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Fuel Management in Ghana's Tropical Forests: Implications on Implementation Cost, Fuel Loading and Fire Behaviour

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Abstract

Fuel management can play enormous role in fire management in tropical dry forests. However, unlike the temperate forests, knowledge on implications of different fuel management methods in tropical forests is often inadequate. In this study, the implications of prescribed burning and hand thinning treatments on implementation cost, fuel loading and post-treatment fire behaviour were tested and compared in degraded forests and teak plantations in two forest reserves of different levels of dryness in Ghana. The study found that prescribed burning was less expensive (62.02 US Dollars ha^{-1}) than hand thinning (95.37 US Dollars ha^{-1}). The study also indicated that the two fuel management methods were able to reduce fuel loading in degraded forests and teak plantations. However, prescribed burning was more effective in reducing fuel loading than hand thinning. While the relative change of fuel reduction was 13% higher in prescribed burning than the hand thinning in degraded forest, it was 41% higher in prescribed burning than hand thinning in teak plantations. The fire behaviour of post-treatment experimental fire was also lower in prescribed burning than the hand thinning and control plots. Fuel management, therefore, has a great potential in fire management in degraded forests and teak plantations in Ghana.

Key Words: fuel management, fuel loading, forest, fire behaviour, cost

Introduction

Increases in human disturbance and loss of original forest cover since early 1980s have led to increase in fuel accumulation in forest reserves in the forest-savannah transitional zone of Ghana (Hawthorne 1994; Swaine et al. 1997). The surge in fuel levels coupled with increase in surface air temperature have consequently enhanced the flammability of most semi-deciduous forests in the zone leading to increased forest fire incidences (Swaine 1992; Swaine et al. 1997; Barnes 2008; Barnes 2009).

Globally, there are many forest stands where drought, which increases fuel desiccation and availability and lack of effective management have led to massive accumulation of fuels and consequent increase in fire incidence. For instance, in tropical Amazon forests, recent interactions of drought, logging and farming, increasing fuel loading and reduction in canopy density have resulted in vast areas of impoverished forests caused by fire (Cochrane et al. 1999; Nepstad et al. 1999; De Mendonca et al. 2004; Cannon 2019). Post-logging fuel loading in these forests are often three times higher than in uncut primary forests. Extensive

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canopy openings and increase in atmospheric greenhouse gases in the former have also created a warmer and drier microclimate, which hastens fuel drying than the latter (Uhl and Kauffman 1990; Cannon 2019). Also, in the Sierra Nevada in the United States much of the forest is characterised by unmanaged stands with dense understoreys that provide the horizontal and vertical continuity of fuels that fires need to move from the ground surface to the forest canopy (Weatherspoon 1996; Moghaddas and Stephens 2007). Naturally, excessive competition for water and sunlight in unthinned stands often weakens or kills trees, thus increasing fuel loading and potential fire severity (Weatherspoon 1996).

It is generally perceived by many ecologists and fire managers that the current risks posed by fuel hazards in many tropical forests could be reduced by introducing fuel management in fire management plans. For decades, frequent and regular judicious use of fuel management methods such as prescribed burning, thinning treatment, fuel conversion and fuel isolation (firebreaks) have been promoted in many forests around the world to regulate fuel levels and reduce wildfire spread and intensity (Adams and Simmons 1994; Agee 1996; Pyne et al. 1996; USDA-USDI 2000; Outcult and Wade 2004; Vaillant et al. 2015). However, the practice is relatively uncommon in tropical forests, particularly, Ghanaian tropical forests. As a result, resource managers and policy makers are exploring the possibility of introducing fuel management into the forest management systems in Ghana (Ministry of Lands, Forestry and Mines 2006).

In implementing fuel management in Ghana however, resource managers ought to appreciate fuel management together with implications on implementation cost, fuel hazard and fire severity reduction. This is because there have been several reports of different implications associated with different fuel management methods on implementation cost and fire hazard reduction in different sites in several temperate forests (Berry and Hesseln 2004; Knapp et al. 2005; Collins et al. 2007; Moghaddas and Stephens 2007; Neil et al. 2007). Currently, knowledge on fuel management and its economic and fire management implications in tropical forest cover types of different levels of dryness in Ghana is poor. It is therefore important that the implications of different fuel management methods such as prescribed burning and hand thinning (Barnes et al. 2017) are thoroughly investigated in Ghanaian tropical forests to enable resource and fire managers chose the appropriate and cost-effective fuel management strategies to reduce fire hazard in their areas of operations. This will also enhance the understanding of the scientific community on fuel management implications on costs, fuel hazard and fire behaviour in tropical forests in Ghana.

To this end, this study tested and compared the effectiveness of prescribed burning and hand thinning treatments in terms of implementation cost, fuel loading reduction after treatment and fire behaviour after experimental wildfire in degraded natural forest and teak plantation stands in two forest reserves of different levels of dryness in Ghana.

Materials and Methods

Study area

The study was conducted between October 2006 and May 2007 in Afram Headwaters and Worobong South (Akim) Forest Reserves within the Dry Semi-deciduous

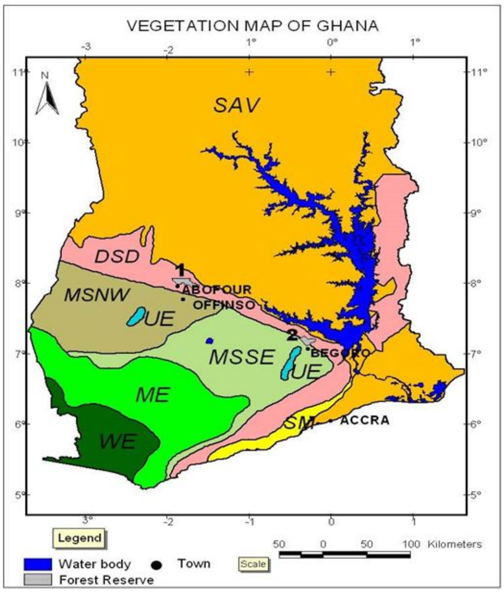


Fig. 1. Distribution of forest types in Ghana. DSD, Dry Semi-deciduous; SAV, Savanna; MSNW, Moist Semi-deciduous North-west; UE, Upland Evergreen; MSSE, Moist Semi-deciduous South-east; ME, Moist Evergreen; WE, Wet Evergreen; SM, Southern Marginal (Hall and Swaine, 1981). 1 and 2 are Afram Headwaters and Worobong South Forest Reserves respectively.

Forest Zone (Hall and Swaine 1981) in the forest-savannah transitional belt in Ghana (Fig. 1). The Dry Semi-deciduous forest occurs within the tropical humid zone, characterised by uniform high temperatures and two peak rainfall seasons in June and October and dry season in August and from December to March.

Table 1. Major differences between Afram Headwaters and Worobong South Forest Reserves in Ghana

Features	Afram Headwaters	Worobong South
Forest District	Offinso	Begoro
Area (km^2)	201	209.35
Climate		
Mean annual rainfall (mm)	1,288	1,674
Mean annual temperature (°C)	29-37	27-35
Geology	Sandstone and granite (Less rocky)	Sandstone (More rocky)
Soil		
pH	5.9	4.5
Calcium (me$^{-100\,g}$)	7.8	2.2
Percent saturation	83	36.5
Topography	Less steep slopes (Few areas above 20%)	More steep slopes (Most areas above 20%)
Floristic composition	*Brossonetia papyrifera* (Exotic invasive species)	None of this species

Source: Hall & Swaine (1976), Forest Services Division (1999). Rainfall figures represent mean of 15 to 35 years records while that of temperature is from 10 to 12 years data from Begoro, Offinso and Kumasi weather stations.

Generally, about half of Afram Headwaters and Worobong South reserves are degraded as a result of fire damage and are mainly colonised by extensive tracts of *Chromolaena odorata* (Compositae) and *Panicum maximum* (Graminae) which can spread fire rapidly when ignited. Where the reserves are less degraded, the original forest patches with partly broken canopy exist. Lifeforms such as marantaceous forbs, climbers, shrubs and tree species (*Celtis-Triplochiton* association) are common.

For management purposes, the Ghanaian Forestry Commission has categorised each of the reserves into: 1) protected areas, which are ecologically sensitive sites and natural forest placed under convalescence after selective logging; 2) plantation areas (mostly teak) and 3) production areas (natural forest earmarked for limited logging). The reserves are also fringed by several local communities who engage in farming, hunting and palm wine tapping. These communities depend on the reserves for non-timber forest products and fertile land for temporary farming, which increase fire risk. Fire usually occurs in the two reserves annually during the dry season causing progressive forest degradation. The major differences between the two reserves lie in climate, size, soil, geology, topography and floristic composition (Table 1). Generally, Afram Headwaters is characterised by higher mean annual temperature and lower mean annual rainfall than the Worobong South since it is closer to the Savannah Zone of Ghana (Hall and Swaine 1976) (Table 1). The climate distinction is more pronounced in the dry periods.

During the study, three sites of different forest cover types were selected in each reserve with two of the sites oc-

Table 2. Differences among three experimental sites before treatment in Afram Headwaters and Worobong South Forest Reserves in Ghana

Forest cover type	Basal area (m^{2}ha^{-1})	Canopy openness (%)	Stand height (m)	Forest condition^1	Fuel group^2	Mean fuel loading (t ha^{-1})
Less Degraded natural forest	21-32	4-10	15-40	Good forest	Woody Dorminant	40.2
Degraded natural forest	4-15	41-54	10-15	Very poor forest	Non-woody Dorminant	17.6
Plantation	15-27	15-32	15-25	No significant forest	Woody/non woody intermix	9.3
p-value	$p < 0.001$	$p < 0.001$	$p < 0.001$			$p < 0.001$

^{1}Hawthorne and Abu-Juam 1995; ^{2}Fuel groups are as described in Barnes (2008).

curring in natural forest (degraded and less degraded) and the other in teak plantation forest (Table 2).

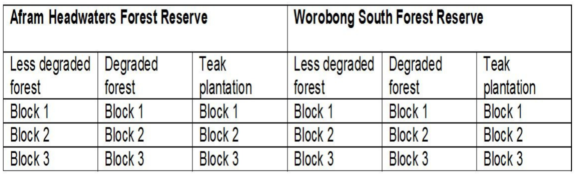
The less degraded natural forest was composed of indigenous species of trees, climbers and forbs. Degraded natural forest was mainly dominated by herbs (*Chromolaena odorata*) and some scattered native tree species with the exception of an exotic *Broussonetia papyrifera* in Afram Headwaters. The plantation stand was mainly planted teak with *Chromolaena odorata* as the major undergrowth. While the less degraded natural forests in the two reserves had recovered for more than 30 years after logging, the plantations had been thinned more than five years previously. The less degraded natural forests had no fire record but the degraded and plantation forests had been invaded by fires with 2-3 years return intervals due to more readily available fuel and warmer weather during the dry season in recent times.

Study methods

Plot layout

Three blocks (replicates), each with dimension of 80 m x 20 m were demarcated randomly in each of the three forest cover types within each reserve. Each block was sub-divided into three 20 m×20 m treatment plots for prescribed burning, hand thinning and control separated by 10m bare-ground firebreaks (n=27 plots per reserve). This implies two forest reserves x three forest cover types x three replicate blocks x three plots summing up to 54 plots. All sides of a block were delineated from the adjacent vegetation by 20m bare-ground firebreaks (Fig. 2, 3).

The geographic positions of all blocks and plots were determined with a GPS and indicated on aluminium tags fixed on trees at the north-eastern corner of each block and plot for identification purposes.



Afram Headwaters Forest Reserve			Worobong South Forest Reserve		
Less degraded forest	Degraded forest	Teak plantation	Less degraded forest	Degraded forest	Teak plantation
Block 1	Block 1	Block 1	Block 1	Block 1	Block 1
Block 2	Block 2	Block 2	Block 2	Block 2	Block 2
Block 3	Block 3	Block 3	Block 3	Block 3	Block 3

Fig. 2. Experimental blocks design in Afram Headwaters and Worobong South Forest Reserves in Ghana.

Fuel inventory

Fuels in all plots were quantified in tonnes per hectare before and after the fuel treatments and experimental wildfire. Downed woody fuels were sampled by the planar intersect method (Van Wagner 1968; Brown 1971; Brown 1974). They were classified and inventoried according to the size class and time lag as described by Deeming (1977).

For the litter layer, a complete sample of litter biomass was collected from eight 1 m × 1 m quadrats by the use of a spade and plastic bags. The samples were oven-dried at 85°C for 48 hours in a laboratory at the Faculty of Renewable Natural Resources of KNUST and dry mass determined. Standing herbaceous vegetation (mainly *Chromolaena odorata*) within degraded and plantation blocks were sampled by cutting them at the root collar in 1 m × 1 m quadrats randomly selected at eight different points in each plot. These materials were put in plastic sacks weighed in the field and sent to the laboratory for oven-dry mass. The dead downed herbs were included in the organic biomass sampling.

Prescribed burning

Prescribed burn plots of all blocks with the exception of that of the less degraded forests were burnt in one month after the last rain of the wet season (first half of December 2006) under controlled conditions. In most parts of the two reserves, one month without rain is sufficient to start fires of low intensity (Forest Services Division 1999). Low intensity fires are appropriate for prescribed burning aiming at reducing understorey fuels in the forest (National Wildfire Co-ordinating Group 1989). The plots in the less degraded forests were not burnt due to lack of sustained ignition and burning of fuels. They were, therefore, excluded

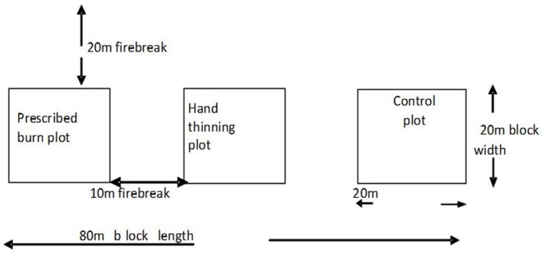


Fig. 3. Experimental block and plots design in Afram Headwaters and Worobong South Forest Reserves.

from the experiment. During the burn, mean surface air temperature, relative humidity and wind speed were monitored with the belt weather kit in order to keep the fire within prescription. Fuel moisture content was measured with 10-hour fuel moisture sticks. Fire intensity (total heat energy yield) were also measured using Beaufait's (1966) technique. The Beaufait's (1966) technique calculates total energy output from the amount of water vaporised from metal cans during burns. Mathematically the fire intensity (total heat energy yield) was determined as:

$$E_T = [(80 \text{ cal/g water}) \times (m_0 - m_1)] + [(540 \text{ cal/g water}) \times (m_0 - m_1)]$$

Where E_T = Total Energy Output

80 cal/g water = energy needed to raise 1g of water to boiling point

540 cal/g water = energy needed to vaporise 1g of water

m_0 of water = initial mass of water in can before burning

m_1 of water = final mass of water in can after burn

Flame height was measured by using different heights pre-calibrated in centimetres along 10 erected live wooden poles of 10 m in height and comparing highest burning marks on trees to determine the flame heights. The poles were randomly placed in a plot before burning. Rate of spread was determined by estimating the mean distance covered by all flaming fronts in a plot over mean time. The area burnt in each plot was measured with a pedometer. All escape fires were controlled by fire crew. After burning each plot, mop up was done to completely extinguish all fires and remnant fuel re-measured.

Hand thinning

Hand thinning (Barnes et al. 2017) treatment was carried out in the hand thinning plots of all blocks within the same days in which the prescribed burning was carried out (hand thinning in the morning and prescribed burning in the afternoon in their respective plots). In this activity, chainsaw and cutlass were used to fell dead and dying (live) standing trees and lower branches which were considered potential fuel. They were cut into pieces together with fallen trees and logs and removed manually for utilisation as fuelwood by local communities, burial in the soil or scattering. Thick floor litter layers (beyond 10 cm), grasses and herbs were gathered and buried through the use of shovels, rakes and mowers. Timing was done in such a way that, 25 minutes was used by five persons to remove fuels in each plot.

Financial analysis of treatment

Cost data were collected for each performed treatment and average computed. The cost components were labour, equipment and consumables. The consumables included fuels for firing, powering of chainsaw machine and on-site transport. The labour cost was calculated on the basis of daily hired labour cost charged by local farmers (5 farmers treated 1 ha per 5 man hours per day for prescribed burning and 0.5 ha per 6 man hours per day for hand thinning). The basis for equipment cost was obtained from purchases receipts from local sellers and Forestry Suppliers Inc. Jackson, MS 39284-8379, USA.

Experimental wildfire

Experimental wildfire was set in the later part of the following February (peak of dry season) in the treated and control plots in the degraded forest and the teak plantation to test its effect on the fire behaviour and fuel loading. In other words, the experimental fire was used as a test fire to study how dry season fire would behave in terms of rate of spread, flame height, intensity and area burnt in the treated plots in degraded forest and teak plantation. During the experiment, high intensity fire was ignited with the combined effects of strip and head fires using two drip torches from one end of each plot. In addition, weather and fuel conditions as well as the fire behaviour such as fire intensity, rate of spread, flame height and area burnt were measured as in prescribed burning. The remnant fuels were re-measured after the burn. All fire control measures were ensured by the fire crew.

Data analysis

A t-test was used to test the difference between the means of cost of treatment between the two forest reserves and that of the prescribed burning and hand thinning treatments. The t-test was appropriate for testing the differences between means of two different population since it produces straightforward and easy-to-interpret results. Differences in fractions of cost components of treatments were tested using Chi squared analysis. The Chi squared test was used because, the test is often used for comparing proportions of individuals that have a particular characteristic in two or more populations. Also, General Linear Model Analysis of Variance was used to test for the differences in fire intensity (Energy output), rate of spread, flame height, area burnt and relative reduction in fuel loading in 1) the two forest cover types 2) the two forest reserves and 3) two treatments and control. The General Linear Model Analysis of Variance was appropriate for comparing groups of treatments with populations not normally distributed under variety of different blocking designs (Townend 2002). Relative change in fuel loading was calculated as follows:

$$\text{Relative change} = \frac{X_0 - X_1}{X_0} \times 100$$

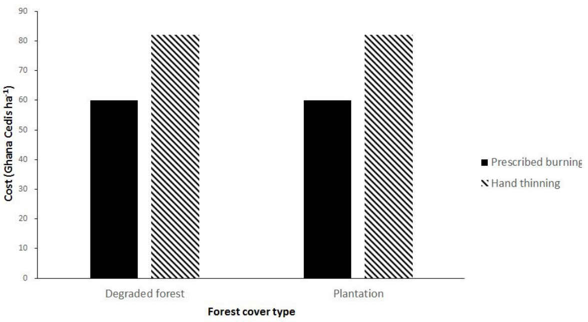


Fig. 4. Distribution of cost estimates for two fuel treatment methods in two forest cover types of Afram Headwaters and Worobong South Forest Reserves in Ghana. Data for the two reserves were pooled.

Where

X_0 = initial fuel loading

X_1 = final fuel loading

All analyses were carried out using SPSS version 15.0 (SPSS Inc., Chicago, Illinois, USA) and MINITAB 14.

Results

Cost of treatment

The mean total cost estimates for prescribed burning and hand thinning in Afram Headwaters and Worobong South Forest Reserves were not different (T-test: $t=0.821$, $df=11$, $N=12$, $p=0.43$) (Fig. 4).

However, the mean cost of treatment was lower in prescribed burning (59.87 Ghana Cedis ha^{-1} or 62.02 US Dollars ha^{-1}) than in hand thinning (91.93 Ghana Cedis ha^{-1} or 95.37 US Dollars ha^{-1}) (T-test: $t=86.87$, $df=11$, $N=12$, $p<0.001$).

Considering the cost components, while 42%, 38% and 20% respectively were spent on labour, equipment and consumables in prescribed burning, 73%, 15% and 13% respectively were spent on labour, equipment and consumables in hand thinning (Chi Squared Test: $\chi^2=20.34$, $df=2$, $p<0.001$).

Prescribed burning conditions and behaviour

The prescribed burn treatments were successful in all

Table 3. Prescribed fire conditions and behaviour within two forest cover types of Afram Headwaters and Worobong SouthForest Reserves

Prescribed fire conditions and behaviour	Afram Headwaters		Worobong South	
	Degraded forest	Teak plantation	Degraded forest	Teak plantation
Microclimate				
Air temperature (°C)	31.4±0.6	30.9±0.5	32.1±0.5	31.1±0.6
Rel. Humidity (%)	51.5±3.4	45.8±3.4	54.3±4.7	53.7±1.3
Wind speed (kmh^{-1})	13.1±1.7	7.3±3.4	40.3±4.1	14.3±5.6
Fuel moisture (%)	11.1±0.9	10.6±0.4	12.4±0.7	10.9±0.3
Fire behaviour				
Heat yield (kJ)	$89.4±9.8^{a}$	$124.6±6.9^{b}$	$370.3±45.7^{c}$	$87.8±5.5^{a}$
Rate of spread ($m\ min^{-1}$)	$0.71±0.11^{a}$	$1.2±0.04^{a}$	$2.4±0.3^{b}$	$1.0±0.3^{a}$
Flame height (m)	$0.72±0.22^{a}$	$1.1±0.12^{ac}$	$2.6±0.22^{b}$	$0.7±0.17^{a}$
Area burnt (ha)	$0.03±0.00^{a}$	$0.04±0.00^{b}$	$0.04±0.00^{b}$	$0.03±0.00^{a}$

Mean±1SE.
Different horizontal superscripts denote significant difference.

plots in the study sites except those in less degraded forest plots of the two reserves. The mean air temperature, relative humidity and fuel moisture content of fuel sticks of the less degraded plots were 26.8±0.3°C, 64.2±2.7%, 19.5± 1.5% respectively. From Table 3, burning conditions such as microclimate and fuel moisture content at the time of the prescribed burning in the two reserves were similar except wind speed (ANOVA, $F_{1,8}=0.79$, $p=0.39$; ANOVA, $F_{1,8}=0.10$, $p=0.78$; $F_{1,8}=0.02$, $p=0.88$; ANOVA, $F_{1,8}=18.60$, $p=0.003$ for air temperature, relative humidity, fuel sticks moisture content and wind speed respectively). Wind speed was higher in Worobong South than Afram Headwaters at the time of burning (Table 3). Air temperature and relative humidity did not vary between degraded forests and plantations (ANOVA, $F_{1,8}=1.88$, $p=0.21$ and ANOVA, $F_{1,8}=0.06$, $p=0.82$ for temperature and relative humidity respectively) All interactions were not significant. However, wind speed and moisture content of fuel sticks were higher in degraded forests than plantations (ANOVA, $F_{1,8}=16.03$, $p=0.004$ and ANOVA, $F_{1,8}=9.40$, $p=0.020$ for wind speed and moisture content of fuel sticks respectively).

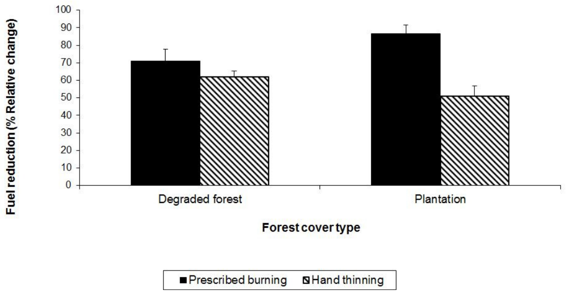


Fig. 5. Reduction (%) in fuel loading after prescribed burning and hand thinning treatments in two forest cover types of Afram and Worobong South Forest reserves in Ghana. Data for the two reserves were pooled. Error bars=±1SE.

Behaviour of prescribed fire between the two reserves were not different except flame height; heat yield (ANOVA, $F_{1,8}=1.42$, $p=0.27$), rate of spread (ANOVA $F_{1,8}=0.28$, $p=0.61$), flame height (ANOVA, $F_{1,8}=16.79$ $p=0.003$) and area burnt (ANOVA, $F_{1,8}=3.70$, $p=0.09$). Flame height in Worobong South exceeded that of Afram Headwaters (Table 3). Fire behaviour also did not differ in the degraded natural forest and plantation cover types except flame height; heat yield (ANOVA, $F_{1,8}=0.39$, $p=0.55$), rate of spread (ANOVA, $F_{1,8}=3.01$, $p=0.12$), flame height (ANOVA, $F_{1,8}=14.59$, $p=0.005$) and area burnt ($F_{1,8}=1.85$, $p=0.21$). Flame height in degraded natural forest was higher than that of plantation (Table 3). All interactions were not significant.

Fuel reduction after treatment

Relative change in fuel reduction after prescribed burning and hand thinning treatments did not differ between the two forest reserves (ANOVA, $F_{1,16}=0.023$, $p=0.88$). The overall mean relative change in fuel reduction ranged from 50.9% in hand treated plantation to 86.5% in plantations treated with prescribed burning in the two reserves (Fig. 5).

From Fig. 5, the relative change in fuel reduction was 12.5% higher in prescribed burning than the hand thinning in degraded forest. It was also 41.2% higher in prescribed burning than hand thinning in plantation (ANOVA, $F_{1,16}=27.59$, $p<0.001$). There was no change in fuel loading in control plots.

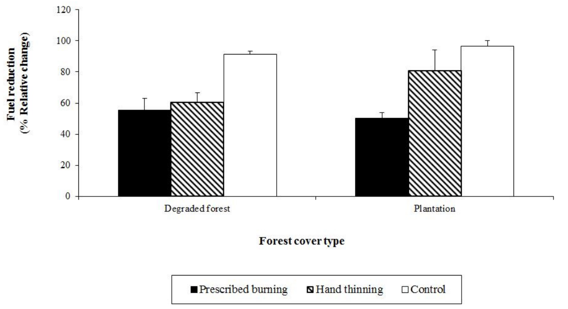


Fig. 6. Reduction (%) in fuel loading after post-treatment experimental wildfire in two forest cover types of Afram Headwaters Forest Reserves. NB, Error bars=±1SE.

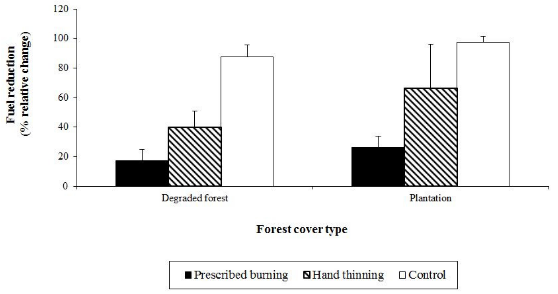


Fig. 7. Reduction (%) in fuel loading after post-treatment experimental burning in two forest cover types of Worobong South Forest Reserves. Error bars=±1SE.

Fuel reduction after post-treatment experimental wildfire

The relative change in fuel reduction after the experimental wildfire, unlike that of the after treatments, was different ($F_{1,24}=6.99$, $p=0.010$) in the two reserves (Fig. 6, 7).

Relative fuel reduction in Afram Headwaters ranged from 50.2% in prescribed burn plots in degraded forests to 96% in control plots in plantations. That of Worobong South ranged from 17.3% in prescribed burn plots in degraded forests to 97.3% in control plots in plantations. However, relative change in fuel reduction did not vary between the degraded forests and plantations in the two reserves (ANOVA, $F_{1,24}=2.94$, $p=0.09$). Relative fuel reduction also varied between the two treatments and the control (ANOVA, $F_{2,24}=26.09$, $p<0.001$). In Afram, the relative fuel reduction increased from prescribed burn plots (52.7%) through hand thinning plots (70.8%) to control plots (94%). Relative fuel reduction in Worobong similarly increased from prescribed burn plots (20.5%) through hand thinning plots (52.9%) to control plots (92.5%).

Post-treatment experimental wildfire conditions and behaviour

The experimental wildfire conditions varied between the two forest reserves as well as degraded forests and plantations in the reserves. Air temperature in Afram Headwaters

Table 4. Conditions and behaviour of post-treatment experimental wildfire within two forest cover types of Afram Headwaters and Worobong SouthForest Reserves

Fire conditions and behaviour descriptors	Treatment					
	Degraded forest			Teak Plantation		
	Prescribed burning	Hand thinning	Control	Prescribed burning	Hand thinning	Control
Afram Headwaters						
Microclimate						
Air temperature (°C)	35.0 ± 0.1^{a}	35.3 ± 0.2^{a}	35.3 ± 0.1^{a}	36.4 ± 6.7^{b}	36.1 ± 0.2^{b}	36.2 ± 0.3^{b}
Rel. Humidity (%)	33.0 ± 0.3^{a}	33.8 ± 0.2^{a}	33.8 ± 0.2^{a}	32.3 ± 0.6^{a}	30.4 ± 0.1^{b}	30.7 ± 0.6^{b}
Wind speed (kmh^{-1})	8.6 ± 2.1	6.5 ± 1.9	10.1 ± 1.2	6.3 ± 1.3	5.2 ± 0.9	2.3 ± 1.2
Fuel moisture (%)	5.7 ± 0.2^{ae}	6.0 ± 0.3^{be}	6.7 ± 0.1^{b}	5.3 ± 0.2^{ac}	5.3 ± 0.1^{ac}	5.1 ± 0.1^{ac}
Fire behaviour						
Heat yield (kJ)	89.4 ± 9.8^{a}	124.6 ± 6.9^{b}	370.3 ± 45.7^{c}	87.8 ± 5.5^{a}	113.9 ± 4.6^{a}	372.3 ± 112.8^{c}
Rate of spread (m min^{-1})	0.71 ± 0.11^{a}	1.2 ± 0.04^{a}	2.4 ± 0.3^{b}	1.0 ± 0.3^{a}	2.0 ± 0.7^{b}	3.4 ± 0.7^{c}
Flame height (m)	0.72 ± 0.22^{a}	1.1 ± 0.12^{ac}	2.6 ± 0.22^{b}	0.7 ± 0.17^{a}	1.3 ± 0.22^{d}	1.9 ± 0.2^{bcd}
Area burnt (ha)	0.03 ± 0.00^{a}	0.04 ± 0.00^{b}	0.04 ± 0.00^{b}	0.03 ± 0.00^{a}	0.04 ± 0.00^{b}	0.04 ± 0.00^{b}
Worobong South						
Microclimate						
Air temperature (°C)	30.9 ± 0.1^{ac}	30.7 ± 0.2^{a}	30.6 ± 0.3^{a}	30.7 ± 5.8^{a}	32.2 ± 0.2^{b}	31.6 ± 0.3^{bc}
Rel. Humidity (%)	33.0 ± 0.3^{a}	54.9 ± 0.8^{a}	55.3 ± 0.6^{a}	53.7 ± 0.3^{a}	51.1 ± 0.5^{b}	52.0 ± 1.4^{b}
Wind speed (kmh^{-1})	4.7 ± 2.1	8.2 ± 1.5	5.2 ± 0.4	3.6 ± 1.5	6.5 ± 1.7	11.2 ± 2.4
Fuel moisture (%)	8.2 ± 0.6^{ac}	8.0 ± 0.1^{bc}	8.1 ± 0.1^{bc}	7.5 ± 2.1^{b}	7.9 ± 0.8^{b}	8.0 ± 0.1^{b}
Fire behaviour						
Heat yield (kJ)	101.9 ± 15.8^{a}	142.9 ± 22.8^{b}	286.0 ± 89.5^{c}	82.8 ± 3.8^{a}	108.7 ± 16.1^{a}	343.5 ± 38.3^{c}
Rate of spread (m min^{-1})	0.49 ± 0.10^{a}	0.94 ± 0.1^{b}	1.7 ± 0.2^{c}	0.13 ± 0.1^{a}	0.76 ± 0.02^{b}	1.3 ± 0.1^{bc}
Flame height (m)	0.29 ± 0.1^{a}	1.28 ± 0.48^{bc}	1.7 ± 0.3^{c}	0.41 ± 0.11^{a}	0.96 ± 0.18^{b}	1.9 ± 0.27^{b}
Area burnt (ha)	0.02 ± 0.00^{a}	0.03 ± 0.00^{b}	0.04 ± 0.00^{c}	0.01 ± 0.00^{a}	0.03 ± 0.01^{b}	0.04 ± 0.00^{b}

Mean ± 1SE.

Different horizontal superscripts denote significant difference.

was higher than that of Worobong South (ANOVA, $F_{1,24}$= 2761.29, $p<0.001$), relative humidity and moisture content of 10-hour fuel sticks of the latter were all higher than that of the former (ANOVA, $F_{1,24}$=2738.52, $p<0.001$; ANOVA, $F_{1,24}$=798.187, $p<0.001$ for relative humidity and moisture content of fuel sticks respectively) (Table 4).

From Table 4, air temperature of plantations exceeded that of degraded forests (ANOVA, $F_{1,24}$=23.94, $p<0.001$). Conversely, relative humidity and moisture content of fuel sticks of plantations were lower than that of the degraded forests (ANOVA, $F_{1,24}$=169.56, $p<0.001$ and ANOVA, $F_{1,24}$=15.16, $p<0.001$ respectively).

On the fire behaviour, total heat energy yield did not vary between the two forest reserves and forest cover types (ANOVA, $F_{1,24}$=0.32, p=0.57 and ANOVA, $F_{1,24}$= 0.05, p=0.86 for forest reserves and forest cover respectively). However, the total heat energy yield was greatest in control plots and lowest in prescribed burn plots with hand thinning plots being intermediate (ANOVA, $F_{1,24}$= 35.37, $p<0.001$) (Table 4).

Rate of spread in Afram Headwaters (ranging from 0.7-2.4 m min^{-1}) was higher than that of Worobong South (ranging from 0.49-1.7 m min^{-1}) (ANOVA, $F_{1,24}$=24.12, $p<0.001$). However, the rate of spread was similar in the degraded and plantation forest cover types (ANOVA, $F_{1,24}$=1.2, $p>0.001$). For the treatments, the rate of spread followed the trend in heat yield (ANOVA, $F_{1,24}$= 25.16, $p<0.001$) (Table 4).

Flame height was generally greater in Afram Headwaters (ranging from 0.72-2.62 m) than Worobong South (ranging from 0.29-2.31 m) (ANOVA, $F_{1,24}$=5.75, $p<0.05$). It was also greater in degraded forests (0.29-2.62 m) than plantations (0.40-1.9 m) (ANOVA, $F_{1,24}$=5.25, $p<0.05$). The trend in flame height among the treatment and control plots was similar to that of the total heat energy yield and rate of spread (ANOVA, $F_{1,24}$=39.68, $p<0.001$).

Area burnt was also generally greater in Afram Headwaters than Worobong South (ANOVA, $F_{1,24}$=37.19, $p<0.001$) but similar in the two forest cover types (ANOVA, $F_{1,24}$= 0.08, $p>0.001$) (Table 4). Again, area burnt followed the same trend as total heat energy yield, rate of spread and flame height in the control, prescribed burn and hand thinning plots (ANOVA, $F_{1,24}$=72.35, $p<0.001$) (Table 3).

Discussions

Cost of fuel treatment

From the results, the absence of differences in the cost of treatments in the two forest reserves and the two forest cover types was because, cost of items (labour, equipment and consumables) were similar in the two forest districts. It also suggests that although the two reserves belong to different forest zones, the levels of fuel loads and effort required for their removal were quite similar. The higher cost in hand thinning than prescribed burning was because of longer man hours required to treat one hectare of land. This agrees with reports from many scientific studies (Rummer et al. 2002; Harrell 2006; Stephens et al. 2012). Rummer and others (2002) reported in Georgia in the United States that prescribed burning is the least expensive treatment compared to all other methods of treatment. However, the costs of treatments in this study were on the lower side comparing to the minimum cost of 125 USD ha^{-1} (GH ¢118.75) for prescribed burning and 500 USD ha^{-1} (GH ¢475.00) for thinning treatment reported in the United States (The Wilderness Society 2003). The differences was due to cheap cost of labour in Ghana and the use of less sophisticated and expensive equipment for treatment in this study.

From a management point of view, it may not technically and economically feasible to undertake prescribed burning on large expanse of forest and this may therefore require prioritisation. However, it is generally accepted that burning large area at one time will drive the cost down for that burn (Gonzalez-Caban 1997; Harrell 2006). For the thinning treatment, the cost may be reduced because of some financial returns, which may come from utilisation of the organic debris removed as fuel wood and other end uses. Nevertheless, it may not be able to pay for the cost by itself. This is because the costs can be influenced by site factors such as size of area, fire regime, elevation, fuel loading and management objectives (Fight and Barbour 2004). In forests in Ghana, the removal of logging residues by local communities as firewood is being piloted but the economic implications have not been published to enable a cost recovery analysis due to lack of adequate data (Forest Services Division 2017).

Prescribed burning conditions and fire behaviour

Lack of success of prescribed burning in less degraded forests with canopy opening of far less than 25% in both reserves was due to unfavourable condition for sustained ignition and burning of fuels. The unfavourable condition was as a result of low air temperature (26.8±0.3°C) and high relative humidity (64.2±2.7%) and moisture content of fuel sticks (19.5±1.5%) under less disturbed forest canopy. This finding is consistent with a report by Ray et al. (2005), Ray et al. (2010) and Juarez-Orozco et al. (2017) that, there is a relationship between canopy openness and fire susceptibility. This is because the lower the forest canopy opening, the higher the moisture content of the understory fuels resulting in lower probability of fire ignition and burning. It can therefore be inferred that, the use of prescribed burning for reduction of fuels may not be possible in tropical forests with canopy opening far less than 25% as observed in this study. The observation also implies that, if forests are well managed by avoiding large gaps that will encourage drying of fuels then forest fire incidence and spread could decline. The higher flame heights recorded in the Afram Headwaters and the degraded forests than Worobong South and plantations were because of higher fuel depth as a result of greater height of *Chromelaena odorata* weeds in the former than the latter.

Fuel reduction after treatments

The similarities in relative fuel reduction between the two reserves and between the degraded and plantation forest cover types were caused by similar levels of fuel loading and burning conditions in the two reserves at the time of treatment. Comparing the two treatments, greater relative fuel reduction after prescribed burning than hand thinning was because prescribed burning was much more effective in removing hazardous fuels than the hand thinning treatment (Personal observation). Prescribed burning burnt off most fuels in the fire front but hand thinning left some organic debris unremoved. The result is consistent with a report by Collins et al. (2007) and Volkova and Weston (2019) that fuel reduction is greater in prescribed fire treatments than thinning treatments. Moghaddas and Stephens (2007) also reported a similar result in mixed coniferous forests in Sierra Nevada in the United States. The implication of this result is that prescribed burning is more effective in reducing fuel, which can support intensive and catastrophic fires during the late dry season than hand thinning.

Fuel reduction after post-treatment experimental fire

In post-treatment experimental fire, higher relative fuel reduction recorded in Afram Headwaters than Worobong South was due to differences in burning conditions. Higher air temperature and lower relative humidity and fuel moisture content in Afram Headwaters than Worobong South favoured fast spread of fire, which consumed fuel over larger area. This result suggests that fuel consumption in drier forests during late season burn is more than that of the less dry forests. On the treatments, higher relative fuel reduction in control plots than treated plots implies that fuel available to support the experimental combustion was higher in the former than the latter two treated plots. It can, therefore, be suggested that fuel treatment can reduce fuel loads, which will support potential wildfire during the late dry season. Greater fuel reduction in hand thinning plots than prescribed burn plots in the late dry season fire was caused by greater fuel availability and consumption during the late dry season burn. This further confirms that prescribed burning was more effective in reducing fuel loading that would support the dry season fire than hand thinning (Volkova and Weston 2019).

Post-treatment experimental fire conditions and behaviour

The range of fire intensity in the two reserves was higher than that recorded by Orgle (1994) during a similar late dry period burn in another Semi-deciduous forest in Ghana. Hence, more plants especially tree seedlings were killed under the former than that of the latter. Even though the range of fire intensity recorded is classified as low (Kennard et al. 2001), such range of fire intensity could still have a negatively impact on the future regeneration of trees in similar forest stands in Ghana. However, the range was lower than that reported by Kennard et al. (2001) in Bolivian tropical forest. The difference could be due to differences in experimental conditions.

Greater rate of fire spread, flame height and area burnt in Afram Headwaters than Worobong South was because of more favourable burning conditions in the former than the latter. Afram Headwaters generally had higher air temperature and lower relative humidity and fuel moisture content than Worobong South during the burn. Generally, the primary factors, which influence severity of fire behaviour in the forest environment are higher air temperature and lower relative humidity and fuel moisture content (Barnes et al. 2004). The implication of this result is that fire in a drier forest reserve at the peak of the dry season will be more severe and difficult to control than that of less dry forest reserve irrespective of the treatment method used. Also, higher flame height in degraded forests than plantations was again due to greater fuel depth in the former than the latter.

Comparing the two treatment plots and control, the increase in fire intensity, rate of fire spread, flame height and area burnt from prescribed burn plots through hand thinning plots to control plots was caused by similar trend in fuel availability during burning. A similar report was made in California mixed conifer forest in the United States by Stephens and Moghaddas (2005). The results in this study as a whole indicate that plots without treatment (control) had highest fuel availability to drive severity of post-treatment fire behaviour. This implies that prescribed burning and hand thinning were useful in reducing the severity of post-treatment fire. However, prescribed burning was more effective than the hand thinning.

Limitations of research results

All burnings were not done at the same time of the day or in the same day. Prescribed and post-treatment experimental burnings in all experimental plots were completed within 10 days. Therefore, burning conditions were not exactly the same in all plots and this could influence the results. The results would have given better inferences, if a fourth treatment involving prescribed burning and hand thinning combined had been included. However, this was not possible due to financial constraints.

Conclusion

The study reveals that prescribed burning is less expensive and more effective in reducing fuel loads and late dry-season fire behaviour than the hand thinning. Although, prescribed burning is not possible in less degraded forests with significant canopy cover (canopy opening <25%), it can be effective in degraded forests and old plantations. It may not be permissible to burn large areas of forests in Ghana. Also, prescribed burning can result in mortality of plants including tree seedlings (Barnes et al. 2017) and air pollution problems (Heikerwal et al. 2015). Rampant fires can adversely affect forest ecosystem health (Jhariya 2017). Therefore, prescribed burning should be prioritised based on fire risk and values at risk. In addition, strategic placement of the treatments in overlapping smaller burning units over large areas of degraded forests and plantations can be carried out to avoid large-scale fires.

On the other hand, hand thinning can be effective in reducing fuel loads and severity of late dry season fire in degraded forests and plantations than forests without fuel management. Even though the treatment is expensive, if it is implemented in conjunction with logging operation, operational cost can be reduced. It can also be effective in creating small buffers in high-risk areas. Generally, in order to prevent unwarranted losses of land cover (Masum and Hasan 2020) from poorly planned prescribed burning and hand thinning, land use plan in the forest area should be incorporated with fuel management plans.

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