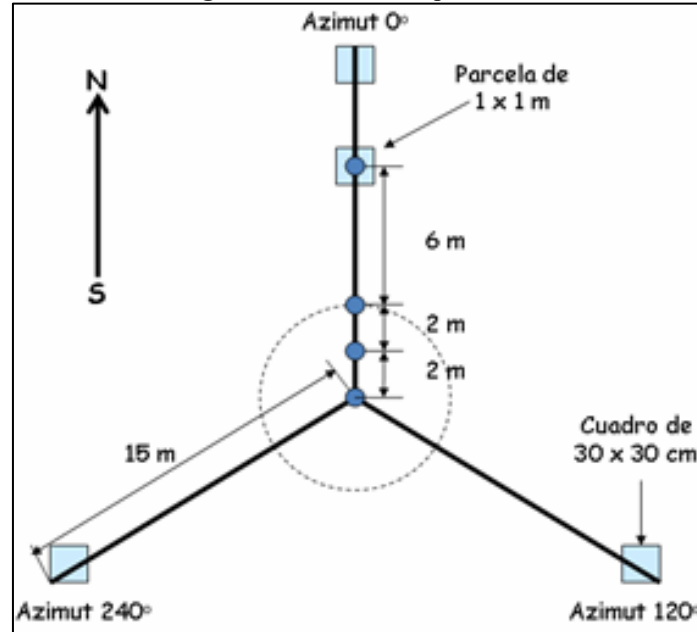
Huambo Province is predominantly covered by miombo woodlands, tropical deciduous forests typical of southern and central Africa, dominated by *Brachystegia*, *Julbernardia* and *Isobertinia* species that form structurally complex stands on well-drained soils (Quissindo et al., 2026; Miapia et al., 2021). These ecosystems exhibit a stratified structure with emergent trees, shrubs, regeneration layers and associated grasses, with more humid sites supporting ferns and herbaceous species (Chiteculo et al., 2018). Miombo woodlands are crucial for rural livelihoods across the region but are increasingly degraded by deforestation, fuelwood extraction, charcoal production and agricultural burning (Quissindo et al., 2026; Miapia et al., 2021; Tchamba, 2024).

Alongside native vegetation, Huambo also contains extensive exotic forest plantations established mainly between 1950 and 1975 to supply fuelwood and raw material for the Benguela Railway and pulp industries. By the late 1970s, plantations of *Eucalyptus*, *Pinus patula*, *Cupressus lusitanica* and other exotic species covered large areas, particularly along the Benguela Railway corridor in Benguela, Huambo and Bié provinces (Quissindo et al., 2026; Miapia et al., 2021; Delgado-Matas & Pukkala, 2015).

2.2. Sampling and data collection planning

Plant species were characterised based on species identification, documented uses, and analysis of fuel moisture content. Species identification was supported by the PlantNet application (Bilyk et al., 2020) and complemented with information from previous studies conducted in the area (Catuti et al., 2022; Quissindo, 2018). PlantNet is a mobile and online platform that uses image recognition and a large plant image database to facilitate plant identification and access to taxonomic and ecological information and has been widely described in the literature (Li et al., 2022; Bilyk et al., 2020).

Dead wood fuels were quantified using the planar intercept method (Brown, 1974). Eight sampling sites were systematically distributed across the study area at 20 m intervals, with four transects established per site, resulting in 32 transects per hectare. Each transect was 15 m long and oriented towards the cardinal directions (transects of 480 linear meters, and data collection every 15 meters). This sampling intensity is considered sufficient to achieve estimation errors of $\leq 20\%$, in line with recommended guidelines (He et al., 2019). For more details, see Figure 2.

Figure 2. Planar intercept method

Source: Authors (2026)

Along the planar intercept transects, fuels were classified into 1-hour, 10-hour and 100-hour time-lag classes following standard procedures (Keane, 2015). Fine fuels (< 0.6 cm diameter) were counted within the first 2 m of each transect, 10-hour fuels (0.6–2.5 cm) from 0–4 m, and 100-hour fuels (2.5–7.5 cm) from 0–10 m. Woody materials > 7.5 cm in diameter were also recorded. Fuel particles were measured using fuel gauges or callipers, and fuel loads were calculated using Equations (1), (2) and (3).

$$P_1 = \frac{(11.64 * n * d_m^2 * s * c)}{(N * l)} \quad \text{Equation 1}$$

$$P_2 = \frac{(11.64 * n * d_m^2 * s * c)}{(N * l)} \quad \text{Equation 2}$$

$$P_3 = \frac{(11.64 * \sum d^2 * s * c)}{(N * l)} \quad \text{Equation 3}$$

Where: P_1 , P_2 , P_3 represents the fuel load ($t * ha^{-1}$) for each respective class; n the number of intercepts; d_m^2 the squared squared-mean diameter for fine/medium fuel classes (cm^2); $\sum d^2$ the sum of squared diameters of intercepted large particles (cm^2); s the specific gravity (density) of the wood; c the slope correction factor; N the total number of sampling lines; l the sampling line length (in feet; 1 m = 3.28 ft).

Dead non-woody fuels were classified as miscellaneous fuels (leaves, grasses, litter, humus, cones and fruits) and sampled using a $3 \times 3 m^2$ frame placed at the end of each transect. All material within the frame was collected, excluding soil, rocks and woody debris, and weighed using a hook scale.

At each test site, a $5 \times 5 m^2$ subplots was established 10 m along the north-oriented transect to collect live fuels. Live herbaceous materials (herbs, lianas and non-lignified seedlings) and green woody materials (< 0.6 cm diameter) were sampled and weighed separately.

Fresh fuel mass was measured with a balance (± 0.1 g). Subsamples were oven-dried at $75^\circ C (\pm 5^\circ C)$

for 48 h to determine dry mass, following He et al. (2019) and Keane (2015). Fuel moisture content by class was subsequently calculated using Equation (4).

$$Hm = \frac{(Ph - Ps)}{Ps} * 100 \quad \text{Equation 4}$$

Where: *Hm* represents the fuel moisture content; *Ph* the fresh weight; *Ps* the dry weight.

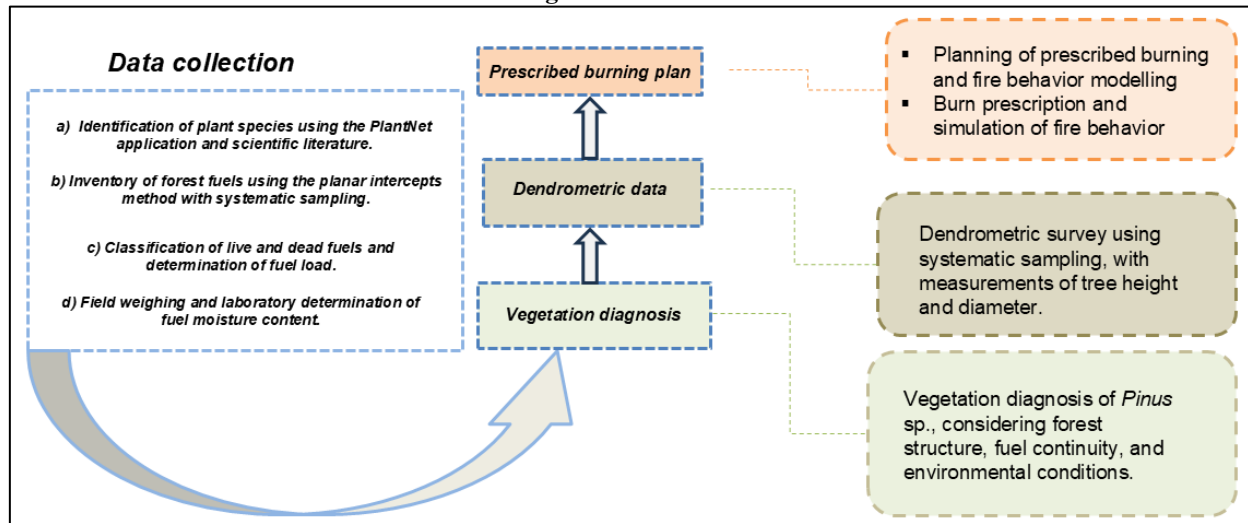
Fuel mass was measured using an SF-400 digital scale with a maximum capacity of 10 kg and a resolution of 1 g (Van Wilgen et al., 1990; Brown, 1974). The scale features a portable design, LCD display, electronic weighing accuracy of 1 g for loads between 1 g and 10 kg, and operates on two AA batteries. The plantation were composed of *Pinus* sp. stands currently at the pole (stem development) stage, characterised by clean boles and thick bark, traits that contribute to reduced fire damage. The understory was generally sparse. To support the prescribed burning plan, an integrated diagnosis of the study area was conducted, including the assessment of meteorological conditions, fuel loads, fire behaviour, floristic composition and soil characteristics, using complementary methods.

Dendrometric measurements were collected using a systematic sampling design, with sampling points established at 20 m intervals along transects oriented to the cardinal directions. At each point, total height, height to first branch and diameter were measured for a total of 30 trees. The analysed variables included three height and diameter, dead fuel quantity, species identification, and diameter and height classes.

A prescribed burning plan involves a series of tasks to be carried out before, during, and after the burn to achieve objectives safely. A burn prescription, defining conditions such as topography, meteorology, fuel characteristics, and fire behaviour, was applied (Brown, 1974). Resources were allocated, and official authorisation obtained from the Forest Guard Corps and the Institute of Forestry Development, with notifications sent to local authorities and communities. Two 25×25m² plots were established to assess flame height, duration, length, and depth of burn. The plan included burn unit location, fuel description, meteorological conditions, desired fire behaviour, burning techniques, monitoring procedures, emergency actions, and mop-up operations. Firebreaks were also established to prevent fire escape, and the plan was designed considering seasonality, fuel characteristics, and expected fire behaviour.

2.2.1. Conduct of burning and data collection

The prescribed burn and data collection employed various equipment, including hoe and machete for site clearing, calipers and diameter tape for tree measurements, a clinometer for height, measuring tape and pulley for distances, Garmin GPS for geolocation, compass for orientation, a smartphone with PlantNet for species identification, and an SF-400 digital scale for sample weighing, with paper bags used for sample storage. The Garmin GPS, PlantNet app, and SF-400 scale, given their specific applications, are described in greater detail. Fig. 3 illustrates the workflow of this research.

Figure 3. Workflow

Source: Authors (2026)

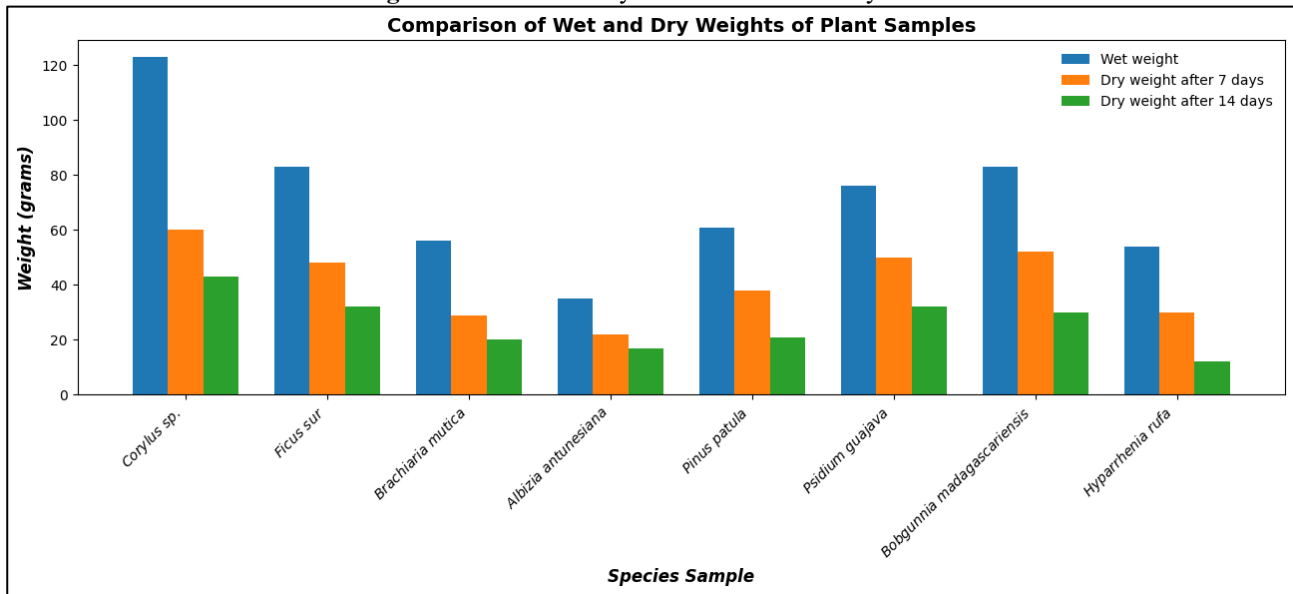
Sampling points and plots were marked and geolocated using the GPS units, recognised for their accuracy in forest fieldwork. Data for the diagnostic assessment were obtained from multiple sources: meteorological information from the Chianga station to schedule the burn, fuel inventory conducted one month prior using the planar intercept method (Brown, 1974; He et al., 2019), and dendrometric measurements collected through systematic transects.

Using field measurements of wind speed, fuel moisture, temperature, and precipitation, calculations were performed with a method adapted to the Miombo woodland context. This approach allowed prediction of fire behaviour and informed the implementation of a prescribed burn under specific environmental conditions.

3. Results and Discussion

3.1. Fuel characteristics and stand structural parameters influencing fire behaviour

Firstly, Figure 4 presents a comparison of the wet and dry weights of eight plant species sampled in the study area, illustrating the moisture content and drying patterns of the different fuel types.

Figure 4. Moisture analysis of fuels in the study area

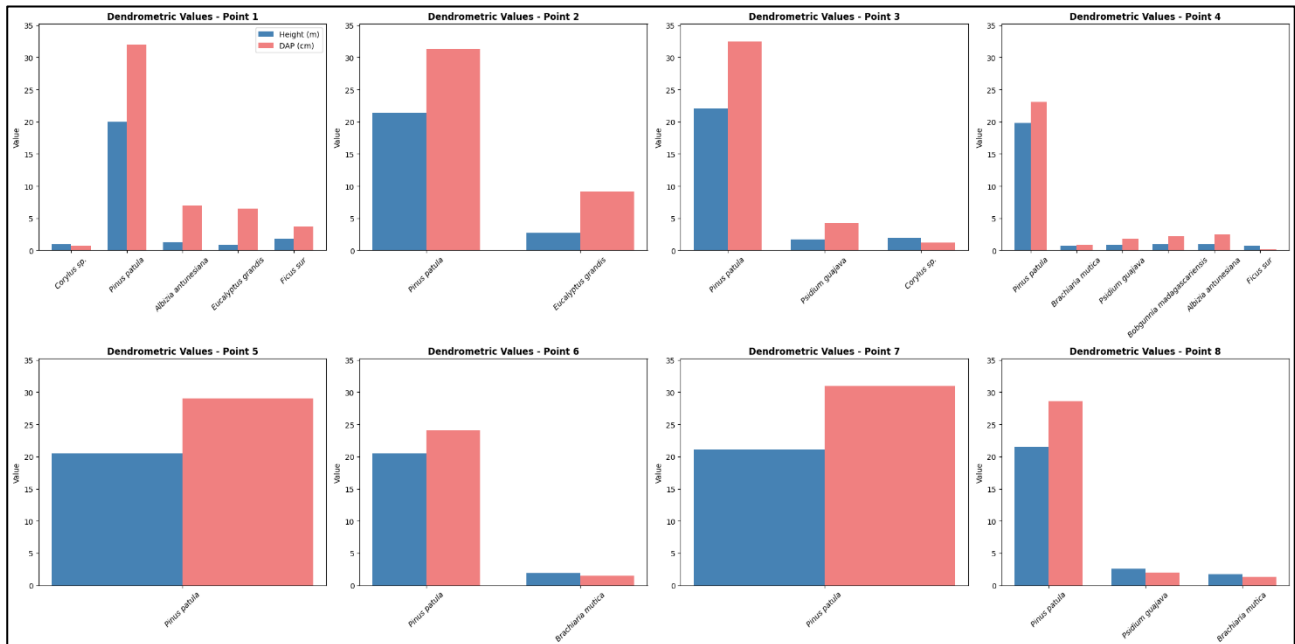
Source: Authors (2026)

The species include both trees and shrubs, such as *Pinus patula*, *Albizia antunesiana*, and *Ficus sur*, as well as grasses like *Brachiaria mutica* and *Hyparrhenia rufa*. The wet weight of each sample was recorded initially, followed by measurements after seven and fourteen days of drying, allowing an assessment of water loss over time. In the local landscape of Huambo, where agricultural mosaics intersect with Miombo woodlands, these fast-drying grasses function as critical fuels not only for plantation fire behaviour but also for fire transmission across agricultural–forest interfaces (Quissindo et al., 2026; Miapia et al., 2021; Quissindo, 2018). Understanding this local fuel dynamic is therefore essential for designing a prescribed burning plan adapted to small-scale land management systems.

The results reveal notable variation in the drying behaviour of the different species. Graminoid species, particularly *Hyparrhenia rufa* and *Brachiaria mutica*, displayed rapid moisture loss, with *Hyparrhenia rufa* showing the greatest reduction, almost completely drying by the fourteenth day. These fast-drying fuels are light and highly flammable, suggesting that they could ignite easily under controlled conditions. In contrast, woody species such as *Pinus patula*, *Corylus sp.*, and *Bobgunnia madagascariensis* retained more moisture initially and exhibited a slower drying rate, reflecting the dense, resinous nature of their tissues. *Pinus patula* demonstrated a marked reduction in dry weight between seven and fourteen days, indicating that although some moisture is lost quickly, a substantial portion of combustible material remains, capable of sustaining a longer fire.

Intermediate species, including *Ficus sur*, *Psidium guajava*, and *Albizia antunesiana*, showed moderate moisture loss. Their leaves and fine branches dried more quickly than the woodier components, suggesting that they can contribute to surface fuel consumption without significantly increasing fire intensity. The analysis indicates that fast-drying grasses are ideal for controlled surface fires, while woody species need careful moisture monitoring to avoid high-intensity flames. These findings support that a properly timed, low-intensity burn can remove forty to seventy per cent of surface fuels, reducing fire risk while preserving the overstorey and ecological balance.

Moving on, Figure 5 presents the dendrometric measurements collected at eight sampling points across the study area, illustrating the structural characteristics of the plant community in terms of both tree height and diameter at breast height (DAP).

Figure 5 Average dendrometric values in the study area

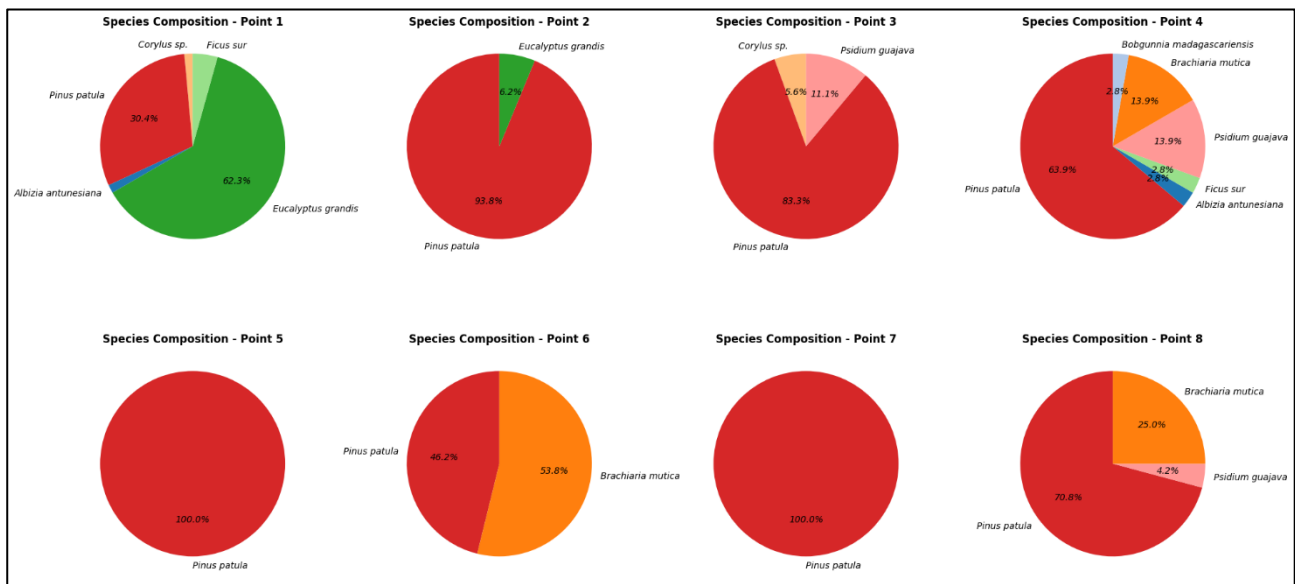
Source: Authors (2026)

Each subplot represents a sampling point, showing values for multiple species where present, with height measured in metres and DAP in centimetres. The dominant species across almost all points is *Pinus patula*, reflecting the plantation composition, while native trees, shrubs, and some grasses appear more sporadically.

The data reveal that *Pinus patula* consistently reaches heights between 19.8 and 22.1 metres and DAP values ranging from 23.1 to 32.5 centimetres. This indicates relatively uniform growth within the plantation, consistent with trees at the pole stage, characterised by clean, straight boles and thick bark. Other species, including *Albizia antunesiana*, *Ficus sur*, *Psidium guajava*, *Corylus sp.*, and *Bobgunnia madagascariensis*, are considerably smaller, with heights generally under 3 metres and DAPs mostly below 7 centimetres, highlighting their role as understory or secondary vegetation rather than overstorey dominants.

Grasses such as *Brachiaria mutica* and other herbaceous species exhibit minimal height and negligible DAP, emphasising their contribution to surface fuels rather than structural biomass. *Eucalyptus spp.*, present at some points, shows moderate height and DAP, suggesting occasional mixed planting or natural regeneration. These dendrometric measurements highlight that tall *Pinus patula* trees could act as ladder fuels if unmanaged, while smaller native and herbaceous species supply combustible material for controlled surface fires. The structural diversity indicates that prescribed burns should focus on surface fuels while protecting the overstorey, aligning with the goal of reducing fire risk and preserving ecological integrity (Hakkenberg et al., 2024; Zhu et al., 2025).

Notably, Figure 6 illustrates the floristic composition of the study area across eight sampling points, showing the relative abundance of different plant species at each location.

Figure 6 Average number of individuals in the study area

Source: Authors (2026)

Each subplot presents a pie chart depicting the number of individuals per species, allowing a visual comparison of species dominance and diversity within the sampled plots. The results highlight a clear dominance of *Pinus patula* across all points, reflecting the plantation's managed nature. In some points, such as Point 1, *Eucalyptus grandis* appears as a highly abundant species, suggesting either previous mixed planting or natural regeneration, while native trees and shrubs like *Ficus sur*, *Albizia antunesiana*, *Psidium guajava*, *Corylus sp.*, and *Bobgunnia madagascariensis* occur in lower numbers, contributing modestly to species diversity. Grasses, particularly *Brachiaria mutica*, are more abundant at certain points, notably Points 4, 6, and 8, indicating that herbaceous species form a significant part of the understory fuel load in some areas.

This composition indicates that while the overstorey is largely uniform due to the dominance of *Pinus patula*, there is considerable heterogeneity in the understory, with native trees, shrubs, and grasses contributing to fine and surface fuels. From a FM perspective, these data suggest that prescribed burns can focus on the surface and fine fuels provided by the understory vegetation, while the overstorey remains largely unaffected. The distribution of species also implies that fire behaviour could vary locally, with plots containing more grasses likely to experience faster surface fire spread compared with plots dominated by low-density woody shrubs.

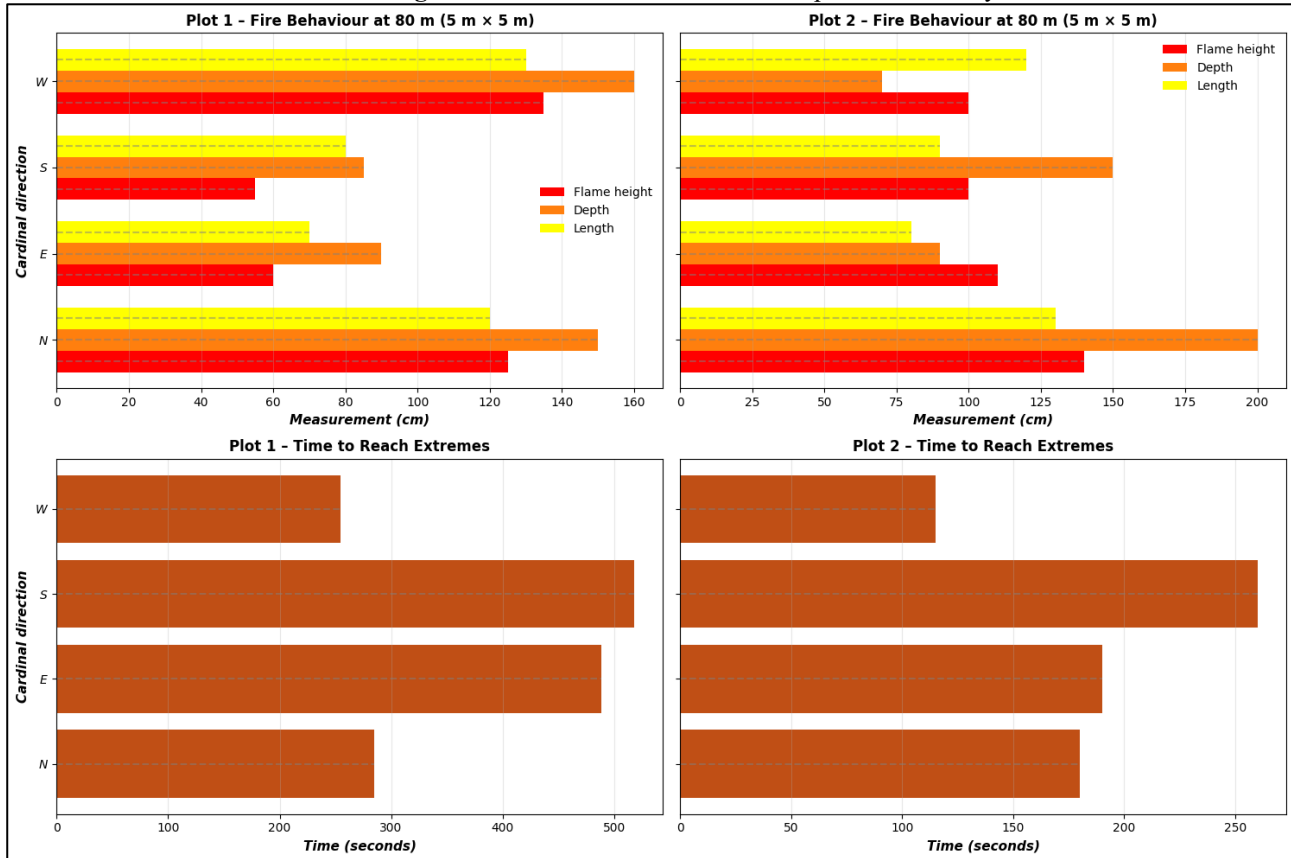
The findings are consistent with the evidence reported by Pausas et al. (2024), who demonstrated that the accumulation of herbaceous biomass enhances the horizontal continuity of surface fuels, thereby creating conditions that facilitate rapid fire spread.

From an integrated fire management perspective, these results indicate that prescribed burning represents an effective strategy for reducing the accumulation of surface fuels within the forest understory. This interpretation is supported by recent studies showing that the application of prescribed fire in *Pinus* plantations significantly decreases fine fuel loads and disrupts vertical fuel continuity, thereby reducing the potential for high-intensity wildfires. Furthermore, when implemented under appropriate environmental conditions and following sound management practices, prescribed burning contributes to maintaining overstorey stand structure while promoting more sustainable forest fuel management (Zhu et al., 2025).

3.2. Observed fire behaviour and intensity metrics in experimental plots

However, Figure 7 presents the fire behaviour observed in two experimental plots, each measuring 5×5m² within the plantation.

Figure 7: area Fire behavior in the two plots under study



Source: Authors (2026)

The top row of the figure shows key fire metrics (flame height, depth, and length) measured in centimetres along the four cardinal directions (north, east, south, west). The bottom row depicts the time, in seconds, for the fire to reach the extremes of each plot in the corresponding directions.

In Plot 1, flame heights varied markedly depending on direction, reaching a maximum of 135 cm towards the west and a minimum of 55 cm towards the south. Fire depth followed a similar pattern, with the deepest advance recorded in the west (160 cm) and the shallowest in the south (85 cm). Flame length mirrored these trends, indicating that fire intensity and spread were strongly directional, likely influenced by wind, slope, and local fuel arrangement. The time analysis shows that the fire reached the northern and southern extremes more slowly (285 s and 518 s, respectively) than the western and eastern edges, consistent with directional differences in flame height and depth.

In Plot 2 exhibited slightly higher maximum flame heights (up to 140 cm in the north) and larger variability in fire depth, with the deepest advance at 200 cm in the north and the shallowest at 70 cm in the west. Flame lengths were generally comparable across directions, but the time to reach extremes was shorter than in Plot 1, particularly in the west (115 s), indicating faster fire propagation. These differences suggest that variations in fuel load, moisture, or local microclimate between plots influenced fire behaviour.

The data of Figure 7 show that fire behaviour can vary considerably by direction, even in small plots,

highlighting the need for careful planning and monitoring to control spread and flame intensity. This information is essential for safely conducting low-intensity, surface burns while minimising risk to overstorey trees.

3.3. Influence of fuel load and stand structure on observed fire behaviour

The rapid desiccation of *Hyparrhenia rufa* and *Brachiaria mutica* within just fourteen days confirms that these grasses function as primary “kindling” for surface fire propagation. In tropical ecosystems, the speed at which fine fuels reach ignition often determines whether a controlled burn remains manageable or escalates into a high-intensity fire (Nieman et al., 2021; Catuti et al., 2022; Catarino et al., 2020; Quissindo, 2018). Their near-complete moisture loss validates their classification as one-hour fuels, critical for sustaining the initial fire front while contributing minimally to overall heat release. In contrast, woody species such as *Pinus patula* and *Bobgunnia madagascariensis* retain moisture over longer periods, with resinous and dense tissues acting as thermal regulators. This characteristic allows prescribed burns to remove forty to seventy per cent of surface fuels without escalating to crown fires, supporting the hypothesis that canopy damage can be minimised through careful monitoring of fuel moisture. As reported in preliminary studies (Miapia et al., 2021; Quissindo et al., 2021; Quissindo, 2018), understanding the local fuel dynamic is therefore essential for designing a prescribed burning plan adapted to small-scale land management systems.

According to Buramuge et al. (2023), intermediate native species, including *Albizia antunesiana* and *Ficus sur*, display moderate moisture loss, reflecting an adaptive strategy that protects vital structural components while allowing leaf litter to dry. Such selective combustion facilitates understory fuel reduction without compromising plant integrity, aligning with evidence that prescribed fire can serve as a conservation tool to maintain ecological diversity while mitigating catastrophic wildfire risk. Synthesising these patterns suggests that the optimal window for prescribed burning in Huambo occurs when grasses are fully desiccated but woody species still retain sufficient moisture. This balance ensures that fire remains surface-bound, providing operationally safe and ecologically sustainable management for smallholder and experimental plantations.

The structural analysis reveals a distinctly two-tiered stand, a feature that strongly influences potential fire behaviour in the Miombo zone. The dendrometric uniformity of *Pinus patula*, with heights reaching 22 metres and DBH exceeding 30 cm, identifies this species as the dominant biomass component and the primary vertical fuel risk if ladder fuels are not managed. The stand is in the pole stage, characterised by clean boles and thick bark, providing thermal resilience to low-intensity fires (Catarino et al., 2020; Bartlett, 2012). The substantial canopy height above 19 metres creates a natural vertical discontinuity, reducing the likelihood of surface fires escalating into crown fires, while understory species such as *Albizia antunesiana* and *Bobgunnia madagascariensis*, generally below three metres, contribute to ecological diversity (Amankwah et al., 2025) and may act as ladder fuels. Their low density, however, suggests that fine fuel load, rather than woody understory biomass, is the most critical factor influencing fire behaviour (Lindenmayer et al., 2023).

Dendrometric measurements of the understory and surface vegetation, combined with moisture dynamics, indicate that grasses such as *Hyparrhenia rufa* and *Brachiaria mutica* dry rapidly and act as primary kindling, whereas *Pinus patula* and *Bobgunnia madagascariensis* retain moisture, moderating flame intensity (Nieman et al., 2021; Quissindo, 2018). Intermediate native species, including *Albizia antunesiana* and *Ficus sur*, show selective moisture loss, allowing leaf litter to dry while maintaining structural integrity, supporting understory biodiversity (Buramuge et al., 2023). The observed patterns align with prior studies showing that surface fuel characteristics largely dictate fire behaviour in tropical plantations and Miombo woodlands, while overstorey trees with thick bark and high canopies remain largely protected (Archibald et al., 2017; Bartlett, 2012). These findings emphasise the importance of fuel stratification and moisture dynamics in predicting fire spread and intensity.

The dominance of *Pinus patula* and *Eucalyptus grandis* highlights the productive character of the area, while understory composition drives fire behaviour in Huambo. Figure 6 shows a mosaic of dense grasses and

native shrubs, where fast-drying grasses promote rapid surface fire spread and native species such as *Albizia antunesiana* and *Bobgunnia madagascariensis* provide resilience and regeneration potential (Buramuge et al., 2023; Catuti et al., 2022; Quissindo, 2018). This floristic heterogeneity supports tailored fire management, with rapid burns in grass-dominated patches reducing wildfire risk and slower, low-intensity burns in shrub-rich areas conserving seedlings and maintaining Miombo biodiversity (Catarino et al., 2020; Amankwah et al., 2025; Lindenmayer et al., 2023).

This floristic heterogeneity in the study area mirrors the mixed land-use character of Huambo, where agricultural activities and Miombo remnants coexist. Prescribed burning strategies must therefore be calibrated to protect productive agricultural plots while maintaining ecological connectivity within the woodland matrix.

3.4. Fire behaviour performance under prescribed burning conditions

The fire behaviour observed in the experimental plots confirms the technical feasibility of prescribed burning in the Miombo of Huambo, with intensities remaining within controllable limits for low-severity surface fires. Flame heights peaked at 140 cm in Plot 2 and 135 cm in Plot 1, well below the 1.5-metre threshold generally considered safe for plantations with clean-bole *Pinus patula* (Bartlett, 2012; Catarino et al., 2020; Quissindo, 2018). Given canopy heights exceeding 19 metres (Figure 5), this ensured minimal risk of lethal scorch to the overstorey, validating the expectation that prescribed burns could reduce surface fuel without damaging mature trees.

Directional variability in flame height and fire spread, such as 135 cm to the west versus 55 cm to the south in Plot 1, highlights the influence of local microclimate and floristic heterogeneity on fire dynamics (Figures 4 and 6). Faster propagation and deeper surface consumption occurred in grass-dense areas (*Brachiaria mutica*), with fire depths up to 200 cm reflecting efficient fuel consumption without excessive soil heating (Archibald et al., 2017). These results underscore the need for flexible ignition techniques, careful monitoring, and the potential for efficient, replicable prescribed burns that are operationally practical for local communities and smallholder plantations (Amankwah et al., 2025; Buramuge et al., 2023; Quissindo, 2018).

Based on this, the proposed action plan for IFM in the Central Plateau of Angola should focus on exploiting the identified phenological window at the start of the dry season, when grasses (1-hour fuels) are sufficiently dry to ignite while *Pinus patula* and native woody species retain moisture, reducing cambial damage. The plan recommends low-intensity burns using point or backburn ignition techniques to keep flame heights below 1.4 metres, maintaining vertical fuel discontinuity without reaching the tree canopy. Combined with systematic monitoring using the planar intercept method, this approach allows controlled reduction of 40–70% of surface fuels, transforming vulnerable plantations into strategic firebreaks that safeguard both forest productivity and Miombo biodiversity within a socio-ecological governance framework.

The action plan is designed as a locally applicable framework for smallholder and plantation contexts in Huambo, integrating prescribed burning with community participation and agricultural land management. This approach aligns with principles of IFM adapted to the socio-ecological realities of the agricultural Miombo region.

3.5. Limitations of study

We faced significant limitations related to operational constraints and methodological reporting. First, the area permitted for prescribed burning was restricted, reducing the spatial extent of experimental treatments and limiting the capacity to generalise fire behaviour results to broader landscape conditions. Such restrictions constrained the evaluation of variability in fuel consumption and fire spread across heterogeneous micro-sites, which is particularly relevant in complex plantation and Miombo landscapes.

Future research should expand spatial coverage where operationally feasible and align objectives with the development of locally relevant fire management frameworks. Such improvements would strengthen the contribution of the work to IFM and sustainable land use in agro-forestry systems in the Miombo Zone.

4. Key conclusions

Finally, this study demonstrates that the *Pinus* plantation in Huambo hosts a structurally diverse assemblage of nine species, including six trees, one shrub, and two grasses, with heights ranging from 0.7 to 22 metres and DAPs from 0.25 to 32 cm. Observed dead material contributes to semi-hazardous fuels, while the variation in understory and fine fuels highlights opportunities for targeted low-intensity prescribed burns. The results confirm that a controlled fire regime, timed to exploit seasonal moisture differences, can reduce 40–70% of surface fuels without threatening canopy trees, supporting both forest productivity and Miombo biodiversity. Effective implementation will require careful planning, monitoring, and collaboration with local communities and research stations to integrate FM into broader ecological and land-use practices.

The findings confirm that locally tailored prescribed burning, implemented within both plantation and agricultural landscapes of the Miombo zone, can reduce hazardous fuel loads while supporting sustainable land management and biodiversity conservation.

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