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Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia

Ronald W. Shea,[1] Barbara W. Shea,[1] and J. Boone Kauffman[2]
Department of Rangeland Resources, Oregon State University, Corvallis

Darold E. Ward
Intermountain Research Station, U.S. Department of Agriculture, Forest Service
Missoula, Montana

Craig I. Haskins and Mary C. Scholes
Botany Department, University of the Witwatersrand
Johannesburg, South Africa

Abstract. Fires are dominant factors in shaping the structure and composition of vegetation in African savanna ecosystems. Emissions such as CO_2, NO_x, CH_4, and other compounds originating from these fires are suspected to contribute substantially to changes in global biogeochemical processes. Limited quantitative data exist detailing characteristics of biomass, burning conditions, and the postfire environment in African savannas. Fourteen test sites, differentiated by distinct burn frequency histories and land- use patterns, were established and burned during August and September 1992 in savanna parklands of South Africa and savanna woodlands of Zambia. Vegetation physiognomy, available fuel loads, the levels of biomass consumed by fire, environmental conditions, and fire behavior are described. In the South African sites, total aboveground fuel loads ranged from 2218 to 5492 kg ha^{-1} where fire return intervals were 1-4 years and exceeded 7000 kg ha^{-1} at a site subjected to 38 years of fire exclusion. However, fireline intensity was only 1419 kW m^{-1} at the fire exclusion site, while ranging from 480 to 6130 kW m^{-1} among the frequent fire sites. In Zambia, total aboveground fuel loads ranged from 3164 kg ha^{-1} in a hydromorphic grassland to 7343 kg ha^{-1} in a fallow shifting cultivation site. Dormant grass and litter constituted 70-98% of the total fuel load among all sites. Although downed woody debris was a relatively minor fuel component at most sites, it constituted 43-57% of the total fuel load in the fire exclusion and shifting cultivation sites. Fire line intensity ranged between 1734 and 4061 kW m^{-1} among all Zambian sites. Mean grass consumption generally exceeded 95%, while downed woody debris consumption ranged from 3 to 73% at all sites. In tropical savannas and savanna woodlands of southern Africa, differences in environmental conditions, land- use patterns, and fire regimes influence vegetation characteristics and thus influence fire behavior and biomass consumption.

1. Introduction

Burning of vegetation biomass contributes substantially to changes in biogeochemical processes at both local and global scales [*Kauffman et al.*, 1992] and produces gaseous emissions such as CO_2, NO_x, CH_4, which may ultimately alter global climatic processes [*Seiler and Crutzen*, 1980]. These emissions originate from wide-scale savanna burning, clearing and burning of tropical forests for cattle production and forestry activities, and various agricultural practices such as shifting cultivation [*Andreae*, 1991]. Globally, it is estimated that approximately 66% of the vegetation burned during the 1980s occurred in tropical Africa [*World Resources Institute (WRI)*, 1990]. Approximately 85% of the biomass consumed in tropical Africa is associated with the burning of more than 440 x 10^6 ha of grassland savannas and savanna woodlands [*Hao et al.*, 1990].

Intentional burning has long been used in western and central Africa to improve game capture, clear unwanted vegetation, and deter parasites and pests [*WRI*, 1990;

[1]Now at 2855 NW Johnson Avenue, Corvallis, Oregon.
[2]Now at Department of Fish and Wildlife, Oregon State University, Corvallis, Oregon.

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Menaut et al., 1991]. In addition, many traditional African agricultural systems incorporate annual or biennial burning [*Stromgaard*, 1985; *Chidumayo*, 1987a] which generally occurs during the dry season and then accelerates as the rainy season approaches. Innumerable uncontrolled fires also range freely across rural landscapes during the dry season. Prescribed fires and natural fires are utilized as management tools for the maintenance of wildlife forage in many national parks and game reserves of southern and eastern Africa [*Trollope*, 1984].

In unperturbed ecosystems, factors such as precipitation regimes, inherent soil properties, competition, and specific physiological attributes naturally regulate phytomass production; however, many savannas are currently altered by the use of mechanized equipment, commercial fertilizers, and variable fallow periods [*Kauffman et al.*, 1992]. Changing environmental factors, population pressures, and evolving cultural practices will ultimately dictate the burning practices applied across the African landscape. The natural variability in the composition and structure of savannas coupled with these anthropogenic effects present's a difficult spatial and temporal problem for estimating overall emissions produced from savanna fires.

In September and October 1992, several hundred international investigators participated in an experiment known as the Southern African Fire-Atmosphere Research Initiative (SAFARI-92) to assess atmospheric and terrestrial impacts of biomass burning in savanna ecosystems of southern Africa. The central hypothesis was that emissions from dryseason fires in southern Africa strongly influence atmospheric/biospheric chemistry over a large portion of the southern hemisphere. We maintain that owing to the complex array of fuel and environmental conditions present in southern African savanna ecosystems, differences in fuel moisture content (live and dead fuels) and total fuel loads directly influence fire effects and combustion efficiency, and thus influence emissions characteristics and nutrient cycling.

To properly characterize these relationships, specific fuel-biomass attributes and burning conditions that dictate emissions composition and distribution must be determined. While fire regimes and land- use practices likely have a major effect on physical and chemical characteristics of fuels and soils, the net effect is poorly understood. Because millions of hectares of savanna ecosystems are presently or potentially subject to fire and intensive land use, direct investigations are essential.

In this paper we present an approach for describing fuel loads (biomass), biomass consumption, and fire behavior that ultimately influence the composition and production of emissions from fires across a broad range of savanna sites in southern Africa. The objectives of the study are (1) to characterize and quantify surface fuel biomass before burning in selected savanna ecosystems in South Africa and Zambia; (2) to document climatic conditions and fuel moisture content at the time of burning; (3) to monitor and record associated fire behavior; (4) to quantify fuel consumption and the mass of residual uncombusted fuels and ash; and (5) to stratify fuels associated with smoke emissions production for two comparison studies [*Hao et al.*, this issue; *Ward et al.*, this issue].

2. Methods

2.1. Study Areas

Tropical savannas occupy approximately 591 x 10^6 ha in Africa [*WRI*, 1990], extending from 20°N to 25°S latitude, with the majority of savanna communities occurring in southern Africa. Savanna ecosystems may be characterized as either moist/dystrophic or arid/eutrophic [*Huntley*, 1982], but often include physical soil attributes, precipitation regimes, predominant vegetation, and the influence of fire or other disturbances on savanna physiognomy [*Cole*, 1986]. Human-caused and human-maintained savannas also present a particular problem for precise savanna classification [*Bourlière and Hadley*, 1983]. The most extensive and distinct African savanna communities are savanna woodlands, savanna grasslands, and savanna parklands [*Cole*, 1963; *White*, 1965] and are typified by a continuous grass stratum and by the degree of tree cover and height.

In this study, we sampled biomass and monitored fire behavior at 10 savanna parkland (bushveld) sites in South Africa (Figure 1) and at one moist savanna grassland site, two moist savanna woodland sites, and one semiarid savanna woodland site in Zambia (Figure 2). The South African sites were differentiated by season of burn and burning- frequency histories. Zambian sites were primarily differentiated on the basis of annual precipitation regimes and community type.

2.1.1. South Africa. The study sites are within 5 km of Pretoriuskop Camp, in southwestern Kruger National Park (31°14'00" E, 25°15'13" S). Elevation is 600 m. Topography is typified by an undulated landscape with prominent granite hills (koppies). Soils are derived from granite weathered to coarse sandy loams and are deeply leached [*Venter*, 1986]. The annual maximum and minimum temperatures are 27°C and 15°C. Annual precipitation ranges from 600 to 900 mm, occurring predominantly in the form of spring and summer storms. Although lightning frequently occurs during October and November, more than 45% of the fires occurring annually in Kruger National Park between 1985 and 1992 resulted from prescribed burning while 10% originated from lightning strikes [*Trollope*, 1993]. Accidental fires and fires originating from poaching or unknown activities accounted for nearly half of the other ignitions occurring in the park during this period. For a complete description of the fire regime and prescribed burning history of the Kruger National Park, see *Stocks et al.* [this issue].

The vegetation of the Pretoriuskop region is classified as Lowveld Sour Bushveld [*Acocks*, 1975], a savanna parkland dominated by *Terminalia sericea* and *Dichrostachys cinerea* subsp. *Nyassana*. Tree height ranged from 3 to 5 m. The shrub component includes *T. sericea*, *D. cinerea* and dense clusters of *Maytenus senegalensis*. Fire-induced coppicing is evident on many trees and shrubs throughout the area. The dominate grasses are *Hyperthelia dissoluta*, *Diheteropogon amplectans*, *Heteropogon contortus*, *Setaria flubellata*, and *Elionurus muticus*. The grass sward was 0.5 to 1 m in height. Small to moderate groups of elephant (*Loxondonta africana*), buffalo (*Syncerus caffer*), white rhinoceros (*Diceros bicornus*), and giraffe (*Giraffa*

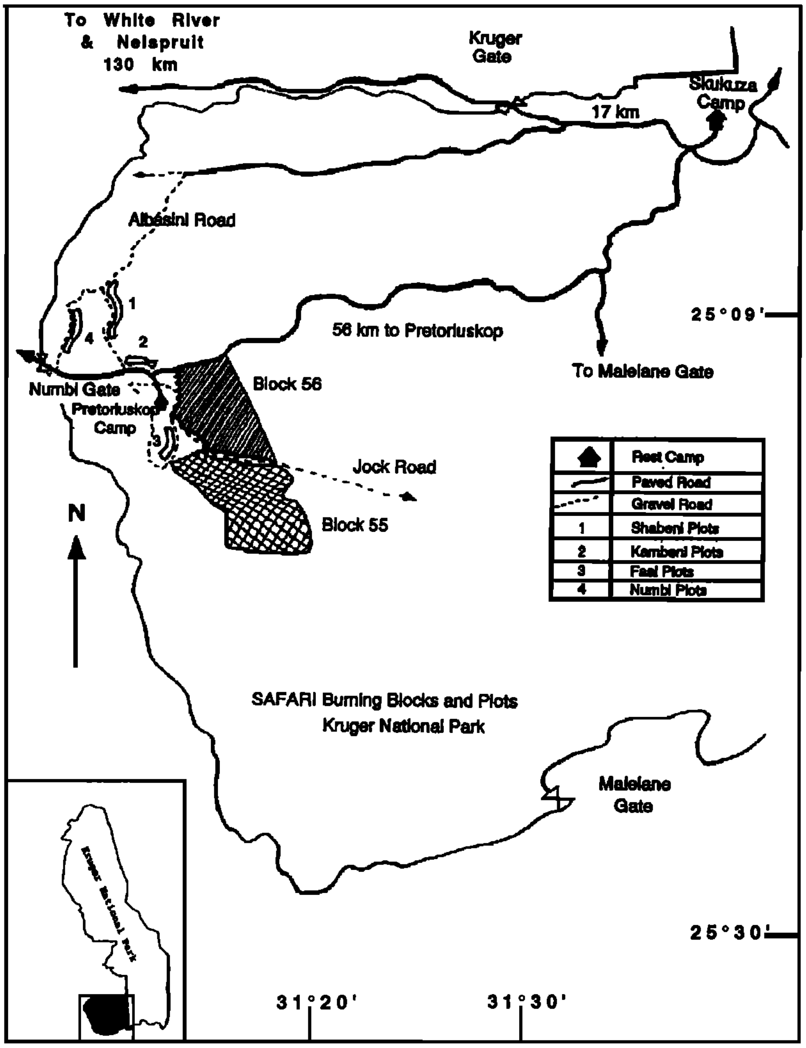

Figure 1. General locations of the study sites near Pretoriuskop, Kruger National Park, South Africa.

camelopardalis) are common on the study area as are moderate to large groups of Burchelli's zebra (*Equus burchelli*), impala (*Aepyceros melampus*), black wildebeest (*Connochaetes gnou*), and kudu (*Tragelaphus strepsiceros*). Animal trails, bedding areas, and other impacts from foraging activities (e.g., elephant-damaged trees) were apparent on many plots.

To quantify the effects of seasonal burning on fuel loads, fuel consumption, and fire behavior, we sampled four late-winter biennial burning plots and three early-spring biennial burning plots. The plots were located at four permanent research areas named (1) Faai, (2) Shabeni, (3) Numbi, and (4) Kambeni. Each plot was ≈ 7 ha in size and had been last burned in 1990, 2 years prior to this study. Two large-scale management blocks were sampled in order to characterize the fire effects from large-scale fires on biomass. These sites were designated block 55 (2333 ha) and block 56 (2043 ha). Block 55 was last burned in 1988, and block 56 in 1990. An additional plot at the Kambeni research area (Kambeni E) was sampled to characterize fuel loads and fire effects following 38 years of fire exclusion. These three sites are representative of savanna communities with distinct burning frequency histories. All study sites were surrounded by a permanent fire break. Prescribed burning was conducted by personnel of the Kruger National Park.

2.1.2. Zambia. The moist savanna study area is in the vicinity of Kasanka National Park, Central Province (12°35'S, 30°21'E). Elevation is 900 m. The topography is essentially flat with interspersed depressions and occasional rocky outcrops on high points. Soils are classified as Acrisols and are typically shallow with a sandy texture. Annual precipitation ranged from 1170 mm in 1989 to 738 mm in 1991 [Kasanka Park Records, Lake Wasa Camp, unpublished data, 1989-1992] and generally occurs from October to March. The annual maximum and minimum temperatures are 30°C and 15°C [Meteorological Department, Lusaka, unpublished data, 1984]. Intentional fires are common from July to October and are primarily associated with shifting agriculture and control of undesirable vegetation.

The vegetation of Kasanka National Park and the surrounding region is a moist savanna classified as "miombo woodland," a multistoried woodland with a discontinuous canopy of semievergreen trees 10 to 20 m in

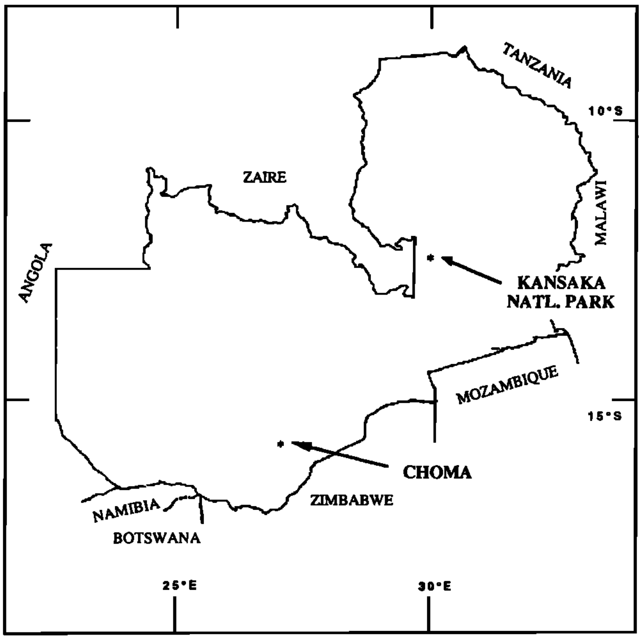

Figure 2. General locations of the study areas near Choma, Southern Province, and Kasanka National Park, Central Province, Zambia.

height [*Fanshawe*, 1969]. The tree canopy is dominated by *Julbernadia paniculata*, *Brachystegia longifolia*, and *Monotes africanus* with the understory shrub layer dominated by *Uapaca sansibarica* and *Eriosema affine*. The woodland herbaceous layer was dominated by a cover of *Hyparrhenia* spp., *Themeda triandra*, and *Diheteropogon amplectans* from 0.5 to 1.5 m in height. Hydromorphic grasslands, known as "dambos," often occur along natural drainage lines and seasonally flooded depressions within the savanna woodlands [*Cole*, 1986]. Tree and shrub establishment is restricted to termite mounds rising above the floodplain.

We sampled three dominant plant communities typically burned every 1-2 years. The first was a 45-year-old miombo woodland excluded from agricultural production in 1947. Local farmers are reliant upon the "chitemene" shifting cultivation system, which utilizes ash (resulting from burning stacked branches lopped from trees in or near the cultivation area) as a fertilizer for various vegetable crops [*Stromgaard*, 1985]. The second community sampled was a "dambo" grassland, and the third was a fallow "chitemene" site last cut in 1989 but not utilized for crops. Because of the proximity to local villages, large wild mammals had no impact on vegetation and fuel biomass in the three study sites. Intentional burning was conducted by local townspeople.

The semiarid savanna woodland study site is located 5 km north of Choma, Southern Province (16°50'S, 26°59'E). Elevation is 400 m. The Choma-Zimba plateau is typified by level terrain with slight depressions. Soils are classified as Acisols and Luvisols that are shallow and poorly drained. Texture is a sandy loam. Mean annual precipitation is 800 mm (1950-1980) and winter drought is typical from April to October [Meteorological Department, Lusaka, unpublished data,1984]. The annual maximum and minimum temperatures are 30°C and 12°C, respectively. Many fires during June to October are related to commercial farming, small-scale traditional farming, and cattle ranching.

The vegetation community of the Choma region is a semiarid savanna (Miombo) woodland dominated by *Uapaca kirkiana* and *Julbernadia globiflora* with a partially closed canopy 8 to 10 m in height. The understory consisted of numerous grasses including *Hyparrhenia* spp., *Shizachyrium jeffreysii*, and *Brachiaria serrata*. Our study site (≈ 2 ha in size) was last burned in 1990, and cattle were present on the site for 3 months during early 1992. Prescribed burning was conducted by the landowner using dried grass as an ignition tool.

2.2. Surface Fuels

In this study, we define fuel loads as all aboveground material derived from flora and/or fauna (biomass) less than 2.5 m in height that is suseptible to combustion by fire (excluding the stems of standing trees). Fuels were partitioned into six categories: litter (defined as dead and downed tree and grass leaves and all other natural detritus),

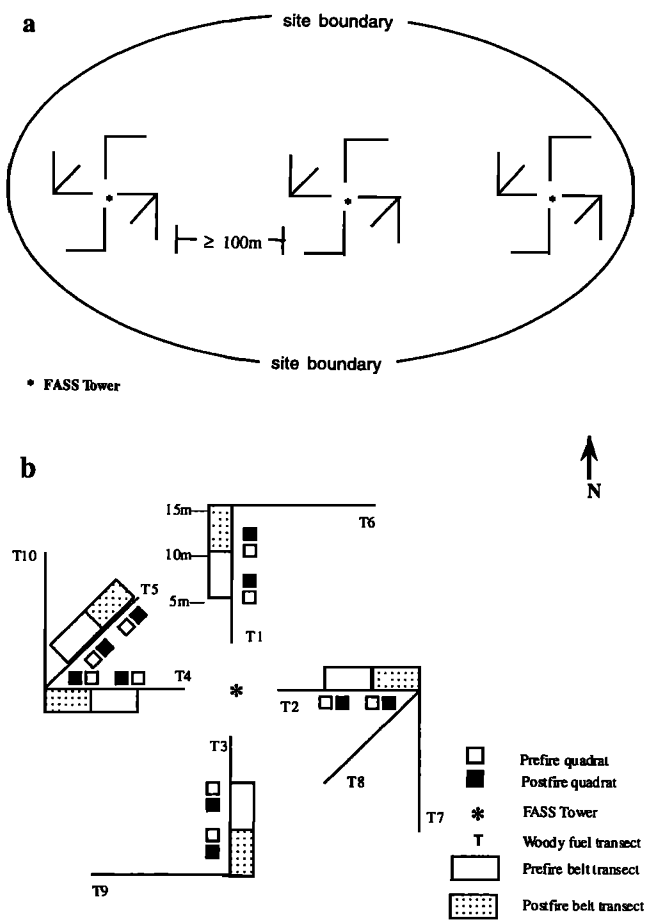

Figure 3. Sampling cluster design: (a) the typical position of the three fuel-sampling clusters with FASS instrumentation and (b) a representative cluster showing the positions of the fuel sampling quadrats, woody fuels transects, and belt transects.

dead standing grass and green grass, herbs, attached tree/shrub leaf foliage (i.e. leaves, flowers, seeds, and fine stems), animal dung (Kruger National Park only), and downed and dead woody debris. Thirty transects were systematically established at each burn site. The arrangement consisted of three clusters of 10 transects, and clusters were separated by at least 100 m to ensure representative sampling (Figure 3a). Each transect was 15 m in length. The beginning and end of each transect was marked with a metal stake for exact relocation after burning. All transect lengths were corrected for slope and the azimuths recorded. A fire atmospheric sampling system (FASS) was positioned at the center of each cluster. For a discussion of results from the emissions characterization component, see companion papers by *Hao et al.* [this issue] and *Ward et al.* [this issue].

Individual fuel components were sampled at the locations illustrated in Figure 3. The mass of downed and dead woody debris was estimated using the planar intercept technique [*Van Wagner*, 1968; *Brown*, 1974]. Fuels were partitioned into distinct diameter classes that nominally dry to 2/3 of their equilibrium moisture content under standard conditions [*Deeming et al.*, 1977] as follows: 1-h fuels (0 - 0.64 cm diam.), 10-h fuels (0.65 - 2.54 cm diameter), 100-h fuels (2.55 - 7.62 cm diameter), and 1000-h fuels (7.63 - 20.3 cm diameter). This classification method facilitates calculation of the percent (%) woody fuel consumption and fuel equilibrium moisture content. These values are also important for determination of specific fire behavior characteristics, for evaluating fire danger potential, and in fire behavior modeling [*Deeming et al.*, 1977].

The length of the sampling plane was 5 m for woody fuels ≤ 0.64 cm diameter, 10 m for woody fuels 0.65 - 2.54 cm diameter, and 15 m for woody fuels > 2.54 cm in diameter. Postfire woody fuel estimates were based upon remeasurement of each transect. To calculate the mass of woody debris, 100 random quadratic mean diameter measurements were made for each of the fuel diameter classes < 7. 62 cm in diameter from each distinct community. Thirty randomly selected samples were collected to calculate the mean wood densities of each diameter class. At the Kruger Park sites, density values for the two most dominant woody tree species [*Van Wyk*, 1972] were used to determine the density of woody fuels > 7.62 cm in diameter. Approximately 25 samples were collected for wood density determination of each diameter class in the Zambian communities.

Prior to each burn, samples of the litter, grass, and herb (< 0.5 m height) components were collected from 30 microplots associated with five of the woody fuel transects. The microplots were 25 x 25 cm or 50 x 50 cm quadrats depending on the continuity of grass cover. Postfire biomass was classified as either ash or remaining uncombusted fuels. Paired plots, positioned adjacent to location of the prefire microplots, served as postfire collection sites. Ash was collected using a portable vacuum system. With care, this technique allows sampling of ash deposited from the intact, prefire fuel bed with minimal ash contamination.

The mass of foliage from shrubs and trees between 0.5 m and 2.5 m in height was estimated by collecting all biomass in a 1 x 5 m plot adjacent to 15 of the 30 woody fuel transects. Animal dung was collected from within the same 1 x 5 m plot. After burning, residual biomass was sampled in a paired plot positioned 5 m away from the prefire site. Postfire sample collection began immediately after cessation of combustion. All nonwoody fuel and ash samples were placed in paper bags, oven-dried for 48 hours at 60°C, and weighed. Fuel and ash loads are expressed on a dry- weight basis in kilograms per hectare.

The combustion factor of each fuel component was calculated following measurement of the postfire residual biomass and is defined as the ratio between fuel consumed and prefire fuel mass.

2.3. Environmental Condition and Fire Behavior

Immediately prior to burning, the moisture content of selected fuel components and the 0 - 2.5 cm and 2.5 - 10 cm soil depths were measured by randomly collecting five samples at each plot. All fuel samples were oven-dried 48 hours at 60°C. Soils were dried 72 hours at 70°C. Moisture content was expressed on a dry- weight basis and calculated through determination of fresh and ovendry weights.

Burn date and ignition time were recorded and ambient air temperature (degrees Celsius), relative humidity (percent), wind speed (kilometers per hour), and direction recorded at the time of ignition and then every 30 min during each fire. Documentation also included mapping of the ignition pattern, and at least six random observations were recorded of the following fire behavior characteristics (as described by *Alexander* [1982]): type of fire, flame length (meters), flame height (meters), flame depth (meters), flame angle (degrees), flame residence time (seconds), and forward flaming- front spread rate (meters per second). The majority of flame length and flame height estimates were visually determined using the three FASS towers (each constructed in 3-m-length sections to a known height) to calibrate the estimate. Several estimates were made using a clinometer (percent). Residence time was measured by recording the time the primary flaming front remained at one point while the rate of spread was measured by recording the time the flaming front moved between two points. The two points were marked and then measured following the fire. Time measurements were obtained using a handheld electronic stopwatch. On the basis of specific fire behavior and fuel characteristics, fire line intensity (the rate of heat release per unit length of fire line) of all fires was estimated using the equation presented by *Byram* [1959].

Fire intensity was calculated using a value of 16890 kJ kg^{-1} for the heat of combustion (as estimated for grass fuels in southern Africa by *Trollope* [1983]). Fire intensity is reported in kilowatts per meter.

3. Results

3.1. Aboveground Fuel Loads

3.1.1. South Africa. Total prefire fuel mass ranged from 3555 to 4778 kg ha^{-1} among the late-winter burn plots (Table 1). Total woody debris fuel loads were between 631 and 1964 kg ha^{-1}, and the majority (55-79%) of wood

Table 1. Aboveground Fuel Biomass Before and After Prescribed Fire and the Combustion Factor (CF) in Four Late-Winter Biennial Burning Plots in Lowveld Sour Bushveld Savanna at the Kruger National Park, South Africa

Component	Kambeni 5			Faai 1			Numbi 4			Shabeni 1		
	Prefire, kg ha-1	Postfire, kg ha-1	CF, %	Prefire, kg ha-1	Postfire, kg ha-1	CF, %	Prefire, kg ha-1	Postfire, kg ha-1	CF, %	Prefire, kg ha-1	Postfire, kg ha-1	CF, %
Litter	1802 (223)	100 (19)	92 (5)	1229 (154)	443 (82)	64 (5)	1178 (162)	164 (31)	86 (5)	1850 (495)	80 (65)	86 (8)
Grass-dormant	1818 (259)	4 (1)	100 (0)	669 (100)	16 (3)	97 (2)	1195 (217)	2 (0)	100 (0)	442 (162)	0 (8)	100 (0)
Grass-green	0 (0)	0 (0)	...	0 (0)	0 (0)	...	215 (152)	0 (0)	100 (0)	1334 (478)	81 (12)	91 (2)
Total grass	1818 (259)	4 (1)	100 (0)	669 (100)	16 (3)	97 (2)	1411 (225)	2 (0)	100 (0)	1776 (358)	81 (14)	94 (3)
Dicots	0 (0)	0 (0)	...	27 (18)	3 (1)	90 (7)	0 (0)	1 (0)	...	20 (9)	3 (2)	85 (1)
Tree/shrub leaves	5 (3)	2 (1)	86 (16)	39 (18)	20 (5)	51 (7)	13 (5)	12 (4)	10 (5)	30 (16)	9 (7)	76 (12)
Dung	0 (0)	5 (1)	...	0 (0)	29 (8)	...	29 (15)	18 (5)	30 (16)	137 (105)	6 (11)	90 (16)
Wood debris*												
0 - 0.64 cm	194 (40)	92 (27)	66 (10)	507 (106)	507 (106)	0 (0)	212 (88)	102 (42)	60 (11)	102 (35)	46 (61)	56 (13)
0.64 - 2.54 cm	507 (117)	306 (89)	52 (9)	717 (140)	701 (142)	4 (4)	274 (79)	250 (66)	16 (5)	81 (21)	48 (90)	40 (16)
2.54 - 7.62 cm	182 (73)	50 (37)	81 (13)	199 (78)	199 (78)	0 (0)	149 (87)	149 (87)	0 (0)	166 (69)	166 (70)	0 (0)
> 7.62 cm	234 (234)	234 (234)	0 (0)	541 (541)	541 (541)	0 (0)	310 (310)	310 (310)	0 (0)	283 (283)	283 (283)	0 (0)
Total wood debris	1117 (395)	682 (329)	60 (8)	1964 (598)	1948 (600)	3 (3)	945 (347)	810 (328)	20 (4)	631 (302)	543 (407)	43 (11)
Total fuel biomass	4778 (486)	789 (324)	87 (3)	3909 (649)	2435 (603)	44 (5)	3555 (486)	994 (327)	76 (5)	4444 (569)	715 (302)	84 (5)
Ash		95 (17)			59 (11)			609 (113)			261 (49)	

Numbers given are mean values with standard errors in parentheses.
* Ranges refer to diameter of wood debris.

debris was < 7.62 cm in diameter. At the Faai 1 plot, woody debris accounted for 50% of the total fuel load while only 17% was composed of grass. In contrast, grass accounted for 38 to 40% of the total fuel load among the other three plots. Litter ranged from 1178 to 1850 kg ha^{-1} and constituted > 31% of the total fuel load among all late-winter plots.

Prior to burning, total fuel loads ranged from 2218 to 5200 kg ha^{-1} among the three early-spring burn plots (Table 2). Grass comprised 28 to 63% and litter > 26% of the total fuel load in all plots, while woody debris accounted for only 30% of the total fuel load. However, total woody debris fuel load at Shabeni 5 was twice that of Faai 4, and more than 6 times greater than that of Kambeni 3. Average tree density (> 4 m height) was 44 ha^{-1} among the late-winter and early-spring burn plots.

Total aboveground fuel mass ranged from 3892 to 7084 kg ha^{-1} among the three distinct burning- frequency history sites; nearly 2 times higher in Kambeni E (38 years since last burned)(Table 3) than that of block 56 (2 years since last burned). Average tree density (> 4 m height) was 32 ha^{-1} in the large blocks. In contrast, tree density was 533 ha^{-1} in Kambeni E. Litter accounted for 33 to 62% of the total fuel loading among these three sites and was from 1.7 to 3.4 times greater at the block 55 and Kambeni E sites, respectively. However, the litter component at Kambeni E consisted primarily of tree leaf detritus, while litter at block 55 was predominantly grass leaf detritus. The mean total prefire grass fuel load ranged from 1561 to 2419 kg ha^{-1}, composing 40 to 44% of the total fuel load. Dead standing grass was the predominant fuel in the large block sites but composed < 20% of the total aboveground fuel in Kambeni E. Dicot seedlings, tree/shrub leaves, and animal dung accounted for < 4% of the total fuel load among all sites. Prior to burning, the mean mass of total wood debris ranged from 844 kg ha^{-1} in block 55 to 1227 kg ha^{-1} in Kambeni E, but accounted for only 15 to 17% of the total fuel load. In contrast, total wood debris composed 24% of the total fuel load in block 56. Fine woody debris ≤ 2.54 cm diameter was 2.2 to 3.5 times greater in the Kambeni E compared to that of the other sites (Table 3).

3.1.2. Zambia. In Zambia, total prefire fuel loads ranged from 3164 kg ha^{-1} in the dambo grassland to 7343 kg ha^{-1} at the fallow chitemene study site (Table 4). These were comparable to the total fuel loads measured at the South African sites (3567 to 7084 kg ha^{-1}). Total fuel loads at the semiarid and moist miombo woodland sites were quite similar (5100 and 5772 kg ha^{-1}, respectively). Tree density (> 5 m height) was 200 ha^{-1} in the semiarid miombo, and was 574 ha^{-1} (trees > 5 m height) in the moist miombo. At the fallow chitemene site, tree density was 130 ha^{-1}, but the majority of these trees were < 2 m in height. Wood debris composed 43% of the total fuel load at the fallow chitemene site and was 2.5 to 5.3 times greater than that of both miombo sites. The majority of wood debris > 2.54 cm in diameter had been previously removed for use as fuelwood by local farmers at the semiarid miombo. In the dambo, standing trees and wood debris were completely absent, and grass composed 99% of the prefire fuel load (3164 kg ha^{-1}). In contrast, grass fuels ranged from 671 kg ha^{-1} in the semiarid miombo to 2462 kg ha^{-1} at the fallow chitemene site. Dead standing grass composed 67 to 98% of the available grass fuel load at all sites.

Surface litter ranged from 1490 kg ha^{-1} in the fallow chitemene to 3806 kg ha^{-1} in the moist miombo (Table 4). Litter was absent in the dambo. Dicot seedlings and tree/shrub leaves composed < 2.5% of the total fuel load at all sites.

3.2. Environmental Condition and Fire Behavior

3.2.1. South Africa. Prescribed burning of the late-winter plots was conducted from August 6 to 14, 1992 (Table 5). Burning techniques were based upon fuel loading, fuel moisture, and current fire weather information. Ambient air temperatures at the time of burning were similar among late-winter plots, ranging from 23° to 31°C. In contrast, relative humidity ranged from 19% at Faai 1 to 44% at Kambeni 5. Other weather conditions were relatively similar at the time of burning. All plots were ignited around midday (1100-1400 hours). Ignition was started at the downwind side of each plot (i.e., as a backing fire) and then was rapidly effected across the upwind side to produce a head fire. The total burnout period generally lasted < 15 min in all plots.

The moisture content of the 0 - 2.5 cm soil depth was significantly different among the late-winter burn plots, ranging from 1.3% at Shabeni 1 to 14.5% at Kambeni 5 (Table 5). Moisture content of the 2.5 - 10 cm soil depth at Kambeni 5 was also significantly higher than that at the other plots. The moisture content of litter ranged from 4.4% at Kambeni 5 to 9.9% at Numbi 4. Grass moisture content was between 13 and 26%, while a mean moisture content of 107% was measured for tree/shrub leaves. However, the moisture content of woody debris ≤ 2.54 cm diameter at Kambeni 5 was 7.5% higher than that measured in Shabeni 1, and ranged between 3 and 11% at all late-winter burn plots. Average flame lengths were 1 to 3 m among all plots (Table 5). Occasional flame lengths exceeding 5 m were observed at Kambeni 5 and Numbi 4. Rates of fire spread ranged from 0.2 m s^{-1} at Faai 1 to 0.4 m s^{-1} at Kambeni 5. Fire intensity ranged from 475 kW m^{-1} at Faai 1 to 2414 kW m^{-1} at Kambeni 5.

The early-spring burn plots were burned during September 10 to 15, 1992 (Table 6). Lighting techniques and burning conditions were comparable to those in the late-winter burn plots. Weather conditions were similar, with the exception of a higher relative humidity at Kambeni 3 (40%, compared to 24% at Shabeni 5 and 32% at Faai 4), throughout the burning period. The mean fuel moisture content of grass was at Faai 4 was 15%, compared to 9.5% at Kambeni 3. Conversely, the moisture content of woody fuels ≤ 0.64 cm diameter was 1.1% higher at Kambeni 3. There were no other measurable differences among specific fuel components between the early-spring burn plots. Mean soil moisture content was < 0.7% at each depth in both plots. Fire behavior was very similar at Kambeni 3 and Shabeni 5, with mean flame lengths of 3 to 6 m and flaming front spread rates ranging from 0.3 to 0.7 m s^{-1} (Table 6). Fire intensity ranged from 480 kW m^{-1} at Faai 4 to 3579 kW m^{-1} at Kambeni 3.

Table 2. Aboveground Fuel Biomass Before and After Prescribed Fire and the Combustion Factor in Three Early-Spring Biennial Burning Plots in Lowveld Sour Bushveld Savanna at the Kruger National Park, South Africa

Component	Faai 4			Kambeni 3			Shabeni 5		
	Prefire, kg ha-1	Postfire, kg ha-1	CF, %	Prefire, kg ha-1	Postfire, kg ha-1	CF, %	Prefire, kg ha-1	Postfire, * kg ha-1	CF, %
Litter	584 (98)	12 (4)	98 (0)	1133 (66)	0 (0)	100 (0)	1418 (141)	nd	...
Grass-dormant	588 (102)	2 (1)	100 (0)	2425 (242)	0 (0)	100 (0)	1810 (232)	nd	...
Grass-green	52 (12)	6 (2)	90 (3)	72 (33)	0 (0)	100 (0)	185 (69)	nd	...
Total grass	639 (101)	8 (3)	99 (0)	2497 (254)	0 (0)	100 (0)	1995 (291)	nd	...
Dicots	184 (112)	4 (1)	94 (2)	45 (35)	0 (0)	100 (0)	166 (57)	nd	...
Tree/shrub leaves	5 (2)	4 (1)	26 (3)	3 (2)	0 (0)	100 (0)	4 (3)	nd	...
Dung	21 (13)	11 (5)	46 (3)	20 (9)	0 (0)	100 (0)	117 (102)	nd	...
Wood debris †									
0 - 0.64 cm	282 (81)	199 (66)	34 (13)	47 (19)	11 (11)	86 (14)	221 (53)	30 (10)	79 (8)
0.64 - 2.54 cm	217 (64)	205 (60)	3 (11)	125 (38)	60 (23)	68 (11)	370 (58)	246 (38)	33 (6)
2.54 - 7.62 cm	298 (194)	298 (194)	0 (0)	77 (47)	77 (47)	0 (0)	320 (62)	342 (79)	0 (0)
> 7.62 cm	0 (0)	0 (0)	...	0 (0)	0 (0)	...	648 (490)	648 (490)	...
Total wood debris	798 (249)	703 (235)	13 (11)	249 (66)	148 (66)	40 (7)	1560 (539)	1266 (512)	29 (6)
Total fuel biomass	2218 (352)	741 (244)	67 (5)	3936 (293)	148 (66)	96 (2)	5200 (692)	...	...
Ash		125 (42)			282 (52)			nd	

Numbers given are mean values with standard errors in parentheses; nd denotes no data.
* Postfire nonwoody biomass and ash data lost in oven fire.
† Ranges refer to diameter of wood debris.

Table 3. Aboveground Fuel Biomass Before and After Prescribed Burning and the Combustion Factor (CF) in 1992 at Three Sites With Distinct Burning-Frequency Histories in Lowveld Sour Bushveld Savanna Near Pretoriuskop, Kruger National Park, South Africa

Component	Block 56 (1990*)			Block 55 (1988*)			Kambeni E (1954*)		
	Prefire, kg ha-1	Postfire, kg ha-1	CF, %	Prefire, kg ha-1	Postfire, kg ha-1	CF, %	Prefire, kg ha-1	Postfire, kg ha-1	CF, %
Litter	1302 (245)	8 (2)	99 (1)	2222 (206)	53 (10)	97 (2)	4397 (358)	392 (73)	91 (3)
Grass-dormant	1430 (241)	0 (0)	100 (0)	2390 (272)	0 (0)	100 (0)	1310 (174)	65 (12)	96 (2)
Grass-green	132 (20)	0 (0)	100 (0)	29 (9)	0 (0)	100 (0)	54 (19)	0 (0)	100 (0)
Total grass	1561 (242)	0 (0)	100 (0)	2419 (273)	0 (0)	100 (0)	1364 (173)	65 (12)	96 (9)
Dicots	67 (30)	0 (0)	100 (0)	7 (4)	0 (0)	100 (0)	65 (23)	5 (1)	92 (5)
Tree/shrub leaves	18 (8)	5 (1)	75 (10)	0 (0)	0 (0)	...	61 (8)	5 (1)	90 (3)
Dung	9 (8)	5 (1)	50 (12)	0 (0)	0 (0)	...	56 (23)	11 (3)	91 (9)
Wood debris †									
0 - 0.64 cm	133 (34)	25 (10)	83 (5)	196 (51)	47 (16)	83 (5)	584 (120)	196 (60)	75 (7)
0.64 - 2.54 cm	193 (50)	137 (38)	28 (8)	326 (78)	209 (56)	49 (10)	544 (93)	342 (70)	42 (7)
2.54 - 7.62 cm	55 (23)	55 (23)	0 (0)	132 (38)	121 (34)	15 (11)	99 (36)	88 (35)	29 (18)
> 7.62 cm	566 (566)	283 (283)	50 (0)	189 (189)	189 (189)	0 (0)	0 (0)	0 (0)	...
Total wood debris	947 (577)	500 (291)	47 (6)	844 (250)	567 (210)	32 (7)	1227 (207)	627 (123)	49 (5)
Total fuel biomass	3892 (710)	514 (293)	91 (2)	5492 (470)	620 (209)	90 (2)	7084 (384)	1100 (193)	83 (3)
Ash		362 (67)			653 (121)			773 (143)	

Numbers given are mean values with standard errors in parentheses.
* Year site was last burned prior to this study.
† Ranges refer to diameter of wood debris.

Table 4. Aboveground Fuel Biomass Before and After Burning and the Combustion Factor (CF) of Three Moist Savanna Sites Near Kasanka National Park, Zambia, and a Semiiarid Savanna Woodland Near Choma, Zambia

Component	Dambo Grassland			Moist Miombo Woodland			Fallow Chitemene			Semiarid Miombo Woodland		
	Prefire, kg ha^{-1}	Postfire, kg ha^{-1}	CF, %	Prefire, kg ha^{-1}	Postfire, kg ha^{-1}	CF, %	Prefire, kg ha^{-1}	Postfire, kg ha^{-1}	CF, %	Prefire, kg ha^{-1}	Postfire, kg ha^{-1}	CF, %
Litter	2 (1)	0 (0)	100 (0)	3806 (271)	817 (152)	79 (3)	1490 (194)	66 (12)	95 (3)	3092 (311)	175 (33)	92 (3)
Grass-dormant	2089 (141)	0 (0)	100 (0)	980 (147)	0 (0)	100 (0)	2424 (288)	12 (2)	100 (0)	587 (86)	0 (0)	100 (0)
Grass-green	1025 (103)	9 (2)	99 (0)	207 (94)	0 (0)	100 (0)	38 (14)	1 (0)	100 (0)	84 (22)	1 (1)	100 (0)
Total grass	3113 (198)	9 (2)	100 (0)	1187 (183)	0 (0)	100 (0)	2462 (286)	12 (2)	100 (0)	671 (91)	1 (0)	100 (0)
Dicots	0 (0)	0 (0)	...	158 (52)	0 (0)	100 (0)	169 (33)	0 (0)	99 (1)	74 (20)	1 (0)	98 (1)
Tree/shrub leaves	0 (0)	0 (0)	...	45 (16)	10 (3)	83 (12)	114 (37)	14 (4)	86 (12)	26 (9)	11 (2)	55 (12)
Wood debris*												
0 - 0.64 cm	...	...	...	227 (50)	214 (50)	6 (6)	36 (15)	0 (0)	100 (0)	606 (64)	82 (23)	84 (5)
0.64 - 2.54 cm	...	...	...	325 (75)	325 (75)	0 (0)	139 (27)	166 (43)	0 (0)	521 (58)	188 (40)	70 (7)
2.54 - 7.62 cm	...	...	...	46 (23)	46 (23)	0 (0)	231 (48)	210 (52)	11 (11)	0 (0)	0 (0)	-
> 7.62 cm	...	...	...	0 (0)	0 (0)	...	2759 (790)	2014 (638)	27 (6)	122 (122)	112 (112)	22 (22)
Total wood debris	...	...	...	598 (102)	597 (102)	3 (3)	3165 (798)	2872 (696)	37 (8)	1249 (175)	413 (152)	73 (4)
Total fuel biomass	3164 (199)	9 (2)	99 (1)	5772 (328)	1523 (224)	74 (4)	7343 (708)	2958 (688)	71 (5)	5100 (396)	609 (152)	88 (2)
Ash		613 (114)			1000 (186)			1011 (188)			826 (153)	

Numbers given are mean values with standard errors in parentheses.
* Ranges refer to diameter of wood debris.

Table 5. Weather Conditions and Fuel Moisture at the Time of Burning, and Fire Behavior Associated With Prescribed Burning of Four Late-Winter Biennial Burning Plots in Lowveld Sour Bushveld Savanna at the Kruger National Park, South Africa

Parameter	Kambeni 5	Faai 1	Numbi 4	Shabeni 1
Date of burn	6, Aug. 1992	7, Aug. 1992	13, Aug. 1992	14, Aug. 1992
Temperature, °C	25	31	23	24
Relative humidity, %	44	19	28	25
Wind speed, km h^{-1}	0-3	0-1	5-7	0-1
Wind direction	N	N-NE	NE	NW-NE
General conditions	clear	clear	clear	clear
Moisture content, %				
Litter	4.4 (1.4)	6.7 (0.4)	9.9 (0.2)	5.6 (0.6)
Grass	12.6 (5.0)	21.4 (16.4)	26.2 (7.4)	13.0 (2.4)
Tree/shrub leaves	104.4 (5.0)	106.8 (4.5)	110.7 (5.1)	107.9 (2.1)
Dung	55.8 (11.3)	48.7 (18)	5.6 (1.0)	3.8 (0.7)
Wood 0 - 0.64 cm diameter	5.0 (0.3)	3.7 (0.7)	9.5 (0.7)	2.8 (0.1)
Wood 0.64 - 2.54 cm diameter	10.3 (0.9)	5.7 (0.8)	10.2 (1.0)	5 (0.6)
Surface soil (0 - 2.5 cm)	14.5 (1.2)	9.6 (0.3)	nd*	1.3 (0.2)
Subsurface soil (2.5 - 10 cm)	12.1 (0.7)	3.9 (0.4)	nd	6.3 (5.0)
Fire behavior				
Flame length, m	3 (1)	1 (0)	3 (1)	2 (0)
Flame height, m	3 (0)	1 (0)	2 (1)	1 (0)
Flame depth, m	4 (1)	1 (0)	4 (1)	1 (0)
Rate of spread, m s^{-1}	0.4	0.2	0.2	0.2
Residence time, s	8 (1)	8 (0)	5 (1)	11 (1)
Fire intensity, kW m^{-1}	2414 (313)	475 (78)	1103 (213)	1209 (160)

Moisture and fire behavior data are mean values with standard errors in parentheses.
* No data.

The two large blocks and Kambeni E were burned during September 18 to 24, 1992 (Table 7). The Kambeni E plot was burned in an identical manner as previous small plots, but was initiated under cloudy conditions with very high relative humidity (60%). Ignition of the large burn blocks was similar to that of the small plots. An exception was the use of a propane burner towed behind a small truck to increase both lighting speed and the width of the fire break. Block 56 was burned under clear skies with high temperatures, low humidity, and strong NE winds, and block 55 under partly cloudy skies with a relative humidity of 40% and moderate winds.

Because of high relative humidity, litter moisture content was significantly higher at the Kambeni E plot compared to that measured at the other sites, as was the moisture content of 0.65 - 2.54 cm diameter woody fuels and the 2.5 - 10 cm soil depths. Grass moisture content ranged from 8% in block 55 to 17% in Kambeni E. Flame lengths were between 2 to 4 m at Kambeni E and block 55, and flaming front rate of spread ranged from 0.2 m s^{-1} in Kambeni E, to 0.7 m s^{-1} in block 55 (Table 7). Mean fire intensity was 1419 kW m^{-1} at Kambeni E and 6130 kW m^{-1} in block 55. In contrast, the combination of extreme fire weather conditions and a fairly continuous fuel bed produced flame lengths of 4 to 5 m and a rate of spread as great as 1 m s^{-1} in block 56. However, the direction and rapid rate of flame advance prevented us from obtaining more than one observation.

Table 6. Weather Conditions and Fuel Moisture at the Time of Burning, and Fire Behavior Associated With Prescribed Burning of Three Early-Spring Biennial Burning Plots in Lowveld Sour Bushveld Savanna at the Kruger National Park, South Africa

Parameter	Faai 4	Kambeni 3	Shabeni 5*
Date of burn	10, Sept. 1992	11, Sept. 1992	15, Sept. 1992
Temperature, °C	29	28	33
Relative humidity, %	32	40	24
Wind speed, km h^{-1}	3-8	5-8	6-10
Wind direction	N-NE	NE	NE
General conditions	clear	clear	clear
Moisture content, %			
Litter	3.9 (0.2)	4.0 (0.1)	nd
Grass	14.9 (2.3)	9.5 (0.5)	nd
Tree/shrub leaves	107.8 (1.5)	107.2 (6.5)	nd
Dung	3.1 (0.3)	2.9 (0.1)	nd
Wood 0 - 0.64 cm diameter	1.4 (0.2)	5.5 (0.1)	nd
Wood 0.64 - 2.54 cm diameter	5.6 (0.5)	6.2 (0.2)	nd
Surface soil (0 - 2 cm)	0.3 (0.1)	0.4 (0.1)	nd
Subsurface soil (2 - 10 cm)	0.5 (0.1)	0.7 (0.1)	nd
Fire Behavior			
Flame length, m	1 (0)	6 (1)	4 (1)
Flame height, m	1 (0)	5 (1)	4 (1)
Flame depth, m	1 (0)	4 (1)	3 (0)
Rate of spread, m s^{-1}	0.2	0.6	0.4
Residence time, s	10 (1)	5 (0)	5 (1)
Fireline intensity, kW m^{-1}	480 (52)	3579 (323)	2722 (785)

Moisture and fire behavior data are mean values with standard errors in parentheses.
* Data for moisture content lost in oven fire (nd denotes no data).

3.2.2. Zambia. Prescribed burning was conducted between August 24 and September 3, 1992 (Table 8) around midday (1100-1400 hours) by local agriculturalists using dry grass to ignite the fires. All sites were rapidly ignited across the upwind side of the site to produce a heading fire, and the duration of flaming combustion generally lasted < 20 min. Ambient air temperatures at the time of burning ranged from 27° to 31°C among all sites (Table 8). Relative humidity ranged from 17 to 26% at the sites near Kasanka but was only 9% at the semiarid miombo site near Choma. Wind speed was typically between 0 and 10 km hr^{-1}. All other weather conditions were similar at the time of burning among the sites.

Soil moisture content was very low. The 0 - 2.5 and 2.5 - 10 cm depths ranged between 0.3 and 2% among all four sites (Table 8). Litter moisture content at the moist miombo and fallow chitemene was 8 to 9%, and was 6% higher than that measured at the semiarid miombo site. Moisture content of fine woody debris ranged between 4 and 13%, while the moisture content of grass was between 8 and 16% at all sites. Tree/shrub leaf moisture content ranged from 107% in the semiarid miombo, to 130% in the fallow chitemene site.

Average flame lengths ranged from 2 m at the moist miombo site to 5 m in the dambo site (Table 8). Rates of fire spread were similar in both miombo sites and in the

Table 7. Weather Conditions and Fuel Moisture at the Time of Burning, and Fire Behavior Associated With Prescribed Burning at Three Sites With Distinct Burning Frequency Histories in Lowveld Sour Bushveld Savanna at the Kruger National Park, South Africa

Parameter	Block 56	Block 55	Kambeni E
Date of burn	18, Sept. 1992	24, Sept. 1992	22, Sept. 1992
Temperature, °C	31	26	21
Relative humidity, %	24	41	60
Wind speed, km h^{-1}	8-14	6-8	8-11
Wind direction	NE	NE	NE
General conditions	clear	scattered clouds	cloudy
Moisture content , %			
Litter	3.3 (0.6)	3.5 (0.2)	8.6 (0.2)
Grass	10.9 (1.3)	8.1 (1.5)	16.8 (2.2)
Tree/shrub leaves	144.4 (21.5)	...	102.7 (10.6)
Dung	3.1 (0.6)	10.5 (4.7)	8.4 (1.7)
Wood 0 - 0.64 cm diameter	5.2 (0.2)	6.1 (0.3)	6.8 (0.4)
Wood 0.64 - 2.54 cm diameter	4.5 (0.5)	5.8 (1.0)	8.1 (0.1)
Surface soil (0 - 2 cm)	0.4 (0.1)	0.2 (0.0)	0.6 (0.1)
Subsurface soil (2 - 10 cm)	0.3 (0.1)	0.3 (0.0)	0.7 (0.0)
Fire behavior			
Flame length, m	4-5	4 (0)	2 (0)
Flame height, m	3	2 (0)	1 (0)
Flame depth, m	5	3 (0)	1 (0)
Rate of spread, m s^{-1}	1	0.8	0.2
Residence time, s	1-2	6 (1)	5 (0)
Fireline intensity, kW m^{-1}	5225	6130 (729)	1419 (320)

Moisture and fire behavior data are mean values with standard errors in parentheses.

fallow chitemene (0.1 to 0.5 m s^{-1}), but the rate was much more rapid (0.8 m s^{-1}) in the dambo. Fire intensity ranged from 1734 kW m^{-1} in the semiarid miombo to 4061 kW m^{-1} in the dambo.

3.3. Fire Effects

3.3.1. South Africa. In the late-winter burn plots, the consumption of the total aboveground fuel load was dramatically lower in the Faai 1 plot (44%) compared with that in all other late-winter burn plots (76 to 87%) (Table 1). Litter consumption ranged from 64 to 92%, while more than 94% of the total grass fuel load was consumed by fire at all plots. In contrast, the consumption of woody fuels was somewhat more variable than that of the other components. For example, total woody debris consumption at Faai 1 was 3% and ranged from 20 to 60% in the other plots.

Among the early-spring plots, total aboveground fuel consumption was 67 and 95% at Faai 4 and Kambeni 3, respectively (Table 2). Litter and grass consumption exceeded 98%, while from 14 to 29% of the total woody debris was consumed. Although the percent total woody debris consumption was greater at Shabeni 5, the mass of residual woody debris was higher as well.

In the three distinct burning- frequency history sites, 83 to 91% of the total aboveground fuel load was consumed (Table 3). While there were no measurable differences in the percent nonwoody fuel consumption among the sites, postfire litter biomass in Kambeni E (392 kg ha^{-1}) was

Table 8. Weather Conditions and Fuel Moisture at the Time of Burning, and Fire Behavior Associated With Burning in Three Moist Savanna Sites Near Kasanka National Park, Zambia, and a semiarid Savanna Woodland Near Choma, Zambia

Parameter	Dambo Grassland	Moist Miombo Woodland	Fallow Chitemene	Semiarid Miombo Woodland
Date of burn	25, Aug. 1992	24, Aug. 1992	27, Aug. 1992	3, Sept. 1992
Temperature, °C	31	29	27	30
Relative humidity, %	17	18	26	9
Wind speed, km h^{-1}	6-8	0-3	6-11	5-10
Wind direction	SW-NE	SW	E	E
General conditions	clear	clear	clear	clear
Moisture content, %				
Litter	np*	9 (1.2)	7.6 (2.0)	2.5 (0.2)
Grass	10 (2.9)	15.7 (3.4)	15.4 (3.7)	7.6 (0.3)
Tree/shrub leaves	np	115 (8.9)	130.1 (2.8)	107.6 (9.3)
Wood 0 - 0.64 cm diameter	np	4.8 (0.4)	7.2 (1.0)	4.0 (0.1)
Wood 0.64 - 2.54 cm diameter	np	5.8 (1.1)	13.1 (6.6)	4.7 (0.3)
Surface soil (0 -2.5 cm)	0.3 (0.1)	1.0 (0.1)	0.3 (0.0)	0.7 (0.0)
Subsurface soil (2.5 - 10 cm)	1.4 (0.4)	2.1 (0.0)	1.5 (0.2)	0.9 (0.1)
Fire behavior				
Flame length, m	5 (1)	3 (0)	4 (1)	3 (1)
Flame height, m	4 (0)	2 (0)	3 (0)	2 (0)
Flame depth, m	3 (1)	3 (0)	4 (0)	3 (1)
Rate of spread, m s^{-1}	0.8	0.4	0.3	0.3
Residence time, s	4 (0)	10 (1)	8 (1)	11.5 (1)
Fireline intensity, kW m^{-1}	4061 (352)	2670 (385)	3375 (491)	1734 (322)

Moisture and fire behavior data are mean values with standard errors in parentheses.
* Not present.

from 7.4 to 49 times greater. While total woody debris consumption ranged from 32 to 49%, more than 75% of the fine woody debris was consumed. Mean shrub leaf consumption ranged from 10 to 86% in the late-winter burn plots (Table 1). In contrast, 100% of the shrub leaf biomass was consumed at block 56 and in the early-spring burn plots at Kambeni and Shabeni (Table 2). Dung consumption exceeded 85% at all sites.

The mass of ash ranged from 59 to 609 kg ha^{-1} in the late-winter plots (Table 1) and from 125 to 283 kg ha^{-1} in the early-spring burn plots (Table 2). Among the three distinct burning- frequency history sites, ash mass ranged from 362 kg ha^{-1} in block 56 to 773 kg ha^{-1} at the Kambeni E plot (Table 3). Unstable surface winds strongly influenced ash distribution following fires at all sites.

3.3.2. Zambia. Essentially 100% of the grass fuel load was consumed by fire in all sites (Table 4). Greater than 90% of the litter component was consumed by fire at the semiarid miombo and fallow chitemene sites, compared to 79% at the moist miombo site. In contrast, total woody debris consumption ranged from 3% in the moist miombo to 71% in the semiarid miombo site. After burning, residual wood debris ranged from 413 kg ha^{-1} at the semiarid miombo site to 2872 kg ha^{-1} at the fallow chitemene site, and large quantities of uncombusted litter were measured at the moist miombo (817 kg ha^{-1}). Total residual biomass in the fallow chitemene (2958 kg ha^{-1}) was > 1.9 times higher than that of all other Zambian sites. Consumption of shrub leaves ranged from 55 to 86% at the semiarid miombo and fallow chitemene sites, respectively.

While the mass of ash measured at the moist miombo and fallow chitemene sites was similar (1000 and 1011 kg ha^{-1}, respectively), ash mass remaining immediately after burning in the dambo site was 613 kg ha^{-1} and 826 kg ha^{-1} in the semiarid miombo site.

4. Discussion: Fuels and Fire

4.1. South African Savannas

In the savannas of southwestern Kruger National Park, South Africa, total above-ground fuel loads ranged from 3567 to 5492 kg ha^{-1} where fire return intervals were 2-4 years and exceeded 7000 kg ha^{-1} at a site subjected to 38 years of fire exclusion. *Frost and Robertson* [1987] reviewed several studies reporting aboveground fuel loads in African savannas and found values ranging between 4200 and 9000 kg ha^{-1}, including downed woody debris. Fuel loads in our study were slightly lower and likely resulted from a severe drought during the 6 years prior to our study.

Dormant grass and litter were the dominant fuel components, composing 70 to 84% of the total fuel load at all sites. The ratio of litter to grass was slightly higher in the late-winter burn plots in comparison to all early-spring burn sites with the exception of the Kambeni E plot, where the mass of litter exceeded that of grass by > 3000 kg ha^{-1}. The significantly greater mass of litter, increased density of trees, and lower grass loading in Kambeni E reflect the effects of fire exclusion on the distribution and quantity of fuels.

Because grass fuel loads are usually higher in moist savannas than in arid savannas, fire frequency and fire intensity in moist savannas are typically higher [*Huntley*, 1984]. *Trollope* [1984] reported that in the Kruger National Park, fire intensity is greatest just before the onset of spring rains, a period when fuel moisture and relative humidity values are lowest and grasses are dormant. During our study, prefire moisture content of litter and downed woody debris was typically < 10% at all sites, and flame lengths averaged 4 m. However, high relative humidity and the consequent high moisture content of grass and litter were likely responsible for the low fire intensity at Kambeni E, even though fine fuel loads were high.

The importance of factors other than fuel load should be considered in the interpretation of fire behavior and fire effects in savannas. *Trollope et al.* [1990] reported that average shrub and tree mortality associated with 43 fires of variable intensities (110-6704 kW m^{-1}) was only 1.3% across a broad range of savanna areas in the Kruger National Park and that the primary effect of those fires on woody vegetation was the top- kill of stems and branches. Many of these plants then coppice from the collar region at the base of the stem, a trait often indicative of woody vegetation subjected to frequent fires.

Grazing strongly influences the quantity, structure, and composition of potential fuel loads. *Trollope et al.* [1989] suggested that grass fuel loads < 4000 kg ha^{-1} will not generate the severe fire behavior required to control encroachment of woody vegetation and maintain a dominant grass component. In sourveld communities, grass is palatable to ungulates only 4 months out of the year [*Edwards*, 1984], often resulting in high accumulations of plant material and thus greater fuel mass. However, during periods of drought, sourveld may be subjected to more intense grazing when preferred forage is no longer available. Grass biomass in block 56 and the Faai early-spring burn plot was much less than that of the other early-spring burn sites, and an established network of animal trails was apparent in both areas. *Van Wyk* [1971] suggested there may be difficulties assessing the effects of fire on the small plots owing to the confounding impacts of grazing. Large game animals can also influence fuels in ways other than herbivory. We observed elephants downing trees and breaking large branches that added surface fuels in areas near the study sites. Trampled grass and persistent trails can directly affect the flaming- front rate of spread, and therefore fire intensity. For example, animals had visibly impacted the Faai 4 plot, and the average fire intensity was 480 kW m^{-1}. During fires at the other early-spring burn plots, Kambeni E, and block 55 (where animal impacts were less pronounced) we calculated fire intensities ranging between 1419 and 6130 kW m^{-1}. However at block 56, wind speeds were high and fuel moisture was very low and may have masked the effects of fuel discontinuity on fire behavior.

The woody fuel component has seldom been measured in studies investigating fire in African savannas. Although *Delmas et al.* [1991] suggested that the woody fuel component may be negligible in certain savannas, downed and dead woody debris composed 15 to 35% of the total fuel load on our sites (844 to 1227 kg ha^{-1}). However, downed and dead coarse woody debris was absent on all sites except block 55. One explanation is that the intake of grass and tree branches by one 2500-kg elephant may exceed 170 kg d^{-1} [*Ruggiero*, 1992]. But throughout most tropical savannas rapid decreases in woody debris contacting soil surfaces are likely attributable to termites [*Bourlière and Hadley*, 1983]. It is apparent that considerable variation exists between gains and losses of fuels from sources other than fire in savanna communities. In the Kruger National Park, animals and insects may strongly influence fuels and hence fire behavior characteristics owing to herbivory, trampling, additions of woody debris, and dung production.

In this study, fire consumed 42 to 83% of the 0 - 0.64 cm diameter woody fuels, but <50% of the 0.64 - 2.54 cm diam. fuels at all sites. Because of the unevenness associated with the distribution of woody fuels, the amount of woody fuel consumption was dependent on internal fuel moisture and close proximity to dense accumulations of readily combustible fine fuels. While woody debris consumption did not contribute significantly to the total mass of fuels consumed, woody debris accounted for 627 to 996 kg ha^{-1} of the residual biomass. This represents 33 to 75% of the material composing the postfire aboveground biomass at these sites. The combustion factors of all nonwoody fuel components exceeded 85% with the exception of tree/shrub leaves. Moisture content of tree/shrub leaves ranged from 102-140%, and was likely a factor in limiting leaf consumption. Because the majority of fuels are easily ignited owing to a high surface to volume ratio (i.e., fine woody debris, grass, litter, and herbaceous components), the majority of the biomass was rapidly consumed following the initial passage of the flaming front. Because there were few coarse fuel particles, there was very little smoldering combustion. However, consumption of animal dung occurred primarily through the process of smoldering combustion. Smoldering combustion processes in large dung piles typically lasted 30 to 90 min following passage of the flaming front. Although dung was not a significant fuel component on a mass basis, chemical compounds in the smoke and ash produced during dung combustion may be important emission constituents. Products of incomplete combustion occur primarily during the smoldering combustion process [*Ward and Hardy*, 1991].

Few studies have quantified ash mass following savanna fires. In our study, the mass of ash measured immediately after burning ranged from 2 to 135% of that remaining as uncombusted biomass. Although grass fuel loading is often the primary focus of many savanna fuels studies, all fuel components should be considered in terms of their susceptibility to combustion and hence subsequent contribution to the ash profile [*Kauffman et al.*, 1993]. For example, both block 55 and Kambeni E had significantly higher prefire litter mass compared to all other plots, and litter consumption was >90% at block 55 and at Kambeni E. Consequently, each had much greater ash loads. It follows that ash nutrient content, and therefore nutrient cycling, may be strongly influenced by the chemistry of the individual fuel components, fire behavior (particularly fire intensity), and the degree of fuel consumption.

4.2. Zambian Savannas

Intentional fires are commonly set during the long dry season in Zambia and are primarily associated with shifting agricultural practices [*Peters*, 1950; *Stromgaard*, 1984; *Chidumayo*, 1987b]. These frequent, and often free-ranging fires, generally consume large quantities of dry herbaceous vegetation and other surface fuels and therefore influence Zambian savanna ecosystem structure. Because the degree of agricultural activities and land- use history varied among the sites in this study, there were important differences in vegetational composition and consequent fuel loads.

In the dambo, the predominance of grass provided a continuous fuel bed that directly affected fire behavior. In contrast, only 13 to 20% of the total fuel mass in the miombo sites was grass. Although the quantity of available fuels was substantially lower in the dambo, there was 100% consumption of all fuels, and fire behavior (in terms of fire intensity, rates of spread and flame lengths) was of greater severity than that in the fallow chitemene site and both miombo woodland sites. Complete consumption of fuels in the dambo had occurred within minutes after passage of the flaming front, whereas smoldering combustion of coarse wood debris continued for > 4 hours at the moist miombo and fallow chitemene sites. In these sites, total fuel consumption was 1107 to 2049 kg ha^{-1} greater than that in the dambo.

Total aboveground fuel biomass in the fallow chitemene was notably greater than that of all other sites owing to the large quantity of coarse woody debris (3165 kg ha^{-1}). Although grass biomass and fire behavior in the fallow chitemene were comparable to the dambo, the abundance of litter, live vegetation, and woody debris was considerably different.

In the miombo woodland sites, the mass of litter was much greater than that in the fallow chitemene and dambo, while the mass of woody debris and grass was much lower. This is not surprising considering the high density of trees in the woodland areas (1093 and 1222 trees ha^{-1}). *Malaisse* [1978] measured a mean leaf biomass production rate of 2900 kg ha^{-1} yr^{-1} in a Zairean miombo woodland. Similarily, *Chidumayo* [1990] reported a mean leaf biomass of 3333 kg ha^{-1} in an old- growth miombo woodland in the Copperbelt region of Zambia. Because miombo woodland is deciduous, mean leaf biomass can be assumed to represent the annual contribution of leaf material to the litter profile. In this study, litter biomass was 3092 and 3806 kg ha^{-1} in the miombo woodland sites.

We estimated the mass of litter, grass, and herbaceous biomass to be 5174 kg ha^{-1} in the moist miombo and 3851 kg ha^{-1} in the semiarid miombo. *Rutherford* [1978] reported a total herbaceous production of 4800 kg ha^{-1} yr^{-1} in a central African miombo woodland. These estimates are in good agreement given a 1 year fire- return interval and probable differences in precipitation and hence biomass production but do not account for internal decomposition. The most apparent difference between fuel loads of the moist miombo and semiarid miombo sites was the mass of woody debris (598 and 1249 kg ha^{-1}, respectively). Although combustion factors of litter and woody fuels in the semiarid miombo were substantially greater than those of the moist miombo, fuel loads of all other fuel components were comparable. Ash mass was considerably greater in moist miombo; burning in the semiarid miombo resulted in a much higher percentage of total aboveground fuel consumption. However, there were few differences in the actual mass of fuels consumed. This may be indicative of greater convective losses of ash due to more extreme fire behavior (i.e., greater fire line intensity) in the moist miombo.

Recent land- use activities were quite dissimilar between the miombo sites. For example, collection of fuelwood by local residents resulted in total removal of 2.54 - 7.62 cm diameter woody debris in the semiarid miombo. Human impacts on miombo woodlands are often reflected in the arrangement and mass of the various fuel components and on microclimatic conditions. Relative humidity was 9% immediately prior to burning in the semiarid miombo compared to 18% at the moist miombo site and 26% in the fallow chitemene, while moisture content of all nonliving fuel components was also lower in the semiarid miombo and fallow chitemene. These differences demonstrate the dynamic relationship between environmental conditions, fuel moisture content, and potential fuel consumption.

5. Summary and Conclusions

Fuel characteristics, prevailing environmental conditions, fire behavior, and fuel consumption were quantified in selected savanna ecosystems of southern Africa. In semiarid savannas at Kruger National Park, South Africa, the mean total aboveground fuel load was 4295 kg ha^{-1} at sites burned every 2 to 4 years. On average, 98% of the available grass fuels were consumed while 32% of downed and dead woody fuels were consumed. Heavily concentrated groups of indigenous and/or domestic ungulates may alter successional patterns through the reduction of fine fuels required to carry a fire. Sites with evidence of intense trampling and grazing had a total fuel consumption ranging from 44 to 72%, while combustion factors of more than 80% were measured among nonimpacted sites.

Past and present land- use practices have important influences on fuel characteristics. At a relatively undisturbed moist miombo woodland site in north- central Zambia, the total fuel mass was 5772 kg ha^{-1}, but it was 7350 kg ha^{-1} in a site slashed 4 years earlier for use in shifting cultivation. Woody debris accounted for 43% of the total fuel load in the slashed woodland but was a relatively minor fuel component in savanna parkland sites of South Africa and nonagricultural sites in Zambia. Human-caused fires commonly occur annually or biennially throughout Zambia during the dry season. A combination of low relative humidity, low fuel moisture content, and a large surface-to-volume ratio for the predominant fuel particles has a substantial effect on fire behavior and fuel consumption. A combustion factor of 100% was measured for the total aboveground fuel in a Zambian hydromorphic grassland that burned under comparable conditions.

This study suggests a distinct relationship between vegetational composition, environmental conditions, land-use patterns, and fire regimes in African savanna ecosystems. These factors influence the quantity, distribution, and moisture content of savanna fuels and thus directly influence ignition potential, fire behavior, and emissions chemistry. The study clearly illustrates the complexity and existent variability of African savannas. Comprehensive fuel biomass estimates from these ecosystems are necessary in order to determine current global emissions budgets. Results from this research should provide valuable inputs to current regional, national, and global biogeochemical research efforts and therefore to a more comprehensive global change assessment by the international scientific community.

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C. I. Haskins and M. C. Scholes, Botany Department, University of the Witwatersrand, Johannesburg, South Africa.
J. B. Kauffman, Department of Fish and Wildlife, Oregon State University, Corvallis, OR 97331.
B. W. Shea and R. W. Shea, 2855 NW Johnson Avenue, Corvallis, OR 97330.
D. E. Ward, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, P.O. Box 8089, Missoula, MT 59807.

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