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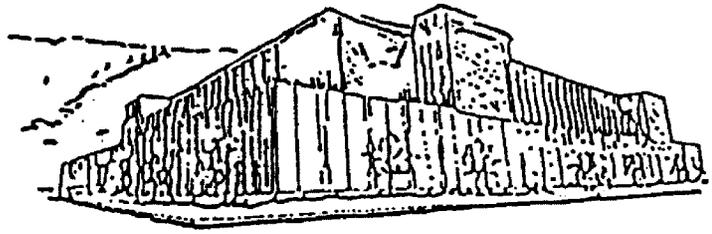
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EARLY DRY SEASON BIOMASS BURNING
IN THE DAMBO AND MIOMBO OF ZAMBIA

by

Erica Ann Hoffa

B.S. Tufts University, 1995

presented in partial fulfillment of the requirements

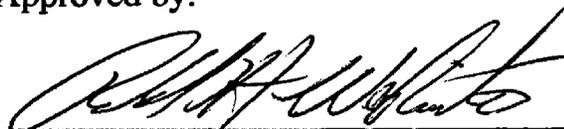
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Master of Science

The University of Montana

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Early Dry Season Biomass Burning of the Dambo and Miombo of Zambia

Director: Ronald H. Wakimoto



African savannas have been the focus of several recent international campaigns to study the quantity of burned biomass and its effects on tropical and global atmospheric chemistry and regional ecosystem dynamics. However, to assess the fire regime it is necessary to understand the fluxes of emissions at ground level and how those fluxes vary throughout the burning season. It has been hypothesized that because the moisture content of vegetation is higher early in the dry season, fires are less intense than later in the season, producing different products of combustion.

Given recent management directives that encourage early season burning in preference to potentially damaging late season burning, the effects of early season emissions may become significant. Additionally, to predict future fire regimes and the resultant emissions, one must discern the causal effects of fire use, i.e. population pressure and/or development and management objectives; together, these factors will influence land use, and ultimately, fire frequency and seasonality.

Fourteen two hectare plots were established in Western Province, Zambia, six in a deciduous open-canopy woodland (miombo) and eight in a seasonally waterlogged grassland (dambo) to determine fuel biomass combustion, fire behavior, and combustion efficiency of early season fires and to correlate these measures of fire intensity with measurements of fuel moisture content. Vegetation was sampled pre-fire for dry weight biomass and moisture content. Fires were lit throughout the season at subsequent plots in the two study sites. Fire behavior was observed, and Fire-Atmosphere-Sampling-System towers collected the emissions, from flaming and smoldering phases of combustion. Post-fire, the plots were re-sampled for remaining biomass and the collected emissions were analyzed.

Linear regression analysis of combustion factors and modified combustion efficiency values on fuel moisture content provide evidence that this relationship is significant. This study will assist efforts to predict regional emissions based on phenology.

“It is generally agreed that one of the best ways of protecting and managing miombo woodlands is to carry out early burning, that is, to burn patches of grass and undergrowth in the early dry season before the grass gets too dry in order to avoid more-intense, more-damaging fires later in the season...However, Morris (1995) states that in Malawi the burning of the woodland at the end of the dry season has both pragmatic value and symbolic significance. Burning of the bush has significance in the regeneration of the cosmic cycle and the subsequent coming of the rains (Schoffeleers 1971). People burn the bush for preparing their gardens for planting, hunting animals and calling the rains. In Malawian cosmology the appearance and the movement of the rains and bush fires appear to replicate a cyclical movement between sky and earth which is associated with a similar movement of the spirits. Fires establish on earth a mirror image of the desired conditions in the sky. They are manifestations of ancestral spirits representing their ascent to the sky in their capacity as rain providers...Morris (1995) rests his case by explaining that burnt woodland is referred to as lupsya; the verb ku-psya meaning not only to cook, roast or burn, but also to ripen,”(Coote in Campbell 1996).

“Since the first suggestions that biomass burning could be a significant factor in global emissions of atmospheric trace gases (Crutzen et al. 1979), the available evidence has increasingly indicated that biomass burning in its various forms represents a major perturbation of atmospheric chemistry comparable in magnitude to the effects of fossil fuel burning,” (Lindesay et al. 1996).

PREFACE

Early dry season biomass burning is an issue that cannot be investigated without a interdisciplinary effort at local, regional, and global scales. The need to study the effect of early season burning is crucial given the recent acknowledgment of the role of anthropogenic disturbance on terrestrial-atmospheric fluxes. In particular, increased fire use in developing countries is contributing to a significant perturbation of atmospheric chemistry at local, regional, and global scales. There is also evidence to believe that increased fire use is resulting in a perturbation of savanna ecosystem dynamics. Should early burning be carried out, as is advocated by land managers, these effects may be lessened by less intense, less damaging, fires in preference to those in the late season. On the other hand, it is unclear what effect moister vegetation in the early dry season will have on the type of emissions; it is also unclear how the overall quantities of emissions of trace gases and aerosols will be affected by early season burning. Furthermore, to what extent will a change in the fire regime challenge indigenous agriculture or other woodland activities? How will a change in the fire regime affect miombo and dambo ecological dynamics? Consideration of many of these questions is necessary, given an understanding of the way fire behavior affects emissions. They must be understood before new fire management policy can be advocated.

This work is an attempt to parameterize early season burning. It is based upon a field season of scientific investigation of emissions in Zambia, and an evaluation of the way fire behavior affects emissions. The study was completed in Zambia because recent field campaigns to investigate late season burns in southern Africa were held there in

previous years, offering the potential to compare the results. It is also a country with a high level of fire use and significant development pressures which necessitate fire management. Chapter 1 is an introductory chapter, presenting the role of fire in a savanna ecosystem, the current uses of fire in Zambian savannas, the fire effects and emissions potential, a history of previous international campaigns to evaluate biomass burning in Southern Africa, and an overview of the study's objectives. Chapter 2 will briefly introduce the political and social history of Zambia and the effects of development pressures by First World countries on the fire regime. Chapter 3 is an analysis of the proportion of fuels that are consumed by fires which occur in the early dry season. They are correlated with measurements of vegetation conditions and fire behavior taken during the field campaign. Chapter 4 carries the work of Chapter 3 further by using estimates of vegetation moisture content to evaluate the combustion efficiency of the burn. This latter parameter has wide implications for the potential to predict emissions from burning in the early dry season. Chapter 5 is a discussion of the study as it relates to fire management of miombo and dambo ecosystems in Zambia, especially with regard to early season burning and the social, cultural, and political implications of such management. It discusses the potential of this study and future studies to improve parameterization of global biogeochemistry models and ways to improve integrated fire management plans.

The integration of the field study completed between May and August 1996 (Chapter 3 and 4) with the analysis of both the development pressure and social rationale for biomass burning in Zambia (Chapter 2) is an important and necessary perspective with which to explore early dry season burning. Currently, scientific publications that discuss the role of emissions from biomass burning typically attribute widespread burning

in the tropics to shifting cultivators and population pressure without further explanation. In Chapter 2, I explore other potential causes of biomass burning in Zambia and socio-economic and cultural rationales for existing land use practices. A thorough understanding of the causes and rationale for land use practices, in combination empirical studies of biomass burning processes and effects, is necessary for predicting trends in emissions and for developing management plans that are responsive and effective.

ACKNOWLEDGMENTS

Many thanks are due to those who have made this project a success. I would like to thank the EPA and the Intermountain Fire Sciences Laboratory (IFSL) of the USDA Forest Service, Missoula, MT, which supplied collaborative funding for this university research through INT-95136-RJVA. Particularly, I would like to thank Darold Ward, project leader of Fire Chemistry, IFSL, for his inspiration, dedication, and advice, in and out of the field. Thank you to Ronald Susott for help with field work and technical assistance. Also, I would like to thank most sincerely my committee: Wei Min Hao at the IFSL, and Steve Siebert and Lloyd Queen in the School of Forestry, University of Montana, for their patience, understanding, and guidance. Special thanks to my graduate advisor and committee chair, Ronald Wakimoto, for his advice and assistance, and for the shipment of herbal tea. Many thanks must also be directed to my Zambian friends without whom this project would have been impossible. Especially invaluable were Gertrude Mubita and Sam Mubita who assisted me in the field and lab through many long, hot days. Their good cheer and unswerving commitment to the project made the work a true joy. Thanks, too, to our workers who dug the many firebreaks by hand, watched our equipment overnight, and offered immeasurable assistance and dependability. I would also like to thank the members of the Forestry Department, Kaoma, for the use of the land and the laboratory room. To Frank Mtonga, thank you for your field assistance, driving prowess, and laughter. I am much indebted to my friends in Montana who supported me through my time away and through the writing process, particularly Sandy Kollenberg, Kathy Hibbard, Bill Patterson, Jim Plummer, Lara Soward, and, Lisa Troy. Special thanks and love to Pearce Smithwick and my family.

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INTRODUCTION

1.1. HISTORICAL FIRE/SAVANNA INTERACTIONS

There can be little doubt that the present floristic composition of very large areas of African tree savanna is, to a marked degree, the result of many centuries of selection through frequent man-made fires (Innes 1971, 157).

It is difficult to separate processes that may have given rise to savannas in the past from those that can be shown to maintain them at the present (Harris 1980, 20).

The term "savanna" originates from descriptions of the Indies landscape by Oviedo y Valdes to describe "land which is without trees but with much grass either tall or short," (Cole 1986). Later, the term "sabana" or "zabana" was adopted by Columbus and his followers from the Arawak people of the Greater Antilles. Here the word described "an open-canopy association of grasses and trees...a park-like landscape with mature trees scattered throughout," (Harris 1980). Today, the word refers to a multitude of environments with structural and physiological differences ranging from shrub expanses to open-canopy forests. The central characteristic, however, is a dominant grass under story i.e., "those tropical and some near-tropical ecosystems characterized by a continuous herbaceous cover consisting mostly of heliophilous C₄ grasses and sedges that show clear seasonality related to water stress. Woody species (shrubs, trees, palms) occur but seldom form a continuous cover paralleling that of the grassy layer," (Frost et al. 1986). Local differences in soil structure, texture, and fertility are combined with climatic variations based on altitudinal and latitudinal gradients to provide countless global definition variations, i.e. the llanos of Venezuela, the cerrado of Brazil, and of primary concern with this work, the dambo and miombo of Zambia. Savanna systems

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account for 10 million km² in tropical Africa (Hao and Liu 1994). Historically, they have provided resources in times of stress, when social and cultural changes (perhaps in association with climate change) have not been in balance with the needs of the people, (Clark in Harris 1980). Even in favorable times, the human-savanna interface has always been critical to survival. The savanna-water interface is particularly important for the seasonally arid conditions of the savanna environment (Harris 1980). Savannas are also important for hunting, non-timber forest products, and fuel harvesting. The grass understory provides areas for agricultural production and livestock grazing. Aside from trampling by elephants, anthropogenic disturbances such as fire are perhaps some of the major defining characteristics of the present savanna mosaic (Cole 1986; Guy 1989).

Recent concern for the stability of these ecosystems, given human dependence upon them, has been prompted by an increasing awareness of human impact. Interpretations of satellite imagery has alluded to the prevalence of biomass burning in the tropical and sub-tropical savannas (Justice et al. 1996; Kaufman et al. 1990) thereby eliciting concern for the effects of large quantities of emissions not only at the regional scale, but increasingly, at the global scale. Concerns over human management of savanna systems have evolved into a recognition that such management has led to significant contributions of trace gases and oxidized compounds to the atmosphere, resulting in up to 25% of the global greenhouse forcing (Andreae 1991).

Dale et al. (1993) reported a modeling technique for Rondonia, Brazil which suggested that land-use history, land-use choices (agriculture or pasture), and market conditions interacted with ecological conditions to control land-use change in that area

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during the past two decades. Indeed, development of climax savanna ecology may be due to interacting socio-economic and ecological factors: soil conditions, geomorphology, climate, and agricultural fire use (San José and Medina 1975).

Some researchers of tropical Africa define savannas as primarily being formed by regular and repeated anthropogenic fire intervals while others argue that anthropogenic fire is a secondary characteristic (Cole 1986; Lamprecht 1986). Those who claim fire is a secondary characteristic point to evidence that grasslands and savannas have been reasonably widespread since the Miocene without human-caused fires. They point to climatic factors that may have caused savanna formation, as evidenced in geological records. For example, the last Glacial period (75,000-10,000 B.P.) is distinguished by the retreat of forest conditions, shown in the palynological record of Lake Chad (Harris, 1980); the upper Pleistocene is then marked by a cooler and drier climate until 7,000 B.P. which resulted in the expansion of open woodlands and grasslands (Clark 1968; Clark in Harris 1980). A warm - cool cycle returned, developing the present mosaic of vegetation generally prominent for the previous 1000 years (Clark 1968).

Whether climatic cycles were the controlling factor or not, they certainly interacted with the extremely complex geologic history of the African plateau to provide the heterogeneous vegetation types that are apparent, even though their relative distribution is also affected by contemporary forces such as fire and elephants (Cole 1986). The current landscape of African bedrock that is inhabited by African savannas was predominantly formed in the late Triassic. After the breakup of Gondwanaland, the Zambezi River ceased to flow to the Atlantic Ocean and instead flowed to the Indian

Ocean. The pediplanation formed by this shift, and additional warping and uplift, created the poorly draining pediplains and sandy, lateritic soils that are currently occupied by *Brachystegia-Julbernardia-Isoberlina* (miombo) woodlands, (Cole 1986). Margins of these laterite systems that are occupied by a fluctuating water table are known as dambo grasslands.

These geologic and climatic forces have certainly shaped the African landscape. Nevertheless, humans have used fire to their advantage for much of the recent African history. Those who argue that this activity has been the predominant cause of savanna formation illustrate that Proto-hominid ancestors and humans have occupied tropical savannas of Africa for more than 2 million years, using fire as an active tool in food preparation (Andreae 1991). Fire was first used for protection and hunting in the volcanic land of the East African rift valleys and to promote animal grazing (Harris 1980; Clark in Harris 1980; Andreae 1991). During the Iron Age (3000 B.P.), pollen records show that agriculturists had restricted the importance of forest pollen in lake Ishiba in northern Zambia and the Lake Victoria basin; concurrent charcoal horizons in the Kalahari sands indicate anthropogenic fire use as the cause for these changes (Livingstone 1971), assuming that lightning-caused fires have remained at constant levels through this time.

At approximately this same time, the late Tertiary, there was a shift from pyrophobic vegetation (*Araucaria* spp.) to pyrotolerant and pyrophilic species (i.e. *Eucalyptus* spp.) (Andreae 1991). Continual fire use also resulted in the transition from forest to grassland. Grass fire corridors may have increased species diversity by separating refugia (Goldammer and Manan 1991) but may have also increased the amount

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of forest edge habitats as vectors for disease (Harris 1980). Fire also increased the available forage for grazing animals, enlarging the carrying capacity of the land and promoting continued grass evolution (Clark in Harris 1980).

African savannas typically occupy landscapes 0-20°S and 0-20°N latitude, at 1000-2000 meters above sea level, at nearly level or gently undulating slopes with drainage to a perennial river. Air and soil temperatures seldom fall low enough to inhibit vegetative growth despite occasional frost pockets. Quite distinctly, savannas occupy regions of strong seasonality, a specific wet and dry period. During the dry period which lasts between 2.5 to 7.5 months, vegetation becomes increasingly water-stressed until the onset of the rainy season (Harris 1980). The rain during the rainy season (whose timing varies at a particular location based on the path of the Intertropical Convergence Zone), arrives sporadically and episodically. Inter-annual precipitation variability is great (Harris 1980).

1.2. EFFECTS OF EXTENSIVE BIOMASS BURNING

Biomass burning in the tropics is of increasing concern for three major reasons: 1) ecological dynamics with regard to fire tolerance, 2) emissions and their effect on atmospheric chemistry and pollution, and 3) nutrient cycling, the latter which may be altered at the scale of an agricultural field or across a landscape.

1.2.1. Ecological Dynamics

In an attempt to describe briefly the ecological dynamics of African savannas under an increasing fire regime, I have focused on only two major topics: 1) fire effects in

savanna systems due to an intense fire regime, and 2) the ecological succession that may occur in the increasingly intense fire regime of Zambian savannas.

1.2.1.1. *Fire Effects*

Alexander (1982) defines fire effects as 1) biophysical alteration or population reduction due to immediate effects of fire and 2) post fire influences. This in turn is dependent on the intensity and efficiency of the burn and the fuel consumption. Fire effects are thus dependent on the heat of combustion, the amount of ash production, and the residual fuels.

Fires decrease the amount of aboveground biomass. Hao et al. (1996) estimated that average fuel loading in miombo woodlands is 4000 kg/ha in areas that are burned every year, 5500 kg/ha in areas not burned for 4 years, and up to 7100 kg/ha in areas not burned for over 28 years. Fires also may lead to the loss of 71% of the total organic matter present before the fire (Malaisse 1978). Fires that ultimately reduce canopy cover will cause an increase in soil temperatures and the mean daily temperature amplitude, decrease relative humidity, increase rain erosivity, and increase soil organic matter decomposition of the remaining surface litter (Malaisse 1978; Robinson 1988; Stromgaard 1989).

In general, fires that lead to grassland systems accelerate nutrient cycling by replacing long-lived trees, that have large carbon storage potential, with annual herbs and grasses, that have small carbon storage pools but rapid turnover. On the other hand, the development of a grass root system may help encourage underground carbon biomass and organic matter production leading to increased microbial production and nutrient storage

underground. Early season burning is presumably less intense due to the high moisture content of the vegetation. In such a fire regime, miombo dynamics may shift in favor of woody plants in preference to grasses. This would be in contrast to late season burns which eventually transform woodland ecosystems into open grass savannas (Frost 1996; Archer 1994).

However, there is presumably a wide range of fire responses in Zambian savannas due to the diversity of species within the miombo and the diversity of fire intensities. For example, species that are well-adapted to the long dry season have long tap roots, even as seedlings. Therefore, fires that occur during seedling stage may only burn the leaves, allowing the seedlings to survive (Trapnell 1959). Also, *Hyparrhenia* grasses release toxins that result in the suppression of emergent tree species (Boughey et al. 1964). Should these grasses become more prominent through late season fire practices, the effect of such allelopathy on tree regeneration is unknown. More work on the impact of fire with regard to soil and vegetation effects based on fuel loads and phenology is necessary to fully understand miombo ecosystem dynamics (Frost 1996).

1.2.1.2. *Succession*

It has been suggested that the *Brachystegia-Julbernardia-Isobertina* woodland (miombo) represents a transition ecosystem from fire-tolerant evergreen forests (muhulu), to *Acacia-Commiphora* bushlands (chipya), and then to grasslands, due to increasing fire and grazing (Malaisse 1978; Lawton 1978). A fire climax ecosystem is marked by seasonally available fuels, such as grass and leaves, understory plants, thick-barked trees, trees that have the ability to heal tree-trunk fire scars, resprouting capability (coppicing,

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lignotubers, dormant buds, etc.), and seed characteristics which favor resprouting (dispersal, serotiny, fire cracking, soil seed bank) (Goldammer 1991). Repeated fires will lead to the invasion of fire-resistant vegetation. In tropical Asia, this has meant the invasion of *Imperata cylindrica*. (Goldammer and Manan 1996). African post-fire grass invaders are the *Poaceae* spp., and the *Andropogon* species.

Trapnell (1959) has divided Zambian ecosystems into 5 ecological groups based on their fire tolerance (Lawton 1978):

- 1) Fire hardy species, intolerant of shade (chipya)
- 2) Moderately fire-resistant, able to invade small shrub environments but not chipya
- 3) Species able to invade under (2) but not (1). Need protection during sapling stage during fires
- 4) Fire sensitive species, usually evergreen, withstand dry season fires
- 5) Ubiquitous fire and shade tolerant species

The *Brachystegia* woodland (miombo) is sufficiently fire-resistant to maintain and re-establish itself, often in association with grasses, but once the micro-climate is destroyed, it regenerates slowly (Clark 1968).

The boundaries of wooded and bush savannas are critical to our understanding of savanna succession. Differing geology and drainage patterns contribute to the heterogeneity of savanna plant distribution by affecting soil genesis and composition (Allen 1986). Therefore, soil nutrient dynamics are thought to be important causes of savanna transitions and may be significantly affected by fire. Höberg (1982, 1986) identified miombo woodland as being dominated by woody species with ectomycorrhizal root symbioses, whereas the bushland has rhizobia and endomycorrhizae associations perhaps indicating different nitrogen and phosphorus concentrations in the two zones.

Jones (1992) could not corroborate this hypothesis, but suggests that fire and grazing act to initiate secondary grasslands which favor *Acacia* bushland over *Brachystegia* woodland. In sub-tropical savannas in other areas of the world, fire suppression and grazing has lead to an invasion of woody species, often through a shift in nutrient dynamics (Archer 1994).

The only long-term study to evaluate fire-induced succession in Zambia was initiated by Trapnell (1959) in the 1930s in Ndola, Zambia. These plots have been the basis for our understanding of fire tolerance in the miombo. However, the plots undergoing fires were all burned at the same time, every year, thus undergoing more extreme conditions than are usually present in nature; the fire exclusion plots were never under the influence of fire, also an unusual circumstance (Frost 1996). Because the plots were fenced, they also were not grazed by domestic livestock or wildlife. To accurately predict ecological dynamics of savanna systems, field studies must continue for decades, impractical for immediate policy management. Field studies which also incorporate models to simulate savanna dynamics are of critical importance, especially in light of disturbances such as fire and grazing (Ojima et al. 1994).

Chidumayo (1988) demonstrated that fires lower the species diversity, mainly through the loss of a large number of under-story species in the coppice regrowth. Hochberg et al. (1994) developed a model to describe the spatial spread of a single tree species in Lamto, West Africa, and concluded that, in this case at least, fire induces tree patchiness. The resulting edge effects may further decrease species diversity despite an increase in landscape diversity. There are presumably a wide range of fire responses to

species diversity that vary in regard to stage of growth, time of year, and succession state (Trapnell 1959) which are independent of the actual fire intensity (Allan 1965).

1.2.2. Emissions

Emissions from biomass burning cause a significant perturbation of atmospheric chemistry; however, there is still ongoing research on the magnitude of the fluxes and their implications. Quantification of these emissions and their implications is important for estimates of the magnitude of greenhouse gas fluxes, and local and regional pollution.

1.2.2.1. Quantification

Savanna fires account for 25% of burned biomass globally (Crutzen and Andreae 1990). It has also been estimated that 40-75% of savannas themselves are burned each year (Hao and Liu 1994; Andreae 1991). Of the 750 million hectares of savannas burned per year, Hao et al. (1990) estimated that 50% were in Africa. In more recent work, Hao et al. (1996) estimated that 2.0×10^9 tons of biomass were burned in Africa in 1990, resulting in the release of 145 Tg of CO which is 30% of the release from industrial sources worldwide (WMO 1995 in Hao et al. 1996). Generally, the rates of biomass burning have increased 50% since 1850 and it has been estimated that this increase has resulted in a significant release of greenhouse gases (CO, CO₂, CH₄) and trace gases (ozone, hydrocarbons, nitrous oxides, and sulfur compounds) (Houghton 1991). Given that atmospheric emissions from fossil fuel combustion account for 5200 Tg C/year and that Hao and Liu (1994) estimated that biomass burning accounted for 1800 ± 800 Tg C/year, Andreae calculated that biomass burning accounts for 25% of the global greenhouse forcing (Andreae 1991). There have been significant challenges to these

calculations particularly since the estimates of area burned or resultant emissions are based on compound equations such that an error from field or satellite measurements will be magnified in the final estimate (Robinson 1988). Also, these estimates rarely take into consideration secondary or tertiary fires on the same site. Nevertheless, it is generally accepted that the rate of biomass burning in the tropics is increasing and that this constitutes a small but significant portion of the release of potential greenhouse gases and is a significant producer of trace gas pollutants on global, regional, and local scales.

1.2.2.2. *Implications*

The qualitative effects of biomass burning on the atmosphere are generally known. Aerosols derived from the fire process, for example, can generally be divided into two categories: 1) carbonaceous and 2) non-carbonaceous. Carbonaceous aerosols (0.1 - 0.5 μm) are effective in scattering light, potentially harmful to human health, and may form cloud condensation nuclei (CCN). Graphitic carbon, on the other hand, absorbs light, may transport pollutants due to its larger size, and acts as a surface for catalysis reactions producing acid rain. The ratio between light scattering and light extinction components of smoke aerosols is termed the single scattering albedo (w_0) (Kaufman et al. 1994). The relative contribution of these two properties will determine whether carbonaceous particles contribute to a cooling or a warming of the climate. The w_0 ratio in laboratory experiments is 0.97 for smoldering combustion and 0.66 for flaming combustion (Kaufman et al. 1994). Thus, the fire behavior directly contributes to the effect of carbonaceous aerosols on the atmosphere. Non-carbonaceous aerosols are predominantly responsible for nutrient transport (Robinson 1988).

Nitrogen release from biomass burning is 20-30% of the total emission from all sources (Delmas et al. 1995). Ninety percent of the NO_x emissions are NO. If NO from biomass burning enters the stratosphere it may be responsible for ozone layer depletion via the reaction: $\text{O}_3 + \text{NO} \rightarrow \text{NO}_2 + \text{O}_2$ (White 1989). The FOS/DECAFE-92 research initiative enabled the study of the NO_x emissions from wet savannas. SAFARI-92 allowed similar studies in dry savanna systems (Lacaux et al. 1996). Nitrogen release has been correlated with the amount of plant N-content (Delmas et al. 1995; Ward 1990) and the intensity of the burn (Lacaux et al. 1996). Average determinations of N/C ratios for burned ecosystems is essential since there is very little knowledge of the effects of burning on C and N cycling in tropical systems (Lobert et al. 1991). Emissions from savanna soils are strongly linked to soil water content and soil nitrogen status, indicating there may be a different relationship of wet and semi-arid savannas to N emissions, respectively (Parsons et al. 1996).

Biomass burning is a significant source of methyl chloride (10-40% of the global turnover) (Rudolph et al. 1995) and also a contributor of methane, although the estimates of methane production may be 50-80% lower than previous estimates (Hao and Ward 1993). Despite the uncertainty of the cause, tropical biomass burning is an important source of ozone in the troposphere via secondary reactions (Fishman et al. 1996; Helas et al. 1995; Ward 1990). Ozone in the troposphere in unpolluted regions is 29 ppbv; in especially polluted regions, it can be 88 ppbv (Helas et al. 1995). In tropical Africa, measurements of 40 ppbv is not uncommon during the dry season which is a measurement similar to polluted regions in the eastern United States and eastern Europe

(Andreae 1991; Helas et al. 1995). Vegetation fires may be responsible for as much as one-third of tropical ozone pollution (Lelieveld et al. 1996 in Goldammer and Manan 1996). Ozone in the troposphere is responsible for absorbing thermal radiation, warming the earth's surface, and for acting as a chemical oxidant (Dignon and Penner 1991). During the Transport and Atmospheric Chemistry Near the Equator - Atlantic (TRACE-A) field experiment, conducted in September and October 1992, Browell et al. (1996) found that a maximum tropospheric O₃ column of 56 Dobson Units (DU) was found above biomass burning in Zambia. In general, biomass burning contributed up to half (28 DU) of the O₃ column across the South Atlantic (Browell et al. 1996). The ozone "bulge" (concentrations above ambient levels) observable over tropical regions has been used to evaluate the severity of biomass burning in the dry season (Fishman et al. 1996).

Biomass burning releases 3% of the anthropogenic emissions of sulfur. Yet, over regions undergoing significant biomass burning, sulfur emissions are five times greater (Andreae 1991). Biomass burning is also a significant source of CO, ethyne, propene, and benzene in the atmosphere, resulting in 20-95% of the amount released from industrial sources (Hao et al. 1996).

1.2.3. Nutrient Cycling

Knowledge of nutrient cycling in tropical and sub-tropical African savannas is limited. Nevertheless, such information is critical for agricultural management as well as for proper modeling of nutrient dynamics such as is needed for global estimates of net fluxes of nutrients between the terrestrial biosphere and the atmosphere. Frequent fires in savanna systems may disturb natural nutrient cycling. As a cursory summary, I discuss

the importance of nutrient cycling in savanna systems and the implications of a change in the carbon cycle through increased fire use.

1.2.3.1. *Importance of Savannas*

Biogeochemistry in savannas is currently a subject that is of much interest as effects of disturbance, such as fire, are considered to significantly impact terrestrial-atmospheric interactions. Since emissions from fire are the synthesis of unique combinations of fuel conditions, weather conditions, and land use history at any particular site, it is necessary to understand the nutrient flux at any given temporal and spatial scale to predict emissions. However, a complete understanding of nutrient cycling in the savanna systems of southern Africa is not available. Global biogeochemical models are beginning to separate global vegetation into discrete biomes based on similarities in specific attributes. These attributes are 1) leaf permanence of aboveground biomass, 2) leaf longevity, and 3) leaf type (Running et al. 1995). However, there is little empirical evidence to support savanna categorization. Future research must undertake studies on whether the miombo is nutrient-limited or water-limited, and on contrasting internal plant nutrient cycling with external (plant-litter-soil) cycling (Frost 1996). The role of ectomycorrhizae in soil nutrient systems and on termites in miombo environments must be revisited as they may significantly affect nutrient dynamics (Högberg 1992; Jones 1990).

1.2.3.2. *Carbon*

The extent to which the miombo may serve as a source or sink for carbon is also a current research objective (Kuhlbusch et al. 1996; Frost 1996). The potential for fire to

act as a long term carbon sink through production of inert carbon in the form of charcoal is possible, although Scholes et al. (1996) propose that the amount of charcoal that is actually buried is less than 1% of the total carbon released through fire. Scholes (in Frost 1996; Scholes et al. 1996) suggests that 6-10 Pg carbon could be released by increased conversion of miombo woodlands to agriculture, but a similar amount could be taken up if the forests are managed properly for carbon sequestration, i.e. for well-managed pasture land, plantations, or for high soil organic matter. Hao et al. (1996) and Frost (1996), among others, propose that early burning may differently affect the carbon flux to the atmosphere as compared to late season burning. However, it must be understood that results from burning in the early part of the season must be considered along with the impact of litter fall which occurs during this time (the exact timing of which depends on the previous season's rainfall, (Frost 1996)). Also, it is important to consider the amount of time left for herbage regrowth, the affect on future grazing and agricultural patterns, coppice production, and the ecological dynamics which may result from a shift in the fire regime. All of these factors may mitigate the effect of different carbon fluxes caused by early season burning, thus having an effect on long term carbon storage that may be equally as significant.

Fire increases the rate of cycling between atmospheric CO₂ and biotic carbon pools by rapidly oxidizing organic carbon that would otherwise decompose more slowly. However, studies of biomass burning in tropical forests in West Africa and Brazil indicate that the burning efficiency of initial fires is only 10-30% (Goldammer and Manan 1996; Menaut et al. 1991). Subsequent burns later in the season may consume

more biomass such that actual biomass consumption over the season is significant. Most organic carbon will be left in the tree trunks, however, and the effect that different forest structures have on the carbon pools and carbon fluxes is not well documented (Fearnside 1996; Goldammer and Manan 1996). Transition from a high biomass system to a low biomass system will result in a net carbon loss due to long recovery periods of forested environments following fire. Fearnside (1996) reported that it takes 190 years for the original forest biomass to recover in Brazilian woodlands.

1.3. PREVIOUS RESEARCH

There have been two arenas of research on biomass burning which deserve particular attention: 1) analysis of fire behavior as it may be affected by environmental conditions which is important for characterizing the type of emissions and eventual transport to the upper atmosphere, 2) field studies which have focused on a combination of techniques to evaluate the combustion efficiency of fires in the late dry season and their intensity. Recent international, interdisciplinary field campaigns have focused on the Amazon basin and southern Africa.

1.3.1. Fire Behavior

Attempts to parameterize and predict fire behavior have been in progress for decades with the increasing need to predict crown initiation and wildfire potential. Most equations that predict fire behavior are based on environmental conditions (e.g. wind speed, wind direction, relative humidity, slope), fuel conditions (moisture content, packing density), and fuel type (e.g. herbaceous vs. woody, or equilibrium moisture

content ratings based on woody diameter). Increasingly, these measurements have been used as inputs to dynamic models (e.g. BEHAVE) that predict spotting distances, intensity, direction, etc. Recently, however, attempts have been made to incorporate more predictive and accurate assessments of fire behavior on the landscape scale through remote sensing. Burgan et al. (1991) reported the use of AVHRR NDVI (Advanced Very High Resolution Radiometer, Normalized Difference Vegetation Index) to detect seasonal changes in greenness of grass, shrub, and forested lands to determine fire danger. The NDVI normalizes the difference between the red and near infrared data from the NOAA AVHRR satellite (Justice et al. 1996). It is presumed that NDVI better represents curing processes across a region than field measurements, the latter which can be biased by sampling methods (Chase and Andrews 1993; Henrickson and Durkin 1986). Use of NDVI would presumably give fire managers the ability to 1) detect, locate, and rank areas according to accumulate of green biomass and risk of wildfire, 2) indicate time of senescence of herbaceous vegetation, indicating when fire problems will increase, and 3) identify regions that need the most attention (Miller 1986).

Problems with use of NDVI for drought estimation and fire potential have been summarized elsewhere (Robinson 1988; Goward et al. 1991; Justice et al. 1985). Many of the atmospheric and geometric distortions can be removed by maximum value composites, but this results in less temporal resolution; also, radiance values do not capture the moisture regime with enough sensitivity and thermal channels, for example, should be used to evaluate actual and potential evapotranspiration (Chuvieco and Martin 1994).

1.3.2. Amazon Basin

The increase in interdisciplinary communication and the ability to link remote sensing analysis, field and airborne measurements, fire behavior, and emissions initiated the BASE-A and BASE-B international scientific biomass burning campaigns. BASE-A provided ground and airborne measurements of a diversity of community types in Brazil to assess particulate matter, fuel biomass characteristics, and rates of emission of products of incomplete combustion (Ward et al. 1991; Holben et al. 1991). Another objective of BASE-A was to improve the accuracy of remote sensing of tropical biomass burning so as to better characterize the emissions (Kaufman et al. 1990). Results of BASE-A indicated that biomass burning enhances tropospheric ozone by contributing trace gases and particulate matter, that the rate of emission of trace gases and particulate matter for a particular combustion efficiency was similar in the tropics to North America, and that there was a need to study the relative contribution of flaming and smoldering combustion to the emissions estimation (Kaufman et al. 1992; Ward et al. 1991).

The BASE-B experiment was an effort to provide detailed ground measurements of the emissions, fuels loads, combustion factors and fire behavior of biomass burning in a cerrado (savanna-like region) in central Brazil, and in a moist tropical forest in the eastern Amazon. Ward et al. (1992) presented models from this study that related emission factors (defined as the mass of emission released per unit of biomass consumed, grams per kilogram) of the major gaseous emissions to the combustion efficiency (defined as the ratio of carbon released by fire as CO_2) of the fire. Both the BASE-A and BASE-B efforts analyzed the differences in emissions characteristics from two major

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vegetation types, a tropical grassland and a tropical forest, in the Amazon.

1.3.3. Southern Africa

The Fire of Savannas/Dynamique et Chimie Atmosphérique en Forêt Équatoriale (FOS/DECAFE) project (Lacaux et al. 1991) was an initial attempt to characterize biomass burning in moist West Africa. Results from this campaign elucidated the relationship between fire behavior, emissions, ecology, and global atmospheric chemistry. The Southern Tropical Atlantic Regional Experiment (STARE) was initiated by the International Geosphere Biosphere Program (IGBP), as part of the International Global Atmospheric Chemistry (IGAC) project, to study the effects that biomass burning has on the atmosphere and terrestrial systems of the southern Atlantic region. There were two significant interdisciplinary, international campaigns which comprised STARE: Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE-A), in collaboration with NASA and the Brazilian space agency (Instituto de Pesquisas Espaciais (INPE)), and Southern African Fire-Atmosphere Research Initiative (SAFARI) which occurred in the Brazilian Amazon, and Southern Africa, respectively, in August-October 1992. This latter campaign was particularly influenced by severe drought conditions brought on by an El Niño - Southern Oscillation event (Lindesay et al. 1996).

While the STARE campaigns clarified the magnitude of terrestrial-atmospheric flux over the southern Atlantic during the late dry season, and hypothesized models of trace gas emissions, fire behavior, and remote sensing applications (see Lindesay et al. 1996 for a good review of these results), there were no studies to evaluate the extent of burning on a seasonal gradient nor the effects of emissions in different parts of the season

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which might differently affect global atmospheric chemistry. While a large proportion of fires occur between August and October, the fire season begins as soon as the rain ends and the burns can be initiated. In grassland systems, fires will be set as soon as vegetation begins to cure to provide grass regrowth with higher nutritional content for livestock (Chidumayo et al. 1996). Woodlands will continue to be burned for grazing and agricultural purposes throughout the season. Justice et al. (1996) determined that the peak of this fire regime occurred in Western Zambia between July and September, 1992, perhaps earlier than expected because of the drought conditions. In the same study, these authors also showed that significant earlier burning in Zambia began in May and June, 1992 during the SAFARI-92 study which was more than occurred in 1989, a relatively normal precipitation year. The relative proportion of the causes of these fires, grazing or agriculture, were not evaluated, but, presumably, grazing accounted for the early May and June fires. Without evaluation of this early season burning, a significant amount of information is lost about the cause, extent, and impact of the fire regime.

There are significant management objectives within Africa to encourage early season burning to avoid high intensity late season fires which may be ecologically damaging to the woodlands (Trapnell 1959; Chidumayo 1988; Frost 1996; Walker 1980; San José and Medina 1975; Guy 1989). Although many late fires will continue due to agricultural patterns that coincide with the rains (Clarke et al. 1996), recent initiatives to increase livestock production (UN Chronicle 1981), and continued fire use, which is independent of season (such as charcoal production), may lead to a larger proportion of fires occurring in the early dry season. The implications for global atmospheric chemistry

might be significant if the emissions are greater and/or different due to the higher moisture content of the vegetation (Hao et al. 1996).

1.4. STUDY

With these management implications and with information on the potential effect of biomass burning on atmospheric chemistry, a field study was initiated to further elucidate the role of early dry season biomass burning. The effects of increased biomass burning across a season are not known. Chapter 2 describes the potential causes of an increased fire frequency due to the influence of socio-economic forces on land use practices. Chapter 3 and Chapter 4 are the results of a field study during the early dry season of 1996 to correlate seasonal relationships of intensity to moisture content. Most estimates are currently based on work in the late dry season ignoring the potential impact of fires which behave differently because of a higher moisture content in the early dry season. Results from this empirical study determine the extent to which vegetation moisture conditions effect emissions as the local, regional, and global scales on a seasonal basis.

1.4.1. Objectives

Fire protection increases the risk of destructive accidental fires due to the accumulation of ground fuels and in miombo protection may result in a floristically poorer regrowth. Early burning therefore is a more practical management technique for promoting both tree growth and species conservation in miombo without increasing the risk of fierce accidental fires. (Chidumayo 1988)

The burning of the various dambos early in the dry season is strongly recommended. (Prior 1983)

The objectives of this study were to monitor environmental conditions, measure fuel moisture content and fuel loading, evaluate fire behavior characteristics, and to correlate these measurements with calculations of combustion efficiency (modified combustion efficiency, MCE) and fire intensity on a seasonal gradient in the early dry season (late May - early August). It was hypothesized that emissions would be affected by the moisture content of the vegetation such that the early part of the study would be characterized by products of incomplete combustion and the late part of the study would be characterized by products of more complete combustion. This work could assist the development of algorithms for biogeochemistry models that assess and predict dynamic fire emissions. This work will also assist ecologists and managers who need to evaluate the efficacy of early burning, especially in light of social and cultural implications.

1.4.2. Zambia

Before describing the field study in detail in Chapter 3 and 4, it is necessary to provide some background information on Zambia and its fire regime. The following sections include a country description, a summary of the current use of fire by Zambians, and a description of the dambo and miombo, the two study environments.

1.4.2.1. Description

Zambia is located at 8-18°S and 22-34°E occupying an area of 752,600 km². It is neighbored by Tanzania, Malawi, Mozambique, Zimbabwe, Botswana, Namibia, Zaire, and Angola. In 1994, the population was 7.8 million people with a national growth rate of 3.2%. Fifty-eight percent of the people were considered rural inhabitants, 42% were

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considered urban. The urban growth rate was 3.7% per year. The population density was 10.4 persons/km². (Chipungu and Kunda 1994).

The wet season is between November and April, the cool, dry season is May to June, and the hot, dry season is August to October. The wet season occurs in early November in northern parts of the country, but as the Intertropical Convergence Zone descends, the rains begin a few weeks later in the South. The reverse is true with the onset of the dry season. It begins earlier in the South (late March), and a few weeks later in the North (early April). (Muwamba 1988). Mean annual precipitation ranges from 600-1200 mm. Most of the precipitation occurs in the wet season.

Zambia is part of the Central African Plateau. As such, its altitude ranges from 1000m-2000m above sea level (Cole 1986). Generally, elevations increase southwest to northeast, with the highest elevations occurring in the Northern Province. Temperature and precipitation gradients follow the trends in elevation. The mean maximum temperature ranges from 15-32°C and the mean minimum temperature ranges between 4-10°C (Chipungu and Kunda 1994). The overlap of different temperature, precipitation, and edaphic parameters based on geography, is responsible for 36 agro-ecological zones. However, there are three main regions based on rainfall, the most crucial factor for agricultural production in the dry season. The Western Province, the region of study, receives 900-1000 mm rain/year. It is occupied by semi-permanent small scale and permanent semi-commercial cultivation systems. The main crops include maize, sorghum, and cassava. Cattle grazing and sorghum production are the major occupations of wetlands (Chipungu and Kunda 1994).

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1.4.2.2. *Current Uses of Fire in Zambian Savannas*

In the 1994 State of the Environment Report, Zambian national development objectives were outlined as follows: 1) to expand and diversify the country's economic base, 2) to make agricultural development a high priority, 3) to provide a self-reliant, self-sustaining economy, and 4) to increase the role of women in production (Chipungu and Kunda 1994). The latter three objectives, in particular, imply greater smallholder cultivation and therefore presumably increased fire use in agricultural production (see Chapter 2). Such development pressures have caused significant stress upon the forests of the Zambian environment. Two hundred thousand hectares of forest are used each year for charcoal production, and in the words of the State of Environment Report "destroyed by...shifting cultivation and uncontrolled exploitation," (Chipungu and Kunda 1994). Indeed, the Report states that 80% of woodland clearance is caused by clearing for agriculture and that late fires are one of the major causes of deforestation (Chipungu and Kunda 1994). Such deforestation has caused a 30-50% rise in runoff in the Kafue River which drains the Copperbelt Province (Chidumayo 1993).

Chitemene agriculture is a form of shifting cultivation that is predominantly used by the Bemba, Lamba, and Lala of the Northern Province of Zambia. The chitemene process involves lopping trees for piling and subsequent ignition upon a village garden.

The 'cut and burn' technique of chitemene, as well as the mound cultivation where the grass is naturally composted and which is practiced in the village gardens of chitemene systems...are adaptations which make these systems relatively independent of soil fertility. (Schultz 1976, 12-13)

The chitemene system has received much attention due to the fact that it appears to be particularly destructive to the forests. In reality, the chitemene practice evolved during a period in which it was possible to keep a fallow period for 15-25 years, allowing sufficient regeneration of the forest and simultaneous benefits for agricultural production. Recently, the length of the fallow period has declined significantly such that it is now only 12 years. The frequency of making new gardens is every 1-2 years (Chidumayo 1987; Stromgaard 1985). Increasing pressure for agricultural development has increased the potential for lasting effects on the woodlands due to human interference (see Chapter 2, pp. 43-68).

In addition to the use of savanna woodlands for chitemene production, 88% of all households depend on wood fuel for energy and wood fuel accounts for 66% of total energy consumption (Chipungu and Kunda 1994).

...until the advent of hydroelectricity in the early 1960s, wood clear felled in the *Brachystegia-Julbernardia* (miombo) woodlands was used to generate electricity for the mining industry in the Copperbelt area of Zambia (Lees 1962). This major cause of deforestation has now been replaced by charcoal production for urban household use and the rate of deforestation in the Copperbelt area in 1980 was estimated at 9986 ha per annum (Chidumayo 1987). (Chidumayo 1988)

Charcoal production involves cutting trees at ground level, logging them, and placing the billets at a kiln spot where they are earthed to ensure controlled carbonization following ignition. There is little regrowth of woody plants on the charcoal production kiln spots even after 13 years of felling due to destruction of soil structure, tree roots and seedlings because of the intense heat that is produced. The actual kiln site only covers between 2-

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15% of the total area that is felled (Chidumayo 1988; Chidumayo 1993). Conversion efficiency of charcoal production is between 10% and 25% (Delmas et al. 1991; Emmanuel Chidumayo in Misana et al. 1996). Charcoal production is an important source of income for rural dwellers who sell it to urban areas. In Zambia, 80% of the charcoal that is produced is consumed by urban households. It is also proportional to wealth; 98% of low-income households rely on charcoal in Lusaka, 84% in medium income areas, and 66% for high income areas (Hibajene and Ellegård 1994). The poor cannot afford alternative fuels because of high equipment or connection costs (Hibajene 1994). The charcoal is used for heating during the cool, dry season and for cooking throughout the year. Allen and Barnes (1985) determined that deforestation is caused by population growth and agricultural expansion, and aggravated by wood harvesting for fuel and export.

In the Western province of Zambia, chitemene agricultural production is not practiced. However, there is significant charcoal production and use of fire with clearing of wooded areas for agricultural production. In the nearby Kafue national park poaching involves significant use of fire (personal observation and communication with park scout) to facilitate sighting of animals in the dense woodlands. Fire is also locally used for grazing in the dambo wetlands. Early season fires stimulate more palatable live grass regrowth in grasslands that otherwise would have been completely cured by the middle of the dry season (LeCanut et al. 1996). Protein content of grasses decreases from about 10% during the growing season to about 3% during the dry season (Chidumayo et al. 1996) encouraging fires for secondary growth for improved forage for livestock. This is

especially true of the “sour” grasses which are typical of areas with sandy soils with poor nutritive content (Harris 1980). Fire is used for clearance of pathways to villages along the roads and through the miombo woodlands. One of the main uses of fire is for fertilization of maize crops in areas that normally would be infertile for maize production by people who are unable to fund chemical fertilization (Moore and Vaughan 1994). The heat and ash combine to provide an initially higher nutritional content for crops (Andriesse and Koopmans 1984; Singh 1994). Generally, fire is used for a multitude of purposes in response to other stresses upon the system, so as to facilitate human livelihood.

1.4.2.3. *Dambo*

A dambo is a particular type of African grassland which is seasonally flooded during the rainy season. It is distinct from mangrove, marshland, or other water-inundated systems in Africa. Usually, dambos are at the headwater of a particular drainage system where erosion cuts the valley bedrock such that a shallow depression forms (Mackel 1972 in Prior 1983). Water inflow is mainly by precipitation which then passes into a drainage network, often underground (Dake 1986; Prior 1983). Dambos are differentiated based on the amount of precipitation that is received (most in high rainfall areas of greater than 1000 mm), topography, flow rates, and depth of flooding (Prior 1983). Generally, there is a high ratio of surface area to water depth, although the depth will fluctuate annually due to seasonal variation in precipitation. Ferreira (1981 in Prior 1983) defined the dambos as “an area of land where the water table, either seasonally or permanently, is located in the upper 20 cm of the soil, often reaching the ground surface

during the rainy season.”

Little is known about the relationship of dambos as recharge areas to the perennial stream flow but it is considered significant (Prior 1983; Dake 1986). The National Council for Scientific Research of Zambia has sponsored water balance calculations for a number of dambos (Dake 1986). World Water has supported a three year research project that was funded by the overseas Development Administration of Britain and run by Water and Engineering for Developing Countries (WEDC) to enable an assessment of the risks and benefits of developing dambos for grazing and agriculture, (Dake 1986; Dicko 1992). Livestock production continues to be a high-ranking policy directive for planning units within Zambia (Dicko 1992) which ensures that dambo management will remain important. Currently, dambos occupy 10% of Zambia's land area (Muwamba 1988; Allan 1965).

Dambos are usually fringed by miombo vegetation underlain by sandy soils. A slight topographic gradient from the miombo to the dambo results in an increase in clay concentration toward the center of the dambo. Generally the clays are black montmorillonitic with a blocky structure. The high water holding capacity of the montmorillonite in combination with the topography of the site causes flooding in the wet season. In the dry season, the clays quickly drain to perennial streams, dry, and harden. The slight depression is also responsible for pockets of early morning fog and condensation. During the cold winter nights, this often results in frost. Interestingly, frost, in conjunction with fire, might be an important factor in maintaining a grassland structure (Dake 1986). The species of grass that are supported by these clays is dependent

on the depth of the water table and the duration of flooding (Prior 1983). On hydromorphic soils, the most common species is *Loudetia simplex*. In the Kafue floodplains of the Western province of Zambia, the dominant species is *Hyparrhenia*, accompanied by *Loudetia simplex* - *Scleria hirtella*. On seepage areas *Imperata cylindrica* often dominates. The localized diversity in grass species within a particular dambo is a response to microsite differentiation of pH, soil type, and degree of flooding (Prior 1983).

It is proposed that fire protection is one of the main considerations for dambo protection to ensure minimal erosion. Dambos are critical to future irrigation, perennial stream flow, hydroelectric power, lake levels, and for game reserves (as a watering hole for wildlife) (Prior 1983). Previously, dambos were seen as a breeding ground for insects such as the tsetse fly and malaria-transmitting mosquitoes. However, as tsetse fly control has improved and as the dambos are recognized for their ecological benefits and developmental potential in agriculture and livestock, it is becoming more important to control erosion and conserve water flow by excluding late season fires (Prior 1983; Dake 1986).

1.4.2.4. Miombo

There is continuous debate regarding the categorization of the miombo. Generally, it is often referred to as part of the savanna although it has previously been defined as an open deciduous microphyllous forest, a rain forest, a tropophilous forest, and a heterothermic forest (Malaisse 1978). The miombo has predominantly been classified as a tropical woodland, after Malaisse (1978). More specifically, a mesic

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miombo is classified as a “seasonally dry tropical forest” (Bullock et al. 1995) while a mature, undisturbed miombo is physiognomically a closed deciduous woodland of savanna systems (Walker 1981; Frost 1996). A savanna would have woody species spaced greater than one crown diameter apart and have a more continuous and denser layer of grasses and forbs. The miombo is affected by disturbance such as elephants, fire, and humans, as well as physical variability in soil, climate, time, topography, and geology, thereby forming a multitude of different vegetation structures forming a continuum of woodland and grassland types. This has caused much of the classification confusion. Nevertheless, the miombo, as a particular woodland association within this continuum, is generally typified by the common association of *Brachystegia-Julbernardia-Isoberlinia* tree species. The miombo woodland covers 12.1% of Africa for a total of 3.765×10^6 km² (AETFAT 1959 in Malaisse 1978). However, the miombo woodland covers 80% of Zambia (Chidumayo 1987).

Miombo climate is Koppen Cw with a dry season lasting 186 days on average (Malaisse 1978). Ninety-two percent of the trees are deciduous on average, losing their leaves approximately 2 ½ months before the onset of the rain season (Malaisse 1978; Lawton 1978). Leaf fall contributes to 68% of the total litter (Malaisse 1978). Mean leaf biomass ranges from 2900-3300 kg/ha/yr (Malaisse 1978; Chidumayo 1990). Trees flower between September and October (*Julbernardia* spp. are exceptions, flowering in the latter half of the wet season), coincident with leaf re-emergence. Few species flower during the cool dry season except for pyrophytes which flower in response to higher soil temperatures after fire (Chidumayo and Frost 1996).

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Miombo vegetation is comprised of a continuum of species with regard to fire tolerance: fire-intolerant, fire-tender, semi-tolerant, and fire-tolerant (Frost 1996). The fire intolerant species cannot survive fire and are mainly evergreen species. None were identified in the study site. The majority of miombo species are considered to be fire-tender. They include: *Julbernardia paniculata*, *Isoberlinia angolensis*, *Brachystegia spiciformis*, and *Brachystegia longifolia*. Also present at the study site were *Pterocarpus angloensis*, *Pericopsis angolensis*, *Anisophyllea boehmii*, *Diplorhynchus condylocarpon*, and *Strychnos innocua*, all of which are considered fire-tolerant. Considering that the *Anisophyllea spp.*, *Diplorhynchus spp.*, and *Strychnos spp.* were predominantly young shrubs, while fire-tender species occupied the canopy, it is possible that invasion of fire-tolerant species was occurring at the study site due to increased fire. However, no such conclusions can be confirmed. Frost (1996) summarizes the state of knowledge of miombo fire recovery and equilibrium dynamics.

Nevertheless, there are many adaptations that miombo species have made to their environment in response to fire and drought. For example, under cool fires, a dense coppice phase will emerge with one to three meter tall woody plants (Frost 1996). Miombo trees are also known for a corky bark which is resistant to fire. Tortuosity in the miombo tree trunks protects the trees from fire but it is actually an adaptive response to drought (Cole 1986). Thick, leathery seed casings are another adaptation to drought which protects the seeds from desiccation (Cole 1986).

The use of the miombo woodlands by local peoples is significant. Generally, the miombo woodlands are used for tannins, oils, dyes, timber, poles, tools, energy, wild

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foods (including caterpillars, honey, and mushrooms), browse, litter for fertilization in fundikila cultivation mounds, and medicines (Clarke et al. 1996). As well as this economic value for crop production, trade, and livelihood, the miombo also has significant cultural and religious value. It is used for religious ceremonies and is protected as such by “traditional forest reserves,” by local communities (Gerden and Mtallo 1990). These reserves are also used for meeting places for male elders, burial grounds, natural springs, rainmaking ceremonies, places for teaching young women and initiation of young women or young men (Clarke et al. 1996). Recent attempts at removing control of the forest from local to state entities has meant that indigenous management has been undermined (Kajembe 1994; Makumuri 1995) and that land tenure has become an issue of contention within and among many communities, and between communities and state authorities (Clarke et al. 1996).

The significant traditional use of miombo woodlands and dambo grasslands is a example of the integral connection between livelihood and natural resource availability. The use of fire is critical to survival in an otherwise infertile landscape and is one adaptation to resource limitation. Before I examine the results of the field study, it is necessary to understand the trends in land use as they have been influenced in recent years by development and population pressure. Understanding the socio-economic and cultural conditions and practices, as well as land use and biophysical effects, associated with biomass burning is necessary to develop management guidelines and predictive models.

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DEVELOPMENT AND FIRE USE IN ZAMBIA

Abstract: Fire is a tool for subsistence that has been and continues to be an integral part of Zambian rural agriculture and utilization of miombo woodlands. Cash cropping of maize, food subsidies, disadvantageous credit schemes, and urban bias have resulted in marginalization of the small farmer and a subsequent dependence on fire in livelihood processes. Increased use of fire in Zambia is due to socio-economic and political reasons rather than population growth per se. Management pressure that favors early burning over late burning is a response to increasing pressure being placed on miombo woodlands through these processes.

2.1. INTRODUCTION

Most of the scientific studies conducted on savanna burning in tropical regions are accompanied with estimates of shifting cultivation and deforestation (Goldammer 1993; Andreae 1991; Hao et al. 1996). For example, Goldammer (1993) estimates that 500 million people use some form of shifting agriculture on a land area of 300-500 million hectares. Hao and Liu (1994) estimate, based on Food and Agriculture Organization data, that annual deforestation in Africa has increased 12% between 1980 and 1990. The “drastic” effects of “slash and burn” have commonly been blamed for natural resource depletion and environmental degradation (Clark in Harris 1980). While such analyses are the needed to estimate the amount of area burned and the associated decreasing fallow periods in an historical context, I argue that burning practices increasingly reflect economic development and modernization processes as constructed by Fire World countries. Specifically, I argue that Zambia, a country representative of the increased fire use in Southern Africa, is responding more to global market forces than demographic pressure, although the latter is certainly significant. Fire has co-evolved in Zambia with the physical limitations of the land but the recent emphasis on private enterprise and

export-led industries has resulted in national and international policies and programs that have marginalized the small farmers of rural areas, encouraging the use of fire by resource-poor households (Moore and Vaughan 1994). Currently, fires initiated naturally by lightning comprise only 10% of the total; the rest are anthropogenic (Frost 1996). The resultant emissions are of concern not only on a global scale, but perhaps, more importantly, on a regional and local scale¹. However, I suggest that tools, such as fire use, are also one means by which humans have traditionally adapted to the physical limitations of their environment. Traditionally, these adaptations, i.e. shifting cultivation, can be sustainable in the long term if not altered by other forces. I argue that the development policies of Zambia, which have been implemented domestically under international pressure, are one such force that have augmented the use of fire beyond its natural or traditional anthropogenic occurrence.

2.2. RECENT POLITICAL AND ECONOMIC HISTORY OF ZAMBIA

“Coffee after Copper”

-Campaign slogan of Coffee Growers Committee of the Commercial Farmers' Bureau (in Kydd 1988)

“Even real socialist countries have to find and use foreign capital”

-Kebby Musokotwane, Prime Minister, 1986 (in Kydd 1988)

¹ The role of tropical circulation of fire emissions is debatable. Norum et al. (1974) proposed through study at Lubrecht Experimental Forest, Missoula, MT that low intensity fires do not produce enough heat to be convected into the upper atmosphere and thus, that the emissions remain in the area under stable conditions. The Intertropical Convergence Zone (ITCZ) in Africa certainly distributes ozone and other chemical species across the Atlantic Ocean via convection and NE winds (Robinson 1988), yet Helas et al. (1995) suggested that 8-13 Tmol ozone/year remains in situ and just downwind of fire activity, resulting in ozone pollution in tropical Africa similar to polluted regions of the eastern U.S. and eastern Europe. The role of smoke particles as cloud condensation nuclei and in human health concerns has been especially emphasized in the tropics (Kaufman et al. 1994; Ward et al. 1989).

The colonial legacy in Zambia (formally known as Northern Rhodesia under British rule) is significant. The policies implemented under British rule had significant environmental and cultural effects, including: tsetse fly eradication, associated resettlement plans, taxation, mining, construction of the railway, incorporation into the world market, and development of a nationalist political framework. The tsetse fly causes Trypanosomiasis ("sleeping sickness"). Until recently, Trypanosomiasis precluded cattle use from most of the miombo landscapes north of the Zambezi river (Matzke in Misana et al. 1996). Colonial eradication programs between 1928 and 1929 included resettlement of indigenous tribes which were at risk of the disease. However, the agricultural potential of these Native Reserves was hardly sufficient for livelihood beyond subsistence, compared to the Crown Reserves set up for European settlers. For example, in eastern Zambia, 9000 km² of infertile land was set aside for 150,000 indigenous people, while 17,000 km² was set aside for only 80 European settlers (Misana et al. 1996). As of 1979, white farmers of the south and central Provinces of Zambia, of which there were only 300-350, produced 40% of Zambia's maize and 60-70% of the total marketed agricultural produce.

Taxation which was initiated by the colonial leadership forced many of the rural poor to enter the market to earn wage labor. This created the perception of a developed vs. undeveloped sector (Misana et al. 1996). The Copperbelt copper mines which provided much of the wage labor and colonial wealth also created urban centers with rapidly growing populations, and high rates of deforestation in the urban woodlands (Moyo et al. 1993, Mupimpila et al. 1995).

The development of a national market board to oversee distribution and pricing of agricultural products, i.e. NAM Board, was an example of the colonial effort to create a national political and economic framework of a country that was initially very diverse, consisting of 77 different tribal groups (Muwamba 1988; Moore and Vaughan 1994). These groups had previously developed their own trade systems and similar methods of livelihood which were not consistent with the development programs of these agricultural boards. For example, the integration of the Zambian nation-state into the global economy resulted in the production of cash crops that could be sold for profit on the global market which resulted in the intensification of agriculture for export crops such as tobacco, rice, cotton, soybeans, and primarily, maize, at the expense of traditional crops such as cassava, sorghum, and millet (Muwamba 1988; Misana et al. 1996).

The construction of the railway by the British South African Co. determined the geographic pattern of development that persists to this day, particularly as it relates to population increases, rapid urbanization, and high rates of deforestation close to the railway (Moyo et al. 1993; Mupimpila et al. 1995). The intensification of development close to travel routes is evidenced by the fact that charcoal production is concentrated 5-15 km from main roads in Zambia (Hibajene and Ellegård 1994).

Political independence for Zambia occurred in 1964 when copper prices were high. Nationalism linked mining and industrialization and resulted in the construction of numerous parastatals. However, the lack of infrastructure and the remoteness of many areas of the country meant that agriculture could not be developed. By 1980, Zambia became dependent on imported food, paid for primarily by copper revenues (Kydd 1988).

When copper prices collapsed in the 1970s the terms of trade for Zambia plummeted 49%. Kydd (1988) has divided the political economic history of Zambia into four stages since this event: 1) 1975-1982, the government extended controls over the market over pricing and trade, 2) 1983-1985, primary liberalization was attempted, 3) October 1985-April 1987, foreign auctions were held, 4) a re-imposition of economic controls until 1988, and, now 5) current structural adjustment policies and liberalization of the market and trade conditions. These back-and-forth policy shifts have been critiqued to be the result of government mismanagement under the Kaunda regime (Stromgaard 1989).

Kenneth Kaunda took office after independence and was not replaced until the elections of 1991, in which Frederic Chiluba became president. The First National Development Plan (1966-71) was a reflection of Kaunda's "humanist" philosophy of government (Fenichel and Smith 1992) which encouraged cooperative farming. The food subsidies and other government spending commitments ("growth from own resources") which resulted from these efforts were not sufficiently subsidized by the government, resulting in the ebbing of support for humanist policies. They were futile policies due to inefficiency in government enterprises and price controls which favored the urban consumer (Stromgaard 1989). In 1990, Zambia owed the U.S. \$7 billion and was the world's most heavily indebted country on a per capita basis. Although Kaunda was continually in opposition to capitalism and structural adjustment policies put forward by the World Bank, the pressure to accept global market interactions was increasingly deemed necessary in light of policy failures.

As a result, in the first multi-party elections in 1991, Frederic Chiluba was elected on the theme of liberalization and privatization. The fact that structural adjustment happened later in Zambia than other African countries (i.e. Tanzania) is explained by the inflexibility of Kaunda's national policies. The new Constitution which was passed in the summer of 1996 is a bible to "entrenching the rights of the individual." One of the tenets in the Constitution was, in fact, titled: "Protection of Fundamental Rights and Freedoms of the Individual." Casper Weinberger, who visited with Chiluba in 1993, referred to the meeting as similar to talking to "a republican espousing the free market systems and foreign capital." Weinberger further lauded the country's severed relations with Iran and Iraq (Weinberger 1993).

Among the requirements for World Bank support of Zambia through structural adjustment was liberalization of the market. Liberalization was designed to allow the market to set prices, to remove government price controls on the agricultural sector, to found the Zambian Privatization Agency (ZPA), to privatize the parastatals, and to attract foreign capital (Due 1993). Specifically included in the structural adjustment agreement was the disbanding of the 146 parastatals. Most have since been sold to foreign entities (Due 1993). Indeed, "the international financial institutions seem to a considerable extent to be pushing against an open door," (Burnell 1994).

In the time of Kaunda, most farmers belonged to cooperative unions. As of 1993, the government was still encouraging small member owned cooperatives at the grassroots level to borrow inputs for crops to be sold on the private market. However, with removal of many fertilizer and food subsidies, there is concern that even these unions will be left

to their own means. They are currently assisted by donors such as the Swedish Cooperative Federation (Due 1993).

2.3. HISTORICAL USE OF THE MIOMBO WOODLANDS

The use of miombo woodlands both by indigenous communities for subsistence, and by institutions as a natural resource base to be used in development plans, is immense. Increasingly the miombo woodlands have become the locus of conflict between these two groups as traditional land use is often not in accordance with government policy. In fact, the miombo responds to a dynamic of ecological, social, and economic processes. To better understand the historical use of the miombo, I will discuss the role of timber, medicinal and food value, and cultural value of the woodlands.

2.3.1. Timber

Timber concessions were originally given to colonial mining operations and railroad companies and individual and community harvesting rights are still restricted; nevertheless, trade in wood products is an important source of income for rural dwellers and illegal harvesting is common (Brigham et al. 1996). The main timber species that is currently harvested is *Pterocarpus angloensis*, favored because of its durability, minimal shrinkage, and workability. It is especially used in furniture making because of its deep red heartwood. The main countries to which the tree is exported include South Africa, Portugal, and Germany. There is also considerable effort in plantation forestry using *Eucalyptus* spp. as poles for future use in house construction.

Trees are also used for making household tools such as bows, axe handles, and for carving. The other significant use of miombo wood is for firewood for cooking and heating, usually in the form of charcoal. In fact, it has been estimated that 85% of households use charcoal for energy (Brigham et al. 1996). Urban demand for charcoal is significant among those who cannot afford electricity which results in a substantial rural market for trade to urban centers. Charcoal producers are supposed to pay royalties to the government for trees that are felled in the process, but this rarely happens so a majority of the production is illegal. Although charcoal only has a 23% efficiency in the kiln, it is easily transported to the cities and provides a cheap energy source (Chidumayo in Misana et al. 1996). The energy problem was not addressed until the Fourth National Development Plan (Misana et al. 1996).

2.3.2. Wild foods

There are a diversity of non-timber forest products, of which wild edible foods are perhaps the most important group. The miombo woodland is harvested for fruits, seeds, tubers, mushrooms, leaves, roots, and insects. Fruits are an important supplement to indigenous diets, providing vitamins and nutrients, especially iron (Clarke et al. 1996). Fruits are harvested in the hot, dry season and the early rainy season. There have been 60 edible species of mushroom identified in Malawi (Clarke et al. 1996; Pegler and Pearce 1980; Pearce 1987) and similar amounts are suggested in the miombo woodlands of Zambia. Their amounts may be declining due to increased soil compaction from grazing, and/or a loss of litter due to canopy loss associated with fire ecological dynamics (Clarke et al. 1996). Mushrooms are eaten fresh or dried as a food source for other times of the

year. Caterpillars and termites are also a food source in some areas with specific tree species. The most important species for caterpillar collection is *Julbernardia paniculata*. Late burns may destroy leaf regrowth and inhibit caterpillar collection.

Honey collection is another significant use of the miombo woodland. Bark hives are used in conjunction with appropriate tree species such as *Julbernardia paniculata* and *Brachystegia* spp. Honey production is a potentially lucrative occupation of many rural poor. However, there is a severe lack of funds to carry out development projects due to the need for transportation and marketing facilities. Late season fires may also be harmful to honey production (Brigham et al. 1996).

2.3.3. Medicines

In a large number of languages, the word 'tree' is very similar to the word for 'medicine'. The miombo provides many medicinal plants that are used for a diversity of ailments. Many are probably not known except within local communities. *Pterocarpus angloensis* is used in circumcision rituals, menstrual disorders and burns, presumably because of its deep red sap. *Diplorhynchos condylocarpon* produces a milky latex substance that is used during girls' puberty rituals. *Ochna pulchra* is considered a strengthening medicine (Cunningham in Brigham et al. 1996).

2.3.4. Other Uses

The miombo is often set aside by indigenous cultures as Traditional Forest Reserves for religious ceremonies and as a sacrament to ancestors (Clarke et al. 1996). The sanctity of many areas of miombo woodlands near village areas is the main reason why these areas are used in a sustainable manner. Other uses of the miombo woodland

include the utilization of leaf litter for fertilization and cattle browse. Benefits of a wooded miombo include soil retention, shade, and shelter from winds and erosive rains.

2.4. TRADITIONAL FIRE USE IN ZAMBIA

The use of fire is traditionally a way in which miombo woodlands have been managed by indigenous cultures (Chapter 1). In order to understand the way development has altered this fire regime, traditional fire use must be understood. To do so, I concentrate on the most well-known Zambian agricultural method involving fire, chitemene, but allude to the diversity and ubiquity of fire use within the country.

2.4.1. Chitemene

Chitemene is a form of shifting cultivation practiced by several tribes (Bemba, Lala, Lamba) in the Northern Province of Zambia. It has been stated that fire is a major problem in management and natural regrowth of savanna woodlands in tropical Africa (Trapnell 1959; Innes 1971). Yet, this ignores the counter argument that traditional agricultural practices, like chitemene, disturb the vegetation through fire but do not alter its fundamental characteristics and composition when allowed to regrow during sufficiently long fallow periods. Fire thus constitutes a tool that promotes advantageous production in otherwise disadvantageous surroundings and during periods of stress. In small-circle chitemene, trees are lopped and carried to a garden circle plot where they are piled and burned. For a garden that is 10% of the area lopped, 25 years are required for regeneration (Allan 1965).

The advantage of using fire in chitemene cultivation is that the phosphorus, potassium, and calcium help fertilization on otherwise nutrient-poor, leached sandy soils which are most common on the Zambian plateau. Acidity is reduced and the physical condition of the soil is actually improved (Moore and Vaughan 1994). Ultimately, fire may reduce weed growth, insect herbivory, and disease pathogens. With a declining fallow period, which is currently 1-2 years on average, there are also negative impacts of fire use such as destruction of organic matter and the lack of regenerative shrubs and trees to negate the erosivity of intense rains that occur during the wet season. *Brachystegia* spp., for example, are the main trees of the northern miombo woodland; they generally have a slow regrowth and it has been proposed (Stromgaard 1989) that increasing fire use and abuse has resulted in an ecological shift into a small woodland system called chipya in which *Brachystegia* trees are absent and there is an increase in grass.

The fertilization effects of potassium and nitrogen after fire are negligible after one to two years of cultivation. Traditional cultivators adapted to the changing fertility by rotating crops and then ultimately abandoning the site after approximately three years (Moore and Vaughan 1994). For example, the first year's production would consist of maize, millet, and cassava, followed by beans, maize, millet, and cassava in the second year, and just beans and groundnuts in the third year taking advantage of the nitrogen fixation of the *Leguminosae*; this latter process is practiced in traditional chitemene systems but has been adapted to the fundikila mound cultivation described by Stromgaard (1989).

2.4.2. Other Uses of Fire

With Zambia's transition to a nation state and the subsequent ecological interest in the chitemene practice, it is easily forgotten that the *nation* of Zambia is a First World construction of what really is a land area that comprises, as aforesaid, a multitude of 77 different tribal traditions. Moore and Vaughan (1994) caution against the immediate critique of culture on the nation state level because the alternative is to treat each tribe separately, which goes against a history of cultural communication and transience in this area. For example, the use of fire by several tribes in the Northern province has been adapted by other regions; and, additionally, there are numerous other uses of fire throughout Zambia. Bemba use of chitemene is, although the most popularized, not the sole use of fire in Zambia. Hunting, cooking, agricultural waste, agricultural field preparation, and grazing, are some of the other uses of fire that are common. In fact, charcoal production for household fuel is now the main cause of deforestation in Zambia (Chidumayo 1987) and the resulting burning of the kilns also results in fire effects.²

The different uses of fire in different areas of the country reflect perhaps the combination of cultural differences and adaptation to the landscape. While chitemene is a form of shifting cultivation that is mainly in the Northern province, as aforesaid, Stromgaard (1989) proposes several adaptations to the system that he argues are a result of ecological adaptation to ecosystem change from continual fire use. Usually, these changes are a response to a decrease in tree density, such as using grass mound

² Charcoal production involves cutting trees at ground level, and piling the logs at a kiln spot (which usually covers 15% of the originally felled area), where they are earthed to ensure carbonization after ignition. Woody plant regeneration and proper soil structure are impaired for as long as 13 years (Chidumayo 1988). It may be a significant source of methane and other non-methane hydrocarbons (Delmas et al. 1991).

composting (fundikila) and large-circle chitemene (the latter involves a larger area in which trees are felled and a larger circle plot).

Fundikila is a mound cultivation used in open savannas that have abundant grass, mainly of *Hyparrhenia* spp. At the end of the rainy season, grass is cut and stacked around trees or stumps and burned later in the season forming a version of chitemene agriculture for some crop production. However, a majority of the cultivation begins at the beginning of the next rain season, after the grass has decomposed, at which time the mounds are flattened and planted with millet during the first year and beans during the second. The limiting factors of fundikila production are the low soil nutrient quality of the soils and the poor nutritive value of *Hyparrhenia* spp.

Fundikila agriculture is perceived as a continuum from shifting cultivation to permanent agriculture due to adaptation to different ecological conditions. Such integral agriculture is traditionally sustainable. In other words, the changes in the fire regime are traditionally dependent on the history of the culture and its ability to adapt to ecological limitations. Pioneer agriculture, however, is favored by increasing development pressure for rural agricultural production of cash crops. The incipient nature of these agricultural systems limit the opportunity for farmers to adapt in a sustainable manner to ecological constraints. Particularly, the importance of cultural co-evolution with the environment is minimized. I argue that this agricultural transition increasingly incorporates fire.

The use of fire for livestock grazing is common, for example. During the dry season, cattle are moved to seasonally waterlogged grasslands (dambos) to graze. As soon as the grass begins to dry, the protein content of the grass decreases from

approximately 10% in the beginning of the dry season to about 3% at the end of the dry season (Chidumayo et al. 1996). Burning of the grass, as soon as fires will carry, results in the stimulation of new regrowth which is more nutritious:

Overall, the low nutritive value of the upland grazing areas together with indiscriminate burning of uplands grazing and localized overstocking have been identified as the main constraints to cattle production. During the first few months of the dry season the rangelands are routinely burnt to provide more palatable grazing. Since this burning is seemingly indiscriminate and without prior planning, the grazing resources on the Kalahari sands [in Western Province] are adversely affected. (Muwamba 1988)

Poaching is one of the main reason for fires in the national parks of Zambia. Fires are often set by poachers in remote areas of the park and account for significantly more area burned than is accounted for by prescribes fires (Ruggiero 1990). Hunting with fire, outside of the parks, is also a significant cause of wildfires, so as to promote better visibility. Park management plans which incorporate fire now try to promote early season burns that are less likely to cause more damaging late season fires. There are advantages and disadvantages of early burning, especially for wildlife conservation purposes. For example, patchy grass, which would remain after an incomplete burn early in the season, is highly productive and would provide wildlife cover. However, some predators, such as lions, rely on a continuous, high, unburned grass cover in which case fire suppression is encouraged for their management (Ruggiero 1990). Nevertheless, continuous fire is advantageous to pastoralists who depend on the maintenance of grassland systems in preference to woodlands for livestock grazing.

2.4.3. Breakdown of Chitemene

With the expansion of new agricultural practices, chitemene has recently been seen as a traditional system that is “breaking down,” (Stromgaard 1989). Moore and Vaughan (1994) challenge the assumption that this “breakdown” is due to population pressure and labor availability alone, as is often proposed. Instead they claim the ecological and agricultural sciences have constructed a knowledge of the system which ignores agriculture’s traditional co-evolution with culture, politics, and ecology. Increasing development pressure has precipitated such interactions.

2.5. THE ROLE OF DEVELOPMENT IN FIRE USE

...it can be argued that the population pressure and the subsequent decline of available woodland have given rise to the adoption of new staple crops, new farming methods, changes in soil preferences, and new settlement patterns....However, despite the low carrying capacity of so-called traditional chitemene systems, it would not be correct to see population pressure as simply causing these changes....The causal mechanisms have much more to do with government policy (on agriculture and settlement), the decline in employment prospects on the value of real wages, subsidies to the producer, and the provision of credit facilities. (Moore and Vaughan 1994)

2.5.1. Maize Subsidies

“Zambia’s cardinal mistake was to subsidize consumption for a long time, thereby delaying diversification”

-Kenneth Kaunda, May 1986 (in Kydd 1988)

“[The Government] would be committing suicide to remove subsidies on mealy meal at a time of low salaries and high unemployment.”

-Kenneth Kauda, March 1987 (in Kydd 1988)

Between 1975 and 1988, the production of maize in the Northern Province increased 850% (Burnell 1994). Population pressure and land use changes are the consequences, and *not* the cause, of a change toward maize production. Kaunda strongly supported food subsidies in his “humanitarian through socialism” efforts. This was especially pursued in the 1950s in the governments “back to land” policies as a result of declining urban incomes (Moore and Vaughan 1994). Maize is the staple food of the Zambian people and it currently elicits the only food subsidy. Zambia was second only to South Africa in maize production in the 1996 harvest, according to the Zambian newspaper, *The Post* (Nov. 1, 1996). Yet, at the same time, 28 million kwacha is owed to the government for fertilizers bought by the government. The government is using credit to source its needs (*The Post* Nov. 1, 1996).

The use of maize as a cash crop in Zambia has altered the traditional relationship of agriculturists to the land. Maize is a nutrient-demanding crop, requiring extensive inorganic chemical fertilization given the generally low nutritive quality of most Zambian soils. In chitemene, fertilization had been naturally provided through biomass burning and the associated increase in alkalinity, base cations, nitrogen, and phosphorus, without the purchase of expensive inorganic chemical fertilizers. The introduction of new agricultural practices has resulted in the stratification of society into resource rich and resource poor households; i.e. those that can support hybrid maize varieties with fertilizer inputs, and those who cannot, and thus are forced to support themselves with production of cassava which is tolerant of low soil nutrients and high soil acidity (Moore and Vaughan 1994).

In traditional shifting cultivation, crops are normally rotated among different plots of land based on loss of soil fertility at one particular site. Government policy on agriculture and settlement, the decline in employment practices and the decline of real wages, subsidies to the producer, and the provision of credit facilities combine to make maize production attractive to farmers (Moore and Vaughan 1994). Since maize must be sold on the market, maize production necessitates settlement near roads and urban areas. The permanent settlement near major roads and urban centers has meant that the same land is used continually for production. As a result, the forests are used continually and eventually depleted. To reap the same resources from the forest, the role of fire for stimulating fertilization in forest fields, for supporting charcoal production, and for hunting, becomes that much more important, especially for the resource-poor. The location of charcoal production sites varies from 5 to 15 kilometers from main roads (Hibanjene and Ellegård 1994). It has also been shown that the number of live trees per hectare is positively correlated to the distance away from the village (Misana et al. 1996).

The transition from a subsidized government-based marketing system to a private enterprise, free market system created considerable market confusion. In 1993, for example, there was a good harvest of which 60% was produced by peasant farmers Burnell (1994). However, since the authorities had set a floor price on maize production, cooperative unions supporting the peasants urged them to hold on to their harvest and sell to private buyers rather than the government. However, no private buyers came forward partially because of tight credit from commercial banks. Therefore, out of necessity, the government put the money that did not go to the farmers into treasury bills. As an

unfortunate result, it was not available for use by the government to purchase grain when farmers could not sell to private buyers. The government was then short on credit and gave promissory notes to farmers; and, as a result of the wait and the poor storage facilities, the harvest was ruined by the oncoming rains (Burnell 1994).

Kydd (1988) argued that it was the very inefficiency of the agricultural system that puts small farmers at the mercy of government subsidies. When maize is sold to parastatals or intermediaries it goes to urban centers and then is trucked back to rural centers to be sold back to the original producers, at a higher price (Kydd 1988). The inefficiency of the system puts the small farmers at a disadvantage as they are marginalized from the market as both consumers and producers. Infrastructure is often non-existent and yet they are strongly urged to enter the market through subsidies. When dealing with the government and cooperative unions which are necessitated by such interactions, the farmers are assumed to be in urban, settled areas. Permanent residence is again necessitated and with it comes the continued use and reuse of the local forests. Thus, the market system that is being adopted by the Zambian government under structural adjustment policies of international governments suffers from a lack of infrastructure such as good roads and storage facilities. As a result of this lack of infrastructure and the number of incentives to pursue maize agriculture, there are population concentrations along the major roads and urban centers, one consequence of which is the destruction of the woodlands, often incorporating fire.

2.5.2. Gender

“...maize cash-cropping has fundamentally altered the relationship between permanent field cultivation and chitemene cultivation, and thus, the gender division of labor.” (Moore and Vaughan 1994)

The link between increased maize production and changes in female labor, in particular, is significant to the use or disuse of fire in agricultural production. Moore and Vaughan (1994) in their study of the Bemba chitemene argue that the chitemene agriculture is strongly dependent on female labor and not solely on male labor as previously assumed (Richards 1939). They argue that marginalization of women in the new agricultural market system has actually encouraged a return to chitemene in recent time (Moore and Vaughan 1994).

As Moore and Vaughan (1994) observe, in a traditional chitemene agricultural system, women cared for the burning and maintenance of village gardens. In maize production, however, there is not a clear division of labor and women are responsible for fertilizing, weeding, shelling, bagging, and grinding. The typically diverse crop production in chitemene had allowed for maize production among numerous “relish” crops such as groundnuts, millet, and vegetables. With the mono-cropping of maize, women are required to put both more effort into the cropping process and into providing relish foods. This often requires that they earn a cash income to buy relish foods in the urban areas. Yet, often the cash is controlled by the male of the household. Labor is very intensive in maize cropping, which leaves little time for child care, fuel wood collection, or market transactions as the market is usually a long walk away. There is little wonder, then, that Food for Work programs in Zambia were very popular in the 1970s; they gave

commodities directly to women. Moore and Vaughan (1994) suggest in their conclusions that the need to control commodities by women is evidenced by the now *increasing* chitemene plots and thus, continued use of fire in agricultural crop production. These observations need to be confirmed by other detailed studies that examine the gender division of labor in Zambia.

2.5.3. Credit, Structural Adjustment, and the Small Farmer

“Large scale mining will continue for 12-20 years, but small-working may go on for 50-60 years.”

-Francis Kaunda, Chairman, Zambia Consolidated Copper Mines, 1987 (in Kydd 1988)

“Commercialization of small-scale agriculture has succeeded.”

-Fenichel and Smith (1992)

Integrated Rural Development Zones as part of the Second National Development Plan (1972-1976) were initiated in response to the failure of the egalitarian concept of the First National Development Plan (1966-71). Their goal was to concentrate resources in areas of high agricultural potential (Fenichel and Smith 1992). This capital intensive approach was moderated by Basic Needs policies of the Organization for Economic Cooperation and Development (OECD) in the 1980s. The overall effect of both of these policy directives was to convince small farmers to pursue market production of petro-chemically dependent hybrid maize varieties for export. However, such production was difficult for small farmers who had little surplus cash to invest in expensive fertilizers. Cultivation, even without fertilizers, was financially challenging. For example, in 1986 it cost 650 kwacha to buy a pair of oxen which was only 53 kwacha less than the entire gross margin of local maize growers (Fenichel and Smith 1992). Credit incentives for

fertilizers were therefore a necessary precondition to increased maize production. Yet, often these credit incentives were not dependable, often being disbursed after optimum planting dates. Small farmers were forced in such cases to use whatever natural resources were available to them to meet production needs. Fire was, and continues to be, an easy and affordable way to gain increased fertility, at least temporarily, from the land for optimal production of maize to be ultimately sold at market in urban areas.

Structural adjustment began in earnest with the World Bank in 1992 with a \$200 million loan. In addition to selling the parastatals, another requirement of the loan was a change in banking policies. The new banking act requires "security for loans, eliminating most smallholder farmers and women from borrowing," (Due 1993). Before the liberalization, these groups could borrow limited amounts from the Lima Bank in Zambia which had branches in many towns.

The World Bank concentrated on securing loans for medium-scale borrowers but did nothing for the small farmers who could not put up collateral. Women were at a particular disadvantage. Women are still currently not allowed to borrow unless their husband's signature is on the loan (Due 1993). Without such collateral to invest, and without opportunities to create external sources of cash through wage labor, many small farmers are left on the outskirts of the maize market, forced to rely on other forest uses (charcoal production, for example) and burning to cultivate new land once their original site fertility declines. As Ivan Bond (in Misana et al. 1996) explains:

...the prevailing economic conditions have resulted in a rate of employment creation below the level of population growth and a declining real wage. Together with farm-level incentives to cultivate, this has resulted in the expansion of settlement and concomitant agro-pastoralism

into previously wild land, including miombo woodlands....Given the structure of subsidies and lack of alternatives, individual households are acting in a wholly rational manner by settling and cultivating marginal agricultural land.

Subsidies on all agricultural commodities, including maize, were completely eliminated in 1993 through these structural adjustment policies. Liberalization of the maize markets and higher pricing guidelines were also a part of these structural adjustment policies. It is unclear whether these higher crop prices will lead to intensification of certain crops with the abandonment of other cultivation practices, or whether the higher prices will lead to more extensive crop production because it will be cheaper to burn and cultivate new land and sell maize on the market than to invest in new fertilizer and machinery inputs on a single plot of land to maintain site fertility (Clarke et al. 1996).

Integration into the world market has also resulted in increased investment in livestock in wet grassland areas known as dambos (Dicko 1992). Credit is given to farmers to stimulate such livestock production. The International Fund for Agricultural Development (IFAD) approved a loan to Zambia of 11 million dollars for livestock development and to increase production of maize, cotton, groundnut and other crops (UN Chronicle 1981). Increased livestock pressure means increased burning of pasture land to ensure protein-rich regrowth in new grass.

2.5.4. Urbanization

The rate of urbanization in Zambia was 8.9% between 1963 and 1969, and 6.7% between 1969 and 1980 (Misana et al. 1996). As a result, Zambia is Africa's third most urbanized country after Algeria and South Africa. The subsidies developed under the

Kaunda regime were a response to the need to feed urban populations. They lead to policy and program bias that favored urban areas and ran counter to the interests of the rural agricultural sector, particularly resource-poor small holders.

A policy of uniform pricing of agricultural producer goods, especially maize meal, was introduced with the objective of protecting the urban consumer and consumers in food deficit rural areas (Mupimpila et al. 1995). Governments became involved in agricultural marketing through agricultural marketing boards ..[thus the state transformed agrarian relations and agricultural production]....Such economic policies were common throughout the region; small holder farmers had little incentive to intensify production. Any increase of production to meet household and cash income need was through increased are of cultivation at the expense of the woodland. (Misana et al. 1996)

As a result of this concentration of policy and resources on the urban centers, rural-urban inequalities have intensified. The United Nations (UN Chronicle 1981) concluded that many rural roads are in poor maintenance, intensifying the difficulties of incorporating rural farmers into the agricultural market. As a consequence of this urban bias, the rural poor must rely on dwindling resources for their food and energy needs and for trade to urban centers, creating enormous pressure on open-access natural resources. These pressures are currently exacerbated by population increases in urban areas creating more demand for rural woodland products, by population increases in rural areas creating more direct pressure for resources, and by government policies which are focused on urban maize markets (Misana et al. 1996).

Another reason for natural woodland resource depletion, other than agricultural land use, is the collection of firewood for charcoal production which is sold to urban centers. The limited employment options in the urban centers has created urban shanty

towns that depend on this source of energy. The rural poor continue to use the miombo woodland for this production despite the fact that it is illegal in many protected areas.

2.6. CONCLUSION

“How do you tell a Zambian from his neighbor?...Every Zambian is born with a match in his hand.”

-local saying in Zambia (personal observation)

Fire has been an integral part of life for small producers in Zambia for millenia. It benefits crop production because of the fertilization effects of ash, enhances hunting, provides charcoal, and improves livestock grazing. Its use is a traditional adaptation to land with low inherent soil fertility. The Zambian development policies since independence have been coincident with an increase in burning. Interest in global atmospheric chemistry has stimulated research into the sub-tropical savanna areas such as Zambia because of the massive amount of emissions released. Population pressure is commonly cited as the primary cause of increased fire use in this scientific literature.

I have argued that increased fire, while affected by population increases, is primarily the result of government and macro-economic development policies that marginalize small farmers by encouraging introduction into the market economy. Cash cropping of maize, and the resultant food subsidies, has necessitated permanent settlement near urban infrastructure necessitating increased use of limited soil and forest resources. Disadvantageous credit schemes, need of chemical fertilization and capital, and gender inequalities have marginalized the small farmer such that he/she is more prone to use fire for successful agricultural production as local forests become depleted. In

addition, the small farmer has increased use of fire for other purposes, such as livestock grazing, and poaching, as a means to earn commodities for the market. A recent increase in traditional chitemene is evidence that achieving the gender balance of the system is also inherently important to small holders. The increasing illegal production of charcoal from rural woodlands to satisfy growing urban energy demands is indicative of a structural urban bias which is a result of market policies and lack of infrastructure development. I have also argued that the use of fire is not subject to one particular culture (i.e. the Bemba of chitemene) but that international development pressures have altered the multi-cultural uses of fire within Zambia. Integrated rural development programs, structural adjustment, and political ideology have altered this traditional co-evolution of livelihood and fire use.

The effects of shifts in the fire regime, whether they be increased atmospheric pollution on the local or global scale, or increased marginalization of the small farmer, must be assessed with an appreciation of the biophysical and socio-economic conditions under which they originated. This chapter summarized the traditional use of fire and the factors responsible for increased burning in recent decades, specifically international and domestic development policies and the resultant integration into a market economy.

The following two chapters analyze the potential emissions of early dry season burning. Scientists who quantify emissions in the early dry season must use the results from the following two chapters in combination with land use information, as analyzed in this chapter, to develop a conceptual understanding of the present seasonal dynamic of the fire regime and its future implications.

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FUEL BIOMASS AND CONSUMPTION FACTORS OF A ZAMBIAN SAVANNA

Abstract: Biomass burning in savanna ecosystems in southern Africa has become a major focus of international scientific campaigns, such as Southern African Fire Atmosphere Research Initiative - 1992 (SAFARI-92), due to concern for its potential effects on regional and global atmospheric chemistry. Most studies of biomass burning have been done in the late part of the burn season. The objective of this study was to determine the intensity and consumption factors for fires in the early part of the burn season. An understanding of the seasonality of the fire regime will improve emissions estimates for southern Africa. Fourteen experimental burns were established between June and August 1996, six in a miombo and eight in a dambo, which were alternately lit through the length of the study period to test the effect of vegetation moisture content on fire behavior. Fuel loading ranged from 1884 kg ha⁻¹ to 3314 kg ha⁻¹ in the dambo and 8953 kg ha⁻¹ to 13233 kg ha⁻¹ in the miombo. Moisture content of live grass decreased from 127% to 69% in the dambo and from 119% to 33% in the miombo. Combustion factors (CF), the percentage of fuel consumed, for the dambo ranged from 44% to 98%. CF values for the miombo ranged from 1% to 41%. Fire line intensity ranged from 288 kJ s⁻¹ m⁻¹ to 5271 kJ s⁻¹ m⁻¹ in the dambo and 25 kJ s⁻¹ m⁻¹ to 5274 kJ s⁻¹ m⁻¹ in the miombo. There was a significant negative correlation between increasing proportion live grass and increasing consumption factor in the dambo ($R^2=0.99$) and in the miombo ($R^2=0.78$). However, weighted grass moisture content in the miombo was also significant ($R^2=0.85$). Fire line intensity was most highly correlated with average fuel moisture content in the miombo ($R^2=0.75$) and with proportion live grass and total fuel load in the dambo ($R^2=0.87$). The range of intensities encountered suggests that CF and intensity are different in the early burning season because of the higher moisture content of the vegetation. Regression equations developed by this work can be used in future emission models.

3.1. INTRODUCTION

In this chapter, the results of field measurements and analysis from early dry season fires in Western Province, Zambia are presented. Combustion factors (CF), the percentage of fuel consumed by the fire, and fuel biomass data are compared with fuel moisture content variables to determine seasonal trends in fire behavior which might differently affect emissions.

Savanna fires may account for as much as 25% of globally burned biomass (Crutzen and Andreae 1990). The first estimates of trace gas release from biomass

burning by Crutzen and Andreae (1990) indicated substantial atmospheric effects. Generally, the amounts of biomass burning in savanna ecosystems are thought to have increased 50% since 1850 and it has been estimated that this increase has resulted in a significant release of greenhouse gases (CO, CO₂, CH₄) and trace gases (ozone, hydrocarbons, nitrous oxides, and sulfur compounds) (Houghton 1991). Between 40 and 75% of savannas are burned annually (Hao et al. 1990). Hao et al. (1990) estimated that 50% of savanna fires are in Africa. In more recent work, Hao et al. (1996) estimated that 2.0×10^9 tons of biomass were burned in Africa in 1990, resulting in the release of 145 Tg of CO, which is 30% of the release from industrial sources worldwide (WMO 1995). Hao et al. (1996) also showed that the significant amounts of CO, as well as ethene, propene, and benzene in the atmosphere are derived from biomass burning and contribute 20 to 95% of the amount released from global industrial activities. Given that atmospheric emissions from fossil fuel burning account for 5200 Tg C/year, Andreae (1991) calculated that biomass burning accounts for 25% of the global greenhouse forcing.

There have been significant challenges to these calculations, particularly since the estimates of area burned or resultant emissions are based on compound equations, such that error from field or satellite measurements will be magnified in the final estimate (Robinson 1988). Nevertheless, it is generally accepted that the rate of biomass burning in the tropics is increasing and that this constitutes a small but significant portion of the release of potential greenhouse gases and is a significant cause of trace gas pollutants.

Most of the previous international campaigns focusing on biomass burning in savanna ecosystems concentrated on the late part of the season. Recently, Shea et al. (1996) reported measurements of fuel biomass consumption, climatic conditions, and fuel moisture content across a broad range of savanna sites in South Africa and Zambia. Their study followed a similar design to this one yet occurred in the late part of the season. Given current management guidelines and development pressure, however, it is possible that early dry season burning will increase. The objective of this study, therefore, was to determine whether fire intensity and consumption factors were different in the early part of the burn season as compared to later in the season due to the higher moisture content of the fuels, and to compare these results with measurements of Shea et al. (1996).

In this aim, fourteen fires were purposely ignited, eight in a seasonally flooded grassland (dambo) and six in a semi-deciduous, open-canopy savanna woodland (miombo) subsequently between June 5 and August 6, 1996 for the following research objectives: 1) determination of fuel consumption factors based on aboveground fuel biomass and fuel moisture contents, 2) determination of fire line and reaction intensity based on fuel biomass and fuel moisture contents, and 3) monitoring of environmental conditions (relative humidity, wind speed, temperature) and fire behavior (rate of spread, flame height, flame residence time) prior to and during the burn. Results of the modified combustion efficiency of these earlier burns are discussed in Chapter 4.

3.2. BACKGROUND

Fires initiated by lightning strikes comprise only 10% of savanna burns; the rest are anthropogenic (Frost 1996). Reasons for burning include stimulation of grass regrowth for improved livestock fodder, agricultural ash fertilization, agricultural forest clearing, charcoal production, hunting, and clearance of village pathways. Yet, frequent fire may negatively affect soil stability, nutrient cycling, honey and fruit production, and the watershed capacity of dambo grasslands (Prior 1983; Dake 1986). Fire also affects savanna ecological dynamics and regional and global pollution (Walker 1980; Stromgaard 1988b; Ward and Hao 1991; Ward and Radke 1993). The causes of this burning are more complex than population pressure alone and can be attributed to numerous policy directives and global development pressures as well (Moore and Vaughan 1994; Chapter 2).

Recent international field campaigns, e.g. SAFARI-92, were conducted to remedy the lack of biomass data available to estimate fuel loading, the lack of knowledge about temporal variations in the fuel load and environmental fire conditions, and the resultant effect these variations may have on emissions. Moreover, these studies alluded to the need to understand inter-annual variability in the timing and amount of burning (Justice et al. 1996). Concurrent with these studies, remote sensing analysis had given indications that geography, phenology, and annual net primary production were variable and predictable (Gray and McCrary 1981; Townshend and Tucker 1984; Justice et al. 1985; Goward and Dye 1987 in Goward et al. 1991). For example, in the United States, NOAA's Advanced Very High Resolution Radiometer (AVHRR) had been used in

Nebraska to monitor fire danger hazard based on estimates of the Normalized Difference Vegetation Index (NDVI). NDVI is a normalized ratio of red and near infrared reflectances, providing a vegetation index that estimates the greenness of the vegetation, while normalizing scene to scene variations in irradiance (Sadowski and Westover 1986; Goward et al 1991).

International efforts at fire prediction based on NDVI are a result of increasing concern about the effects of biomass burning on the global atmosphere. Malingreau (1984) and Malingreau et al. (1985) used NDVI to predict fire behavior on the Indonesian fires of 1982-1983 when five million hectares of land were affected in Borneo by an El Niño induced drought. They determined that strong declines in greenness were associated with peak fire activity. In 1984, UNEP's Global Environmental Monitoring System (GEMS) program coordinators hosted a meeting that inspired further research on AVHRR grassland monitoring (Justice et al. 1985). Concurrent work further elucidated the connection between qualitative and quantitative predictions of biophysical phenomena, many of the studies occurring in Africa (Jenson 1983; Sellers 1985; Tucker and Sellers 1986; Goward 1989; Goward et al. 1991). Efforts which incorporate remote sensing estimations of fire potential, area burned, and fire frequency (Scholes et al. 1996) are validated with field monitoring of seasonal greenness trends. Together, these techniques lead to an understanding of how emissions can be reliably estimated given the complex array of fuel loading, moisture contents, and types of combustion (Griffith et al. 1991).

The fire season in southern Africa is approximately from June to November, although most of the burning occurs in October and November just before the onset of the wet season, when the moisture content of the grass vegetation is driest. Agriculturally, it is logical to burn at this time of the year, for annual crop planting benefits most from the onset of the rains following ash fertilization (Moore and Vaughan 1994; Andriessse and Koopmans 1984). The risks of burning in the late part of the dry season are high when fires are intense enough to develop into wildfires. Also, erosion is accelerated when intense rains of the wet season begin after fires have consumed the aboveground vegetation. Ecological dynamics are also affected. The shift to fire tolerant species (*Pterocarpus angloensis*, *Anisophyllea boehmii*, and *Diplorhynchos condylocarpon*) and eventually to chipya environments is accelerated by late fires (Walker 1980). Populations living within chipya environments have adapted by utilizing mound production thus avoiding fire use altogether (Stromgaard 1988a). Late fires have also been attributed to fungal growth on honey trees, reduction in harvested mushroom and caterpillar yields, and loss of forest productivity for firewood and tree poles used in construction (Clarke et al. 1996; Brigham et al. 1996). The effects on nutrient cycling by burning after litter fall (mid-July) are not known.

Fire is a major management problem for the natural regeneration of savanna woodlands in tropical Africa (Chidumayo 1988). Complete fire protection is impractical due to the many necessary uses of fire by indigenous people, such as agricultural forest conversion, grazing, poaching, charcoal production, and agricultural fertilization for shifting cultivation. For many years, it had been national policy to avoid using dambos in

agricultural and livestock production so that they would be sponges for recharge of natural water supplies. Yet, cropping and grazing practices, which involve fire, have increased within Zambia (Prior 1983).

Attempts to promote early burning have been strongly recommended by ecologists and managers as the best way to avoid dambo erosion and preserve soil organic matter, watershed health, and maintain livestock stocking rates (Prior 1983; Harris 1980). Simultaneously, in the miombo, recommendations for early burning have meant to promote forest health for future forestry activities such as production of non-timber forest products and lumber (Walker 1980; Prior 1983; Guy 1989). The British South Africa Company and the colonial administration promoted early burning in Zambia to prevent wildfires from accidentally occurring (Moore and Vaughan 1994). Similar management guidelines have been evoked for areas to decrease the risk of accidental fires and the accumulation of ground fuels and to promote a healthier regrowth of flora (Chidumayo 1988; Trapnell 1959; San Jose and Medina 1975). In many cases, dambos are more likely to burn earlier in the season for livestock grazing (Muwamba 1988).

3.3. METHODS

3.3.1. Study site

The field site is located approximately 7.5 km southeast of Kaoma, Western Province, Zambia in Kaoma Local Forest No. 310 (14°86' S, 24°82' E). Kaoma District averages 900-1000 mm rain/year, most during the wet season (late November to April). Average daily July temperatures (middle of the dry season) are 17.5-20°C. Elevation is

approximately 1170 meters. Despite the fact that the site is a Protected Forest maintained by the Department of Forestry, both ecosystems are heavily utilized by local agriculturists and villagers for charcoal manufacturing, fuelwood collection, thatch harvesting, honey production, grazing, and agriculture. Local agricultural crops near the study site include cassava, groundnuts, maize, and sweet potatoes. The sites burn every one to two years facilitating agricultural production and livestock grazing.

Soil type transition between the dambo and miombo is dramatic and immediate. Miombo soils in the Kaoma district are at the eastern range of the "Kalahari sands" dominating the Western Province and Angola. The miombo soils contain somewhat more clay than their western counterparts and thus are identified as sandy loams, usually ferrasols or oxisols (Cole 1986). Dambo soils are called black montmorillonitic clays or gleys, depending on the degree of water infiltration (Cole 1986). Soil pH, bulk density, and moisture content were measured during the study period in both the dambo and miombo (see Table 1). Soil pH ranged between 5.4 and 5.9 at each site. Bulk density averaged 0.79 ± 0.17 g/cc in the dambo and 1.43 ± 0.16 g/cc in the miombo with no significant change throughout the study period. Moisture content for each plot was sampled at the burn date, providing a seasonal gradient. Dambo soil moisture content ranged from 4.50 to 7.92% (0-5 cm) and 6.08 to 11.16% (5-10 cm). Miombo soil moisture content ranged from 0.51 to 1.18% (0-5 cm) and 0.73 to 1.08% (5-10 cm). There was no apparent seasonal trend in soil moisture content through the duration of the study period. Shea et al. (1996) found very low moisture contents in the late dry season. For their dambo grassland site, Shea et al. (1996) found surface soil moisture content (0-2.5

cm) of $0.3 \pm 0.1\%$ and subsurface soil moisture content (2.5-10 cm) of $1.4 \pm 0.1\%$. For their semi-arid miombo site, Shea et al. (1996) found average moisture contents of $0.7 \pm 0.0\%$ for the surface soil and $0.9 \pm 0.1\%$ for the subsurface soil. The soil moisture content for the miombo across the two studies is similar, although a higher soil moisture content was found in our measurements of the dambo in the early dry season.

Table 1: Soil conditions in the miombo and dambo during the study period

| | <u>MIOMBO</u> | <u>DAMBO</u> |
|---------------------------------------|-----------------|-----------------------|
| MOISTURE (%) 0-5 cm | 0.51% - 1.18% | 4.50 to 7.92% |
| MOISTURE (%) 5-10 cm | 0.73% - 1.08% | 6.08 to 11.16% |
| PH | 5.4 - 5.9 | 5.4 - 5.9 |
| BULK DENSITY (G/CC) | 1.43 ± 0.16 | 0.79 ± 0.17 |
| TEXTURE | sandy loam | montmorillonitic clay |

3.3.2. Dry Weights

Fourteen two-hectare plots (100 m x 200 m) were established, six in a miombo woodland and eight in a dambo grassland. The dambo and miombo are approximately 500 meters apart. For analysis of vegetation biomass loading, fuels were collected from three distinct sampling clusters which were equally spaced along the long axis of each 2 hectare plot (see Figure 1). The cluster design was used to provide samples that would be concentrated at each Fire - Atmosphere Sampling System (FASS) tower which was placed at the center of each cluster and so that results from this study could be used by the

Intermountain Fire Sciences Lab in Missoula, MT to compare to previous studies (Shea et al. 1996) with the same design. The FASS tower is a self-contained monitoring package that collects real-time measurements of emissions fluxes, wind measurements, and particulate matter for each phase of combustion. The results of the FASS measurements will be discussed in Chapter 4. For complete description of the FASS packages, refer to Ward et al. (1996).

A sampling design similar to that used by Shea et al. (1996) in Africa and by Kauffman et al. (1995) in Brazil was used for this project. Eight (0.5 meter x 0.5 meter) subplots were established per cluster for a total of 24 subplots per plot (see Figure 2). There were ten 15 meter transects per cluster and each subplot was located 4 meters along the transect (with a 2 meter radius around the center of the cluster for the FASS tower). Metal or wood stakes were used to mark the beginning and end of the transects so as to facilitate relocation. Sampling was always performed on the right of the transect to avoid trampling.

The total aboveground vegetation below 2.5 meters, the height below which the biomass would be susceptible to combustion (Shea et al. 1996), excluding tree trunks, was collected from each subplot down to mineral soil. In the dambo, the vegetation was sorted into live grass and standing dead grass. In the miombo, vegetation was sorted into 0-0.64 cm diameter downed wood, 0.65-2.54 cm diameter downed wood, live grass, standing dead grass, standing live wood 0-0.64 cm diameter, litter, leaves, and live wood (including small shrubs (with leaves) under 0.3 meters). Litter was composed of all forest material above mineral soil that was not rooted; it therefore included dry leaves, seeds,

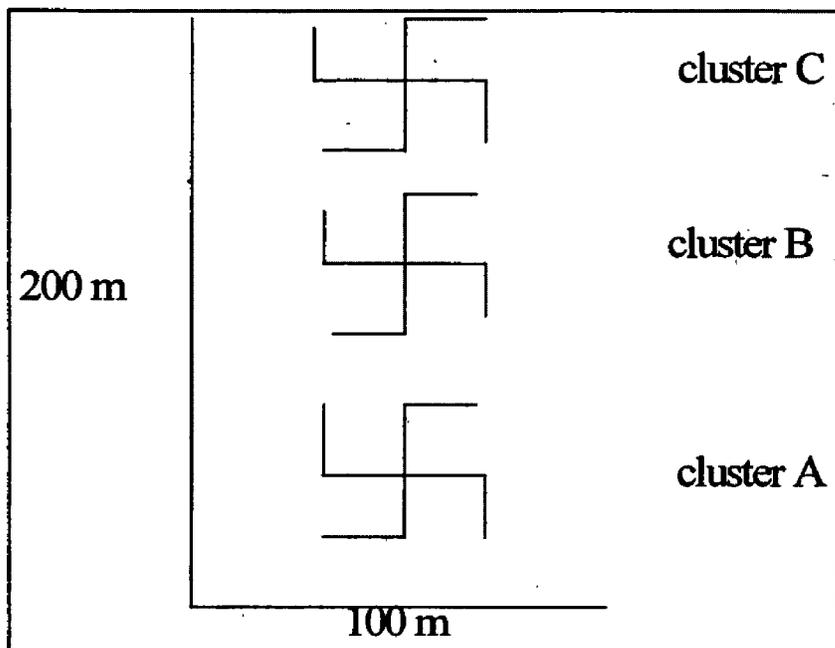


Figure 1: Cluster layout along a plot (see Figure 2 for details)

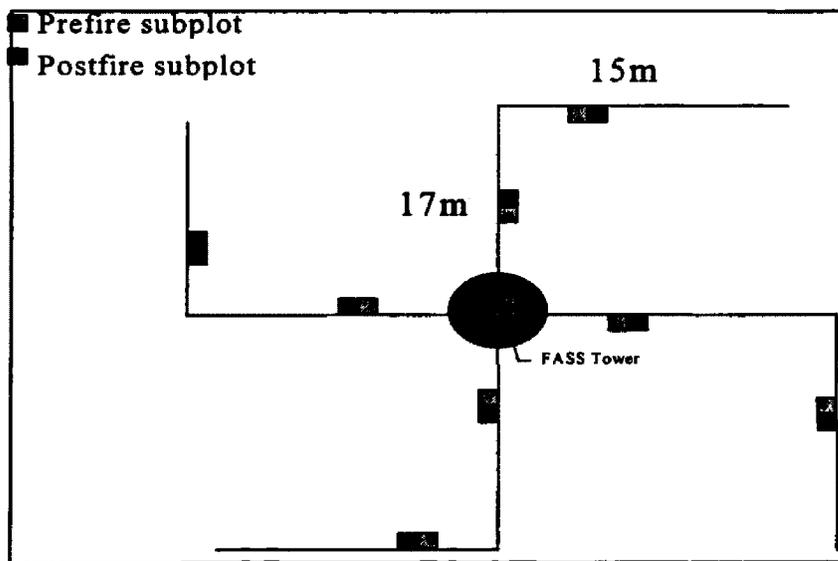


Figure 2: Subplot layout in a cluster

bark, and dead grass. Leaves were stripped from branches under 2 meters which were within the plot, either rooted or hanging into it. The vegetation was sorted into paper

bags and a composite sample from each bag was oven-dried for 48 hours at 60-70°C. The difference in weight before and after the oven-drying was assumed to be the mass of water that had been present, which was then used to calculate the dry weight of the original fuel sample. The problems of using oven-drying for dry weight determinations have been well documented by Simard (1968). The ratio of live herbaceous material to total fuel was calculated to determine the proportion of live grass pre-fire.

The separation of downed wood fuel classes based on size is important for determination of fire behavior characteristics (Simard 1968). The diameter of the downed wood affects the time it takes for the wood to dry to 2/3 of its equilibrium water content, thus affecting its combustion efficiency. While the 1 hour (0-0.64 cm diameter) and 10 hour (0.65-2.54 cm diameter) woody fuels were collected in the subplots, the 100 hour woody fuels (2.55-7.62 cm diameter) were sampled using the planar intercept method (Van Wagner 1968). The 1000 hour fuels (7.63-20.3 cm diameter) were not sampled as they were not expected to significantly undergo combustion due to the relative low intensity of the burns. The downed wood that was measured along the transect was relocated after the burn and re-measured to determine downed woody combustion for that size class.

Plots were successively burned at approximately 1-2 week intervals through the length of the study period between June 5, 1996 and August 6, 1996. The day previous to each fire the pre-fire sampling was performed as described above. On the day following each fire, vegetation was collected in the same manner as pre-fire, but at subplots further

along the transect (but directly above the pre-fire subplot). Ash was also collected (by hand) from the post-fire subplots. These samples were then oven-dried to determine dry weights of the post fire vegetation.

3.3.3. Moisture Content

The moisture content of each type of vegetation was sampled immediately before each burn. They were sampled at random and placed in plastic bags to be taken to the laboratory. They were then immediately oven-dried for 48 hours at 60-70°C and weighed again. The difference in weight was assumed to be equal to the mass of water originally present in the fuel, and thus a percent moisture content of the fuels was calculated.

At the end of each major transect, soil moisture contents were collected immediately prior to the fire. With a soil probe, collections were made at depths of 0-5 cm and 5-10 cm. For each cluster, eight measurements at each specified depth were combined to form a composite sample and brought in a plastic bag to the laboratory. The samples were then weighed, oven-dried for 72 hours at 60-70°C and then weighed again. As with the vegetation samples, the difference in weight was assumed to be equal to the mass of water originally present in the fuel, and a percent moisture content of the soils was calculated.

3.3.4. Environmental Conditions

A Campbell Scientific System, Inc. weather station was set up in the dambo for the length of the study period, which recorded relative humidity, precipitation, temperature, wind speed, maximum wind speed, and wind direction in 15 minute intervals, continuously between June 11 and August 8 (see Table 4 and 5). In addition, a

hand-held turbometer and psychrometer were used at each site immediately prior to and during the fire. The weather station was on bare soil next to the first dambo plot. It was therefore set apart from the miombo by several hundred yards and from later dambo burns. The miombo weather conditions were presumably slightly different than the dambo due to significant tree shading and wind resistance therefore lowering temperature and increasing relative humidity. Measurements of weather conditions taken on-site in the miombo were presumed to be more representative than the dambo weather station recordings.

3.3.5. Fire Behavior

Laboratory experiments that simulate fuel emissions, which have an intrinsic advantage of having known parameters, cannot simulate intense field fire behavior which can be very different (Robinson 1988). The rate of emissions depends on the rate of biomass consumption, the rate of spread, and the combustion efficiency of the fire which is dependent on the phase of combustion (Kaufman et al. 1992). To determine whether moisture content affected CF, fire behavior measurements were taken during the fire. These included flame height (meters), flame angle (degrees), flame residence time (seconds), and advancing flame front rate of spread (meters/second) (Alexander 1982). Flame height was measured by visual comparison with the known height of the FASS tower (constructed by lengths of 5 meter metal tubing). The rate of spread was measured by a stopwatch as the fire front moved between two points over a known distance. Flame residence time was also measured several times during each fire with a stopwatch as an ocular estimation of the time for combustion completion at a particular fuel point.

Intensity is one of the most poorly defined or communicated measures of wildfire behavior (Albini 1976). In this study, two values of fire intensity are compared: fire line intensity and reaction intensity. Fire line intensity is related to the flame height of the fire and thus is closely related to what people would visualize as “fire intensity” (Albini 1976). Fire line intensity was calculated according to Byram (1959):

$$I = Hwr$$

I = fire line intensity ($\text{kJ s}^{-1} \text{m}^{-1}$)

H = heat of combustion (kJ kg^{-1})

w = mass of fuel consumed (kg m^{-2})

r = rate of spread of flame line (m s^{-1})

where a value of $H = 16890 \text{ kJ kg}^{-1}$ was used based on work by Trollope (1983) for grass fuels in Kruger National Park in South Africa. Byram’s Intensity Index is a product of the fuel loading, the fuel heat of combustion and the rate of spread of the advancing flame front. It assumes that the heat evolution is confined to a linear fire line (Robinson 1988). The actual heat of combustion, H, may have been lower in the early burns since the presence of moisture in the fine fuels can affect the quantity of heat that is evolved (Alexander 1982). Use of this H value is only justified by its use in other studies of African fuel heat yields (Shea et al. 1996; Trollope et al. 1996); future studies must evaluate the accuracy of this number for heading fires in environments other than the South African grasslands for which it was originally calculated. In fact, the value of 16890 kJ kg^{-1} used by Trollope is somewhat lower than the basic heat value of 18700 kJ kg^{-1} for low heat of combustion as used by Alexander (1982).

Fire line intensity is related to reaction intensity by the equation:

$$I = I_R D$$

where $I = Hwr$ ($\text{kJ s}^{-1} \text{m}^{-1}$) after Byram (1959), $I_R =$ reaction intensity ($\text{kJ s}^{-1} \text{m}^{-2}$), and D is the depth of the flaming zone (Albini 1976):

$$D = (\text{rate of spread}) * (\text{flaming zone residence time})$$

Reaction intensity is defined as the rate of heat release per unit area of ground beneath the fuel bed (Albini 1976). It is therefore a more direct measure of the ecological effects of the fire as it propagates over a unit area versus fire line intensity which is dependent on external environmental conditions, such as wind speed, which affect flame height.

3.3.6. Vegetation

3.3.6.1. *Dambo*

The transition from a miombo woodland to a seasonally flooded grassland, a dambo, is abrupt, marked by a change of soil type from yellow sand loams to black, montmorillonitic clays. The species of grass found in the dambo are predominantly *Setaria* spp., *Themeda* spp., *Loudetia* spp., and *Hyparrhenia* species (Cole 1986). Little is known about the relationship of dambos as recharge areas to the perennial stream flow, but it is considered significant (Prior 1983; Dake 1986). Currently, dambos occupy 10% of Zambia's land area (Muwamba 1988; Allan 1965). The National Council for Scientific Research of Zambia has sponsored water balance calculations for a number of dambos (Dake 1986). World Water has supported a three year research project, funded by the overseas Development Administration of Britain and run by Water and Engineering for Developing Countries (WEDC), to provide an assessment of the risks and benefits of developing dambos for grazing and agriculture, (Dake 1986; Dicko 1992).

Livestock production continues to be a high-ranking policy directive for planning units within Zambia (Dicko 1992) which ensures that dambo management will become that much more critical.

3.3.6.2. *Miombo*

The miombo is an open-canopy, semi-deciduous woodland with a grass and shrub understory. It covers 12.1% of Africa for a total of 3.765×10^6 km² (AETFAT 1959 in Malaisse 1978). However, the miombo woodland covers 80% of Zambia (Chidumayo 1987). Chidumayo (1987) has used the 1100 mm rainfall isohyet to distinguish between wetter and drier miombos. In this classification, the miombo in the study area can be considered a semi-arid miombo. Western Zambia has five subtypes of miombo and has the lowest species diversity among all Zambian miombo systems which may be related to the low fertility of the Kalahari sands and low rainfall (Chidumayo 1987). Typically, miombos average between 138-175 tree species per hectare (Malaisse 1978; Malimbwi et al. 1994). Tree density (> 5 meters in height) was shown to be 200 per hectare in semi-arid miombos compared to 574 per hectare in moist miombos (Shea et al. 1996). Ninety-two percent of the trees are deciduous, losing their leaves approximately 2 ½ months before the onset of the rain season (Malaisse 1978; Lawton 1978). The trees are not dormant during senescence since many species flower during this time (Lamprecht 1986). The leaf fall contributes to 68% of the total litter (Malaisse 1978). Assuming all were deciduous, Malaisse (1978) measured a mean leaf biomass production rate of 2900 kg/ha/year in a Zairean miombo woodland. Chidumayo (1990) measured a mean leaf

biomass of 3333 kg ha⁻¹ in an old growth miombo woodland in the Copperbelt region. Shea et al. (1996) measured a litter biomass of 3062 to 3806 kg ha⁻¹.

The main canopy species present on the study site were *Brachystegia bussei*, *Brachystegia longifolia*, *Pterocarpus angloensis*, *Monotes africanus*, *Diospyros batocana*, *Cryptosepalum exfoliatum*, and *Julbernardia paniculata*. It is thus a *Brachystegia-Julbernardia* woodland. The dominant understory species were *Strychnos innocua*, and *Diplorhynchus condylocarpon*. *Brachystegia* and *Julbernardia* species generally are fire tender. *Brachystegia longifolia* is semi-tolerant and *Pterocarpus angloensis* is decidedly fire tolerant (Trapnell 1959). The plants develop ligno-tubers at the seedling stage which enable them to withstand substantial drought, and additionally, to survive frequent fire (Cole 1986). The miombo root system also allows for rapid coppicing after felling, fire, or defoliation which makes them particularly stress tolerant (Malimbwi et al. 1994). The uses of the miombo beyond livestock and agriculture are numerous. *Pterocarpus angloensis* is used widely for furniture making, and many species are valued for their ability to host bees that produce honey. Some plants are medicinal and there are approximately 20 kinds of mushrooms that are known to be harvested (Malaisse 1978).

3.4. RESULTS

3.4.1. Fuel Loading

3.4.1.1. Dambo

Table 2 describes the fuel loading (kg ha^{-1}) for the dambo. The results are divided into the sampling categories as described above. Negative values in Table 2 are due to natural sampling variability since the post-fire subplots were sampled, by necessity, at a different spot, although right next to the pre-burn spot. Caution, therefore, must be used when interpreting results from this study. Future studies should be more careful about including consistent paired plot sampling. Also, it should be noted that D212 was excluded from analysis because of a lack of data. Despite these problems, the total pre-fire biomass loading in the dambo on a dry weight basis ranged from 1884 kg ha^{-1} at D156 to 3314 kg ha^{-1} at D199, averaging $2808 \pm 524 \text{ kg ha}^{-1}$. This is less than the value reported by Shea et al. (1996), 3164 kg ha^{-1} , for the single Zambian dambo site observed in their study, but is within the mean fuel loads ($959, 2437, 3922,$ and 4035 kg ha^{-1}) observed by Stocks et al. (1996) in similar environments in South Africa. It is proposed that differences in fuel loads in grassland systems are related to fire frequency, grazing pressure, and interannual climate variation (Stocks et al. 1996, Shea et al. 1996).

Assuming annual or biennial burning of the study site, biomass accretion is dependent on the amount of precipitation from the previous wet season. Personal communication with farmers indicated that annual precipitation the previous wet season was at normal levels. Therefore, these biomass amounts fall within the normal range of

Table 2: Fuel biomass (kg ha⁻¹) of the dambo with standard errors in parentheses

| | <u>D156**</u> | | | <u>6/5/96</u> | | | <u>D165</u> | | | <u>6/14/96</u> | | | <u>D177</u> | | | <u>6/26/96</u> | | | <u>D190</u> | | | <u>7/9/96</u> | | |
|---------------------|---------------------|---------------------|------------|---------------------|---------------------|------------|---------------------|---------------------|------------|---------------------|---------------------|------------|---------------------|---------------------|----|---------------------|---------------------|----|---------------------|---------------------|----|---------------------|---------------------|----|
| FUEL | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF |
| | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % |
| live grass | 1370(82) | 851(177) | 38% | 1413(110) | 876(168) | 38% | 658(60) | 527(180) | 20% | 675(63) | 362(80) | 46% | | | | | | | | | | | | |
| standing dead grass | 1944(135) | 755(246) | 61% | 1803(125) | 922(177) | 49% | 1747(180) | 0(0) | 100% | 2315(271) | 0(0) | 100% | | | | | | | | | | | | |
| live/dead | .70 | | | .78 | | | .38 | | | .29 | | | | | | | | | | | | | | |
| live/total | .41 | | | .44 | | | .27 | | | .23 | | | | | | | | | | | | | | |
| TOTAL | 3314(217) | 1606(423) | 52% | 3226(235) | 1798(344) | 44% | 2405(240) | 537(180) | 78% | 2990(334) | 362(80) | 88% | | | | | | | | | | | | |
| ash | | 87(15) | | | 66(18) | | | 262(71) | | | 209(33) | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | | | | |
| | <u>D199</u> | | | <u>7/18/96</u> | | | <u>D207</u> | | | <u>7/29/96</u> | | | <u>D218</u> | | | <u>8/6/96</u> | | | | | | | | |
| FUEL | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF |
| | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % |
| live grass | 632(106) | 334(47) | 47% | 598(83) | 254(56) | 58% | 648(107) | 66(15) | 90% | | | | | | | | | | | | | | | |
| standing dead grass | 2019(268) | 0(0) | 100% | 1286(207) | 257(149) | 80% | 2539(118) | 0(0) | 100% | | | | | | | | | | | | | | | |
| live/dead | .31 | | | .47 | | | .25 | | | | | | | | | | | | | | | | | |
| live/total | .24 | | | .32 | | | .20 | | | | | | | | | | | | | | | | | |
| TOTAL | 2651(374) | 334(47) | 87% | 1884(291) | 511(205) | 73% | 3187(22) | 66(15) | 98% | | | | | | | | | | | | | | | |
| ash | | 171(34) | | | 186(36) | | | 253(23) | | | | | | | | | | | | | | | | |

****D156 refers to Dambo plot burned on 5 June, 1996, Julian calendar day 156**

Table 3: Fuel biomass (kg ha⁻¹) for the miombo with standard errors in parentheses

| | M157** | | | 6/6/96 | | | M169 | | | 6/18/96 | | | M186 | | | 7/5/96 | | |
|---------------------------|---------------------|---------------------|------------|---------------------|---------------------|-------------|---------------------|---------------------|------------|---------------------|---------------------|----|---------------------|---------------------|----|----------------|--|--|
| FUEL | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | | | |
| | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | | | |
| live grass | 439(73) | 456(85) | -4% | 210(18) | 33(24) | 85% | 463(95) | 190(18) | 59% | | | | | | | | | |
| standing dead grass | 643(37) | 480(19) | 25% | 787(32) | 847(58) | -8% | 842(67) | 989(102) | -18% | | | | | | | | | |
| total grass | 1082(110) | 936(103) | 13% | 997(49) | 880(82) | 12% | 1305(162) | 1179(120) | 10% | | | | | | | | | |
| litter | 3547(254) | 3659(354) | -3% | 3990(276) | 3650(214) | 9% | 2629(145) | 2252(56) | 14% | | | | | | | | | |
| leaves | 471(56) | 388(35) | 42% | 519(68) | 704(59) | -36% | 1547(135) | 1019(238) | 34% | | | | | | | | | |
| live woody | 690(32) | 800(18) | -16% | 517(104) | 374(48) | 28% | 822(68) | 756(104) | 8% | | | | | | | | | |
| 0-0.64 cm | 1279(84) | 1181(88) | 8% | 1756(247) | 1199(162) | 32% | 1028(47) | 1094(35) | -6% | | | | | | | | | |
| 0.64-2.54 cm | 1884(129) | 1916(235) | -2% | 3599(373) | 2033(105) | 44% | 1913(216) | 1349(66) | 29% | | | | | | | | | |
| total woody | 3163(213) | 3097(323) | 2% | 5355(620) | 3232(267) | 40% | 2941(263) | 2443(101) | 17% | | | | | | | | | |
| TOTAL FUEL BIOMASS | 8953(668) | 8880(833) | 1% | 11378(116) | 8840(671) | 22% | 9244(583) | 7649(619) | 17% | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | |
| | M197 | | | 7/16/96 | | | M205 | | | 7/24/96 | | | M210 | | | 7/29/96 | | |
| FUEL | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | pre fire | post fire | CF | | | |
| | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | kg ha ⁻¹ | kg ha ⁻¹ | % | | | |
| live grass | 156(11) | 216(16) | -38% | 526(149) | 64(14) | 88% | 62(22) | 130(33) | 52% | | | | | | | | | |
| standing dead grass | 955(50) | 423(100) | 56% | 1165(61) | 20(7) | 98% | 348(12) | 692(7) | 95% | | | | | | | | | |
| total grass | 1111(61) | 639(116) | 43% | 1691(210) | 84(21) | 95% | 410(34) | 822(40) | 88% | | | | | | | | | |
| litter | 2642(91) | 2242(26) | 15% | 5342(146) | 4531(138) | 15% | 4100(229) | 1970(202) | 52% | | | | | | | | | |
| leaves | 1480(192) | 442(100) | 70% | 751(159) | 352(27) | 53% | 393(47) | 526(83) | -34% | | | | | | | | | |
| live woody | 955(50) | 423(100) | 11% | 1310(114) | 545(26) | 57% | 1413(95) | 626(36) | 56% | | | | | | | | | |
| 0-0.64 cm | 1024(64) | 1339(67) | -31% | 1479(89) | 1162(54) | 21% | 1183(122) | 1094(69) | 8% | | | | | | | | | |
| 0.64-2.54 cm | 1777(104) | 1406(73) | 21% | 2660(303) | 3766(508) | -42% | 3313(257) | 1313(17) | 60% | | | | | | | | | |
| total woody | 2801(168) | 2745(140) | 2% | 4139(392) | 4928(562) | -19% | 4496(379) | 2407(86) | 46% | | | | | | | | | |
| TOTAL FUEL BIOMASS | 8989(562) | 6491(483) | 28% | 13233(1021) | 10440(479) | 21% | 10812(783) | 6351(600) | 41% | | | | | | | | | |

**M157 refers to Miombo plot burned on 6 June, 1996, Julian calendar day 156

loading for a dambo in a normal precipitation year at an annually or biannually burned site and caution must be made when extrapolating to years which had either more or less precipitation. The amount of live grass that remains in the early dry season is also dependent on rainfall in the wet season. Live grass dry weights ranged from 598 kg ha⁻¹ to 1413 kg ha⁻¹, averaging 856 ± 367 kg ha⁻¹ for the dambo. The amount of standing dead grass ranged from 1286 kg ha⁻¹ to 2539 kg ha⁻¹, averaging 1950 ± 406 kg ha⁻¹. The proportion live for each plot ranged from 0.20 to 0.44, averaging 0.30 (see Figure 3).

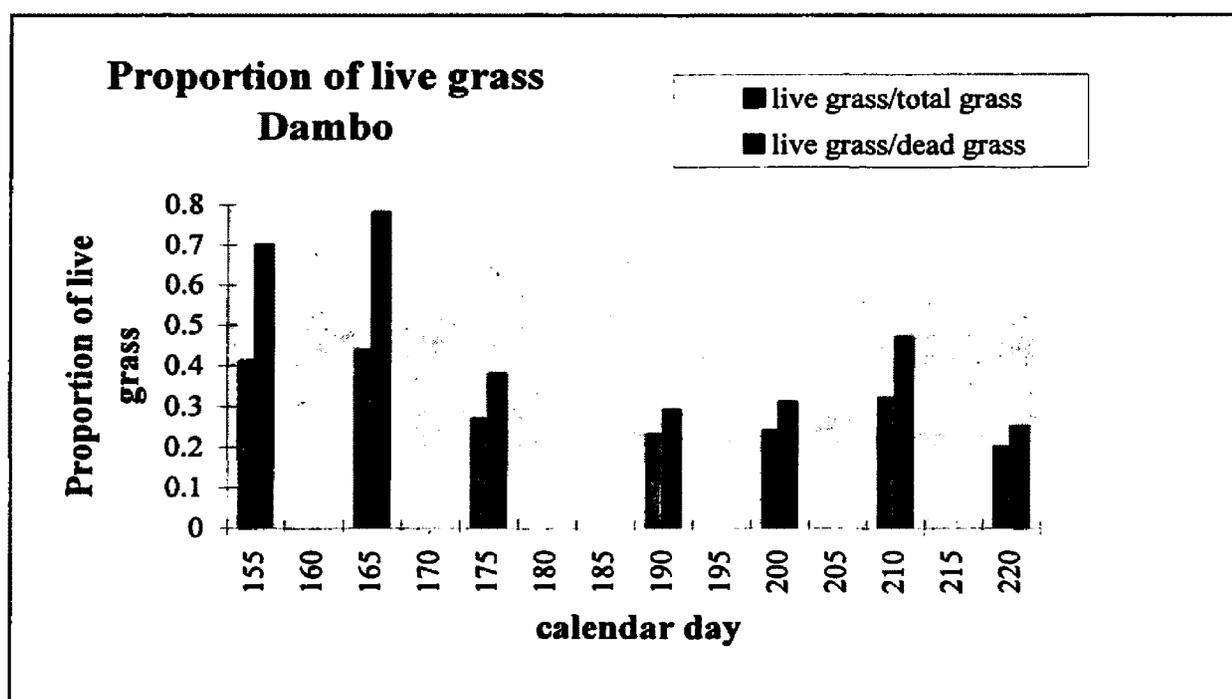


Figure 3: Histogram of proportion of live grass to total grass and the ratio of live and dead grass for calendar day, dambo

Total post fire biomass for the dambo, on a dry weight basis, ranged from 66 kg ha⁻¹ to 1798 kg ha⁻¹. The average post fire biomass loading was 745 ± 674 kg ha⁻¹. Post fire biomass loading of live grass ranged from 66 kg ha⁻¹ to 876 kg ha⁻¹ (average = 467 ± 304 kg ha⁻¹). Post fire biomass loading of standing dead grass ranged from 0 kg ha⁻¹ to

922 kg ha⁻¹ (average = 276 ± 398 kg ha⁻¹). Ash collected after the burn ranged from 87 kg ha⁻¹ to 253 kg ha⁻¹ (average = 176 ± 76 kg ha⁻¹).

3.4.1.2. *Miombo*

The aboveground fuel loading of the miombo plots, on a dry weight basis, ranged from 8953 kg ha⁻¹ to 13233 kg ha⁻¹, averaging 10435 ± 1707 kg ha⁻¹ (see Table 3). This number is larger than the 7343 kg ha⁻¹ for a fallow chitemene site and 5100 kg ha⁻¹ for a semi-arid miombo found by Shea et al. (1996). Normal precipitation for the 1996 wet season, compared to the lower than normal precipitation of the 1992 study by Shea et al. (1996), may account for the slightly higher biomass loading in this study (Justice et al. 1996). The differences among sites may be due to different land uses, the significant amount of litter found at the study sites during the dry season after the immediate leaf fall, or natural variability. However, this value is in agreement with Goldammer (1991) who suggests that available fuel loads range from 5 to 10 tons/hectare in deciduous forests and open tree formations including savannas. The amount of herbaceous material ranged from 410 kg ha⁻¹ to 1691 kg ha⁻¹, averaging 1099 ± 419 kg ha⁻¹. This is less than the 3851 kg ha⁻¹ of herbaceous material found by Shea et al. (1996). Total woody biomass ranged from 2941 kg ha⁻¹ to 5355 kg ha⁻¹, averaging 3816 ± 1016 kg ha⁻¹. Litter ranged from 2629 kg ha⁻¹ to 5342 kg ha⁻¹, averaging 3708 ± 1023 kg ha⁻¹. The proportion of litter ranged from 0.28 to 0.40, averaging 0.35. The proportion of woody fuels (0 - 2.54 cm diameter) ranged from 0.31 to 0.47, averaging 0.36. The proportion of live grass to total grass ranged from 0.14 to 0.41, averaging 0.26. The proportion of live grass to total

fuel load in the miombo ranged from 0.01 to 0.05, averaging 0.03. The ratio of live grass to dead grass ranged from 0.18 to 0.68, averaging 0.38 (see Figure 4).

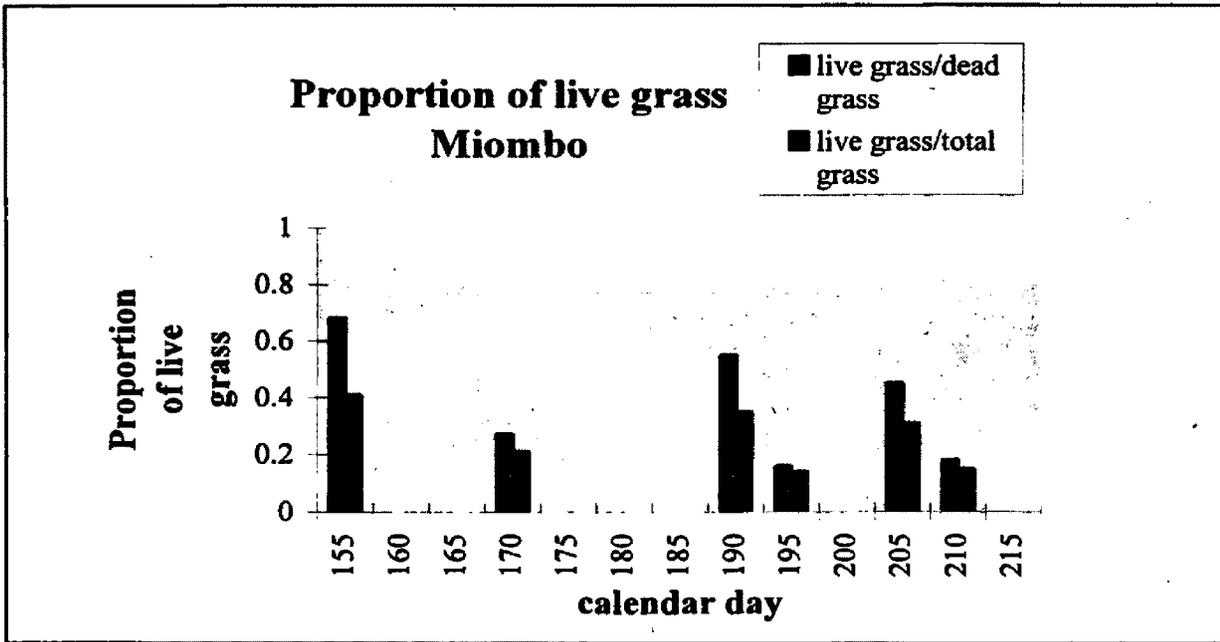


Figure 4: Histogram of proportion of live grass/total grass and proportion of live grass/dead grass on calendar day, miombo

Post-fire fuel biomass in the miombo ranged from 6351 kg ha⁻¹ to 10440 kg ha⁻¹. The average post fire biomass was 8109 ± 1580 kg ha⁻¹. Post fire biomass loading of live grass ranged from 33 kg ha⁻¹ to 456 kg ha⁻¹ (average = 182 ± 152 kg ha⁻¹). Post fire biomass loading of standing dead grass ranged from 20 kg ha⁻¹ to 989 kg ha⁻¹ (average = 575 ± 346 kg ha⁻¹). Total woody fuel biomass remaining ranged from 2407 kg ha⁻¹ to 4928 kg ha⁻¹ (average = 3142 ± 937 kg ha⁻¹) (see Figure 5). There was no significant change in amount of woody biomass among the plots that were studied, indicating no seasonal variation in woody biomass amounts.

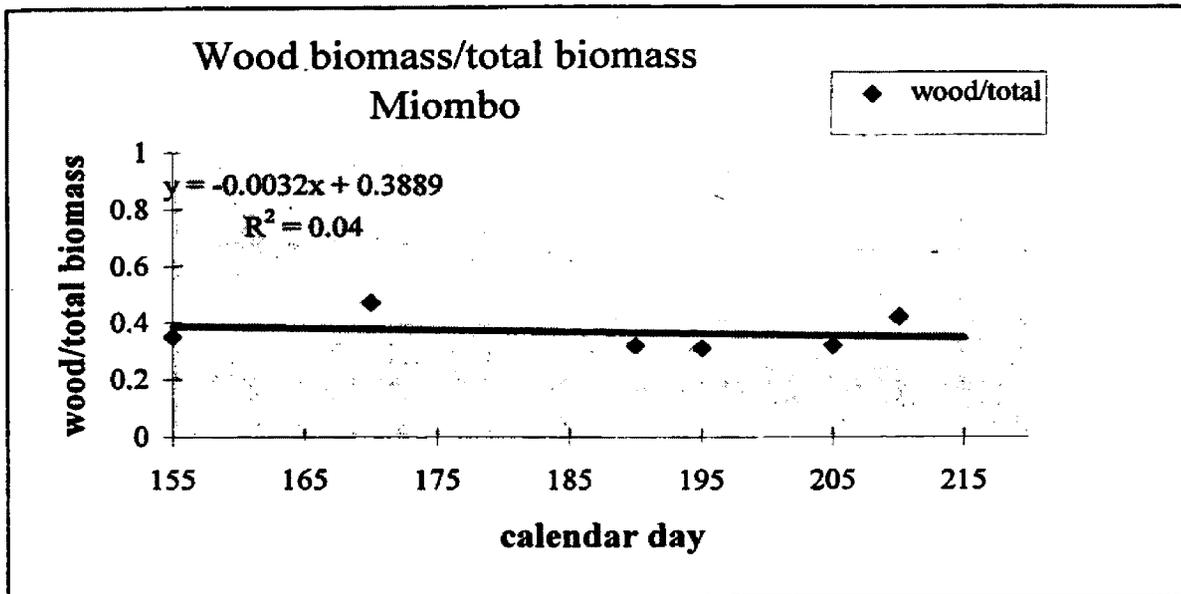


Figure 5: Linear regression of wood biomass/total biomass on calendar day, miombo

3.4.2. Moisture Content

3.4.2.1. Dambo

Table 4 describes the environmental conditions, vegetation moisture content and fire behavior results of the dambo. Pre-fire moisture content of the live grass in the dambo ranged from 69% to 127% (see Figure 6). The moisture content of the standing dead grass ranged from 13% to 38%. The average moisture content of all the grass ranged from 37% to 82%.

3.4.2.2. Miombo

Table 5 describes the environmental conditions, vegetation moisture content and fire behavior results of the miombo. The moisture content of the miombo live grass was between 33% and 119%, whereas for the standing dead grass, the moisture content ranged very little, from 4% to 13% (see Figure 7). The low measurements of live grass moisture

Table 4: Environmental conditions, moisture content, and fire behavior, dambo

| | D156** | D165 | D177 | D190 | D199 | D207 | D218 |
|--|---------|---------|---------|---------|---------|---------|---------|
| Date | 6/5/96 | 6/14/96 | 6/26/96 | 7/9/96 | 7/18/96 | 7/26/96 | 8/6/96 |
| Time | 1330 | 1200 | 1230 | 1320 | 1330 | 1330 | 1330 |
| Temperature (°C) | 27 | 23 | 23 | 24 | 21 | 25 | 30 |
| Relative Humidity(%) | 26 | 31 | 30 | 24 | 41 | 27 | 22 |
| Wind speed (m s ⁻¹) | 1.94 | 1.15 | 1.67 | 1.37 | 2.29 | 1.72 | 1.37 |
| Maximum wind(m s ⁻¹) | 4.14 | 2.38 | 3.08 | 3.08 | 4.05 | 2.77 | 2.51 |
| Wind direction | NE | E | SE | SE | SE | E | E |
| Sky | clear | clear | clear | clear | clear | clear | clear |
| Live grass (%moisture) | 127.13 | 106.87 | 77.43 | 98.28 | 72.33 | 71.38 | 69.41 |
| Standing dead grass (%moisture) | 37.18 | 12.67 | 17.31 | 18.00 | 23.84 | 37.81 | 33.91 |
| Flame height, observed (m) | 0.3-1.5 | 0.3-1.0 | 1.0-3.0 | 1.8-4.5 | 0.3-3.0 | 1.5-2.1 | 2.0-6.0 |
| Flame height, predicted (m) | 1.05 | 1.33 | 1.67 | 3.33 | 3.14 | 1.21 | 3.99 |
| Rate of spread(ms ⁻¹) | 0.10 | 0.20 | 0.25 | 0.80 | 0.80 | 0.17 | 1.00 |
| Residence time (s) | 5.0 | 4.5 | 5.5 | 7.0 | 7.0 | | |
| Reaction intensity (kJ s ⁻¹ m ⁻²) | 576 | 536 | 574 | 634 | 559 | | |
| Fire line Intensity (kJ s ⁻¹ m ⁻¹) | 288 | 482 | 789 | 3551 | 3131 | 394 | 5271 |

** D156 is Dambo plot burned on 5 June, 1996, Julian calendar day 156

content are perhaps due to inaccurate sampling of “live” samples; the higher values are what one would expect in the early dry season.

3.4.3. Fire behavior

3.4.3.1. *Dambo*

Fire behavior measurements for the dambo are also displayed in Table 4. Observed flame height ranged from 0.3 to 5.0 meters for the fires at different times during the study period. Rates of spread ranged from 0.10 to 1.00 m s⁻¹ (see Figure 8). The residence time ranged from 4.5 to 7.0 seconds for those fires for which measurements

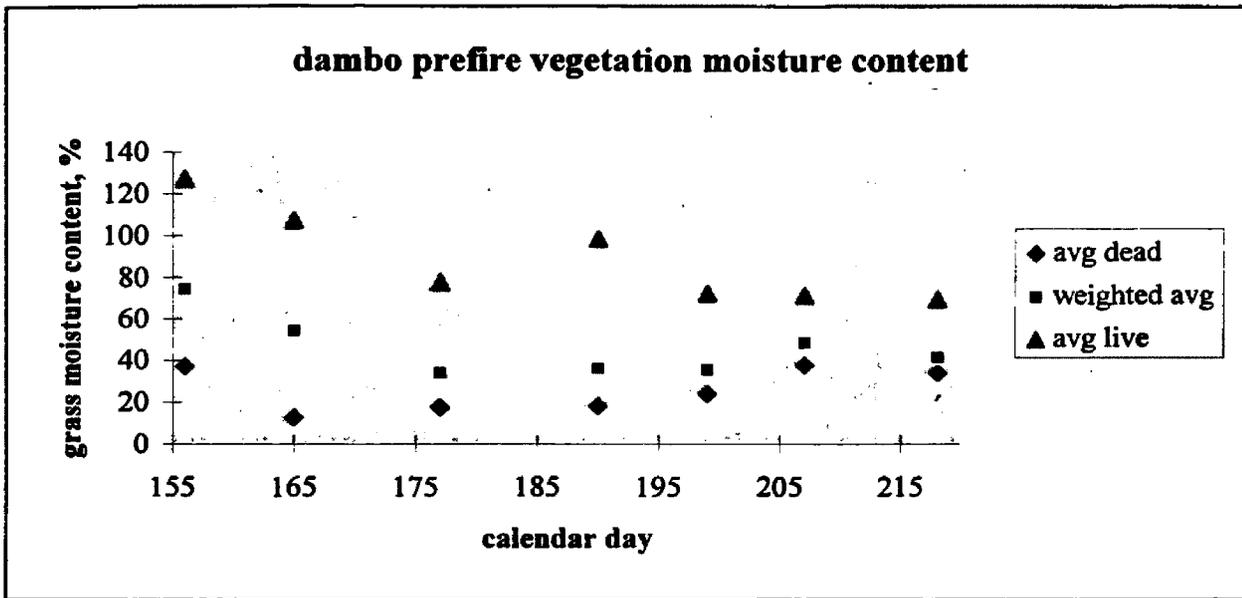


Figure 6: Fuel moisture content, dambo

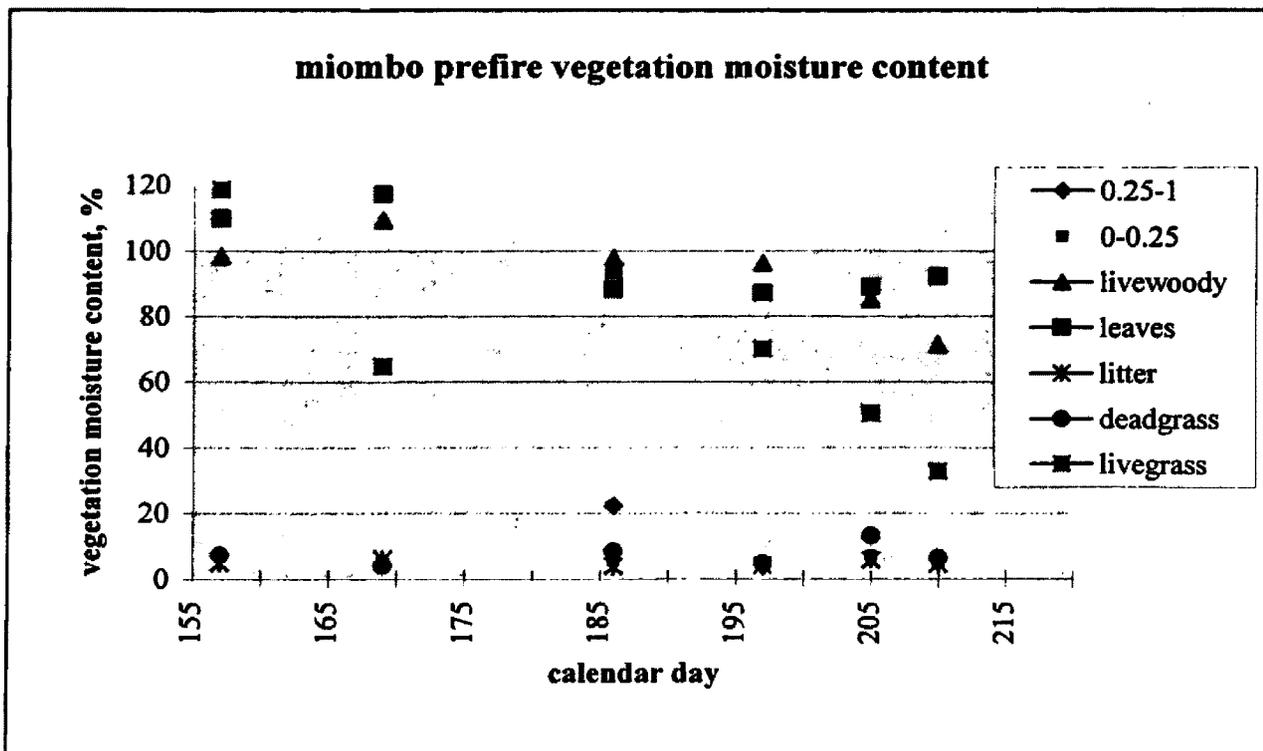


Figure 7: Fuel moisture content, miombo

Table 5: Environmental conditions, moisture content, and fire behavior, miombo

| | M157** | M169 | M186 | M197 | M205 | M210 |
|---|---------------|-------------|-------------|-------------|-------------|-------------|
| Date | 06-Jun-96 | 18-Jun-96 | 05-Jul-96 | 16-Jul-96 | 24-Jul-96 | 29-Jul-96 |
| Time | 1330 | 1330 | 1315 | 1330 | 1330 | 1330 |
| Temperature (°C) | 24 | 27 | 29 | 29 | 24 | 28 |
| Relative Humidity (%) | 30 | 21 | 15 | 10 | 28 | 21 |
| Wind speed(m s⁻¹) | 0.57 | 1.76 | 0.70 | 1.01 | 2.91 | 1.28 |
| Maximum wind(m s⁻¹) | | 3.83 | 1.63 | 2.47 | 7.27 | 11.14 |
| Wind direction | NE | NE | NE | SE | SE | SE |
| Sky | clear | clear | clear | clear | clear | clear |
| Live grass (%moisture) | 118.58 | 64.92 | 93.82 | 70.14 | 50.54 | 32.75 |
| Standing dead grass (%moisture) | 7.35 | 4.17 | 8.44 | 4.75 | 7.09 | 4.54 |
| Flame height, observed, (m) | 1.0-2.0 | 0.1-4.5 | 0.1-4.5 | 0.3-5.0 | | |
| Flame height, predicted, (m) | 0.34 | 1.73 | 1.69 | 3.25 | 4.41 | 3.99 |
| Rate of spread (ms⁻¹) | 0.20 | 0.20 | 0.30 | 0.80 | 0.50 | 0.70 |
| Residence time (s) | 5.0 | 4.5 | 5.5 | 7.0 | 7.0 | |
| Reaction intensity (kJ s⁻¹ m⁻²) | 16 | 534 | 215 | 603 | 1872 | |
| Fire line intensity (kJ s⁻¹ m⁻¹) | 25 | 854 | 808 | 3375 | 6553 | 5274 |

**** M157 is Miombo plot burned on 6 June 1996, Julian calendar day 157**

were taken. Values for fire line intensity, based on the formula by Byram (1959), increased from 288 kJ s⁻¹ m⁻¹ to 5271 kJ s⁻¹ m⁻¹ for the dambo (see Figure 9). Reaction intensity ranged from 536 kJ s⁻¹ m⁻² to 634 kJ s⁻¹ m⁻² for the fires for which it could be calculated.

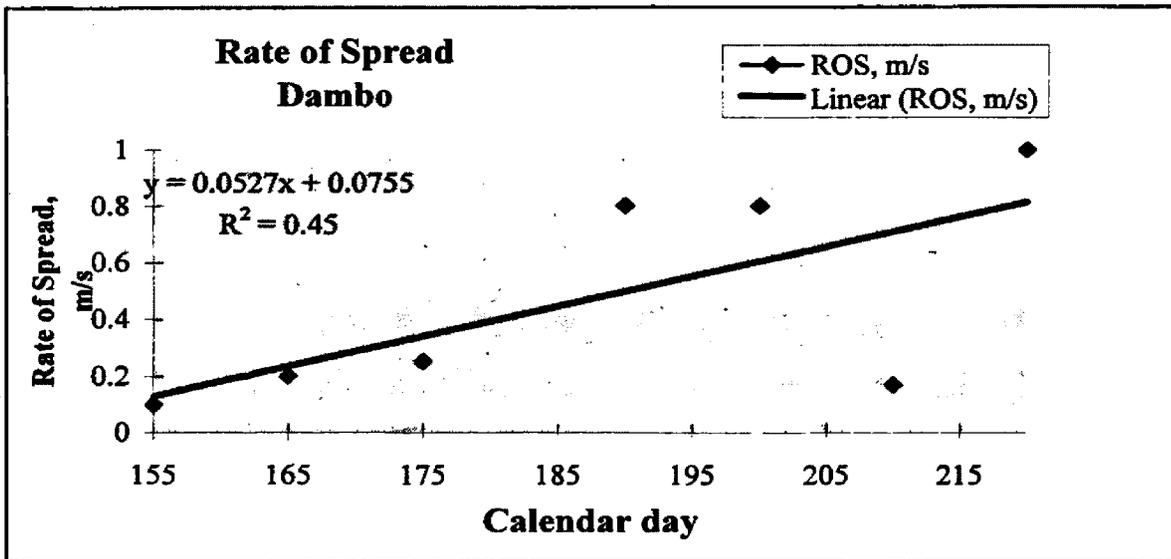


Figure 8: Linear regression of rate of spread on calendar day, dambo

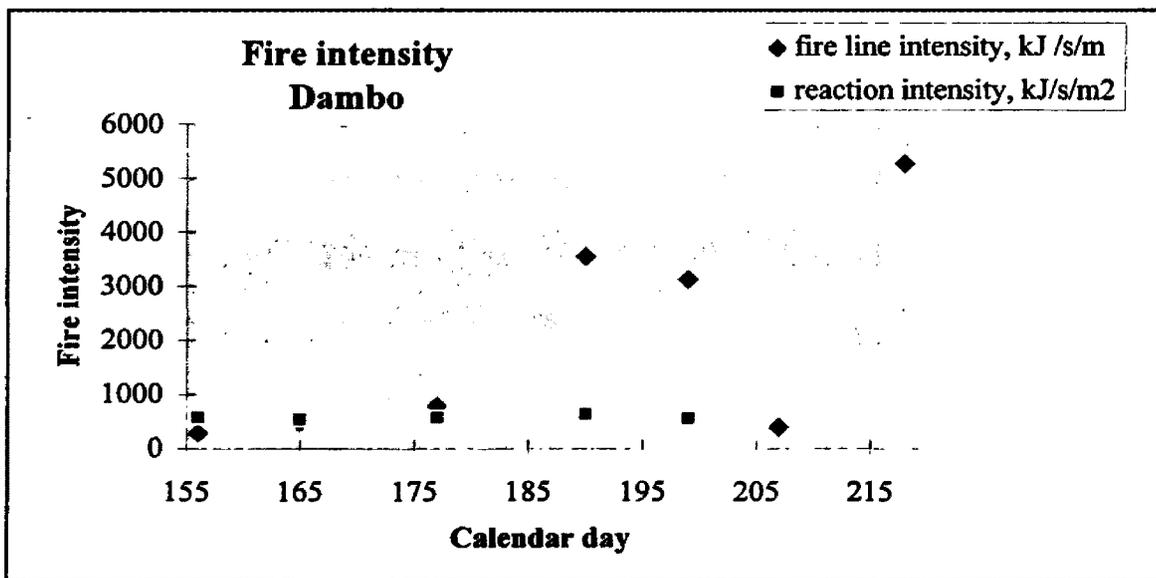


Figure 9: Scatterplot of fire line and reaction intensity on calendar day, dambo

The average value for fire line intensity for the length of the study was $1987 \text{ kJ s}^{-1} \text{ m}^{-1}$, which compares well with Trollope et al. (1996), who observed fire line intensity values of $93 \text{ kJ s}^{-1} \text{ m}^{-1}$ to $3644 \text{ kJ s}^{-1} \text{ m}^{-1}$. Reaction intensity was very similar for the first five fires, where residence time measurements were taken. Values ranged from $536 \text{ kJ s}^{-1} \text{ m}^{-2}$ to $634 \text{ kJ s}^{-1} \text{ m}^{-2}$.

Byram (1959 in Ward 1983) report an approximate relation between flame height, h , in meters, and intensity, I , in $\text{kJ s}^{-1} \text{m}^{-1}$ as:

$$h = 0.0775 (I)^{0.46}$$

where $I = Hwr$ (see above) such that the equation can be rewritten as

$$h = 0.0775 (Hwr)^{0.46}$$

Observed values of r , rate of spread, and w , weight of available fuel, and Trollope's (1983) value of H , heat yield, were included in the above equation, such that a predicted value of flame height, h , was derived. The predicted values for the dambo ranged between 1.05 and 3.99 meters, which is similar to the observed range of values (see Table 4).

The R^2 for the predicted flame height on the calendar burn day in the dambo is 0.46 which indicates little correlation to seasonality (see Figure 10). The predicted flame height from fire D207 is an outlier which lowers the coefficient of determination. When D207 is excluded from the data analysis, the coefficient of determination improves to 0.92. The observable trend is therefore an increase in the flame height as the dry season progresses which supports the hypothesis that the fires are more intense as the vegetation moisture content decreases.

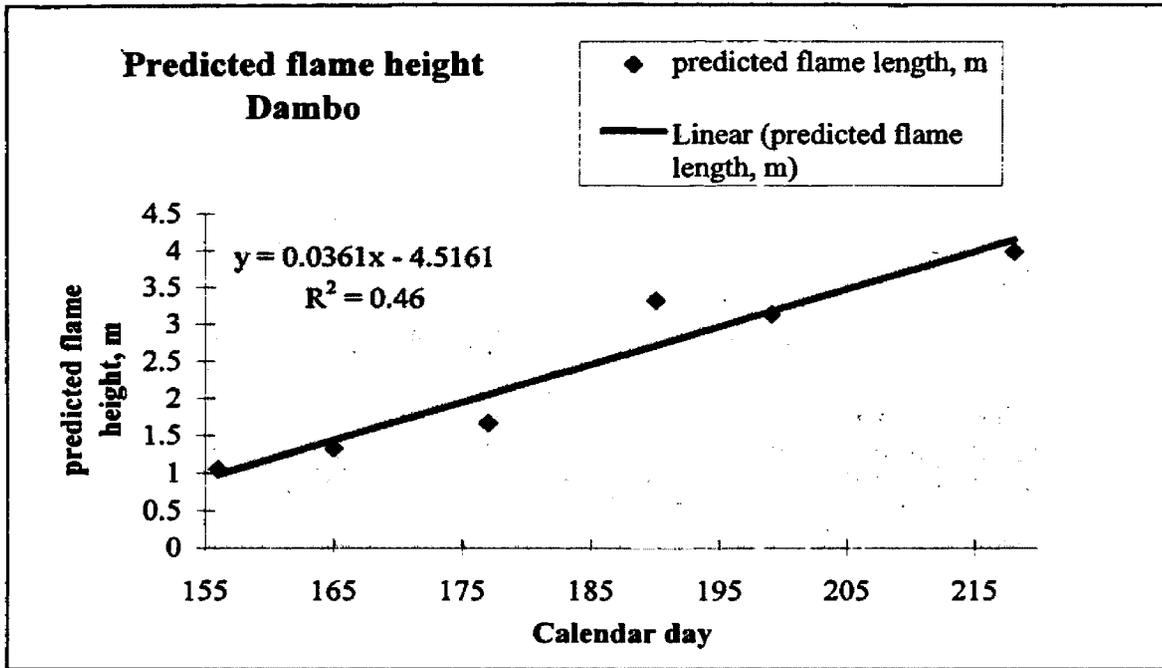


Figure 10: Linear regression of predicted flame height on calendar day, dambo

3.4.3.2. *Miombo*

Fire behavior measurements are displayed in Table 5. Observed flame heights ranged from 0.10 to 5.00 meters. Rates of spread ranged from 0.20 to 0.80 m s⁻¹ (see Figure 11). The coefficient of determination for the rate of spread for the length of the study is 0.60. Residence times ranged from 4.5 to 7.0 seconds. The predicted flame heights, as calculated from the above equation, were between 0.34 to 4.41 meters, which is similar to the observed range of values (see Table 5 and Figure 12). There is significant variation in predicted flame heights during the length of the study ($R^2 = 0.86$). Fire line intensity ranged from 25 kJ s⁻¹ m⁻¹ to 5274 kJ s⁻¹ m⁻¹, averaging 2815 kJ s⁻¹ m⁻¹. Reaction intensity ranged from 16 to 1872 kJ s⁻¹ m⁻², averaging 648 ± 725 kJ s⁻¹ m⁻², for the first five miombo fires where residence times were measured (see Figure 13). The significant variation between these values is due to the spotty nature of the first fires in the miombo.

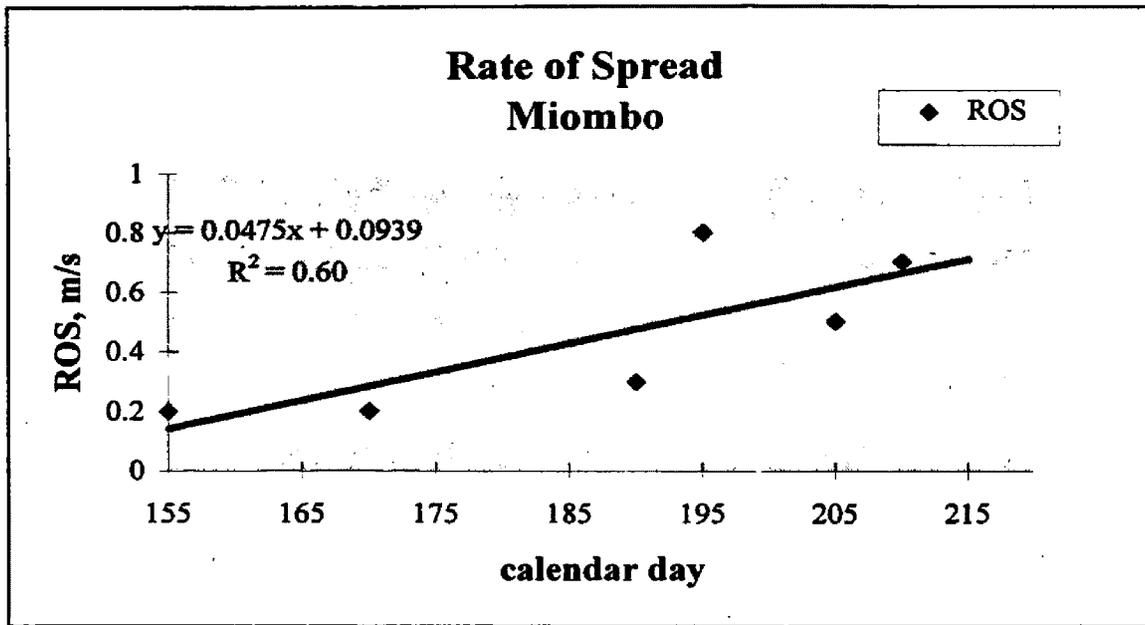


Figure 11: Linear regression of rate of spread on calendar day, miombo

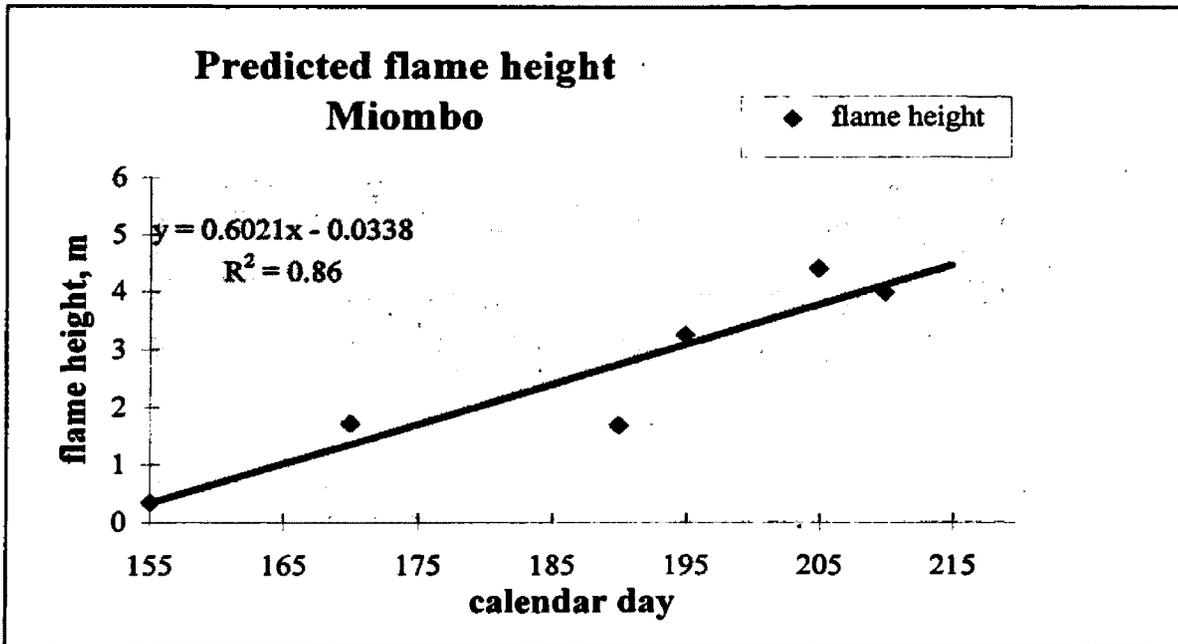


Figure 12: Linear regression of predicted flame height on calendar day, miombo

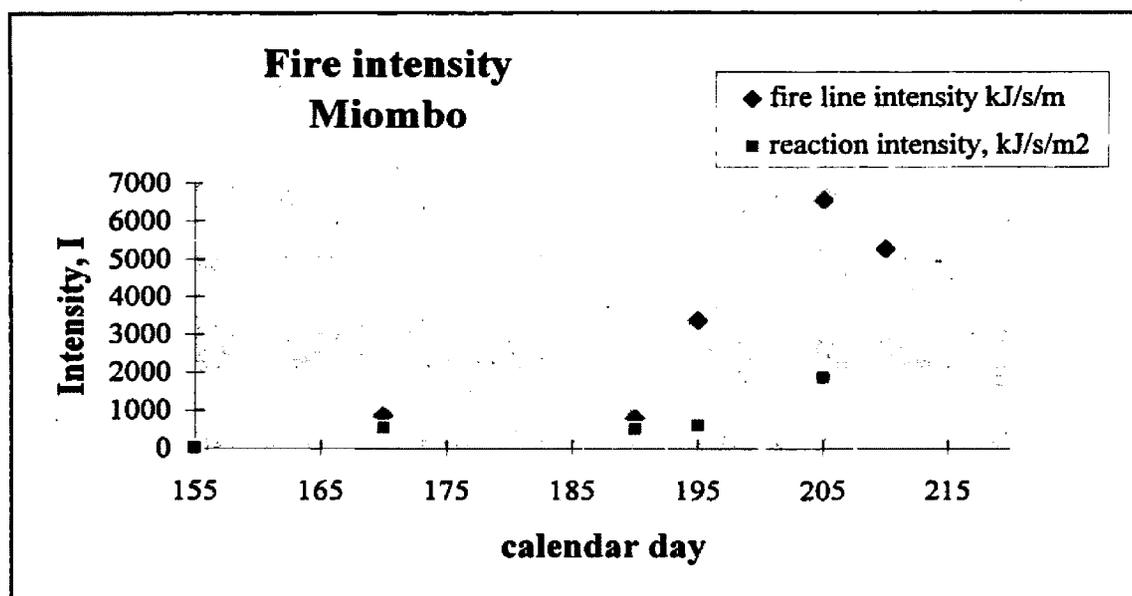


Figure 13: Scatterplot of fire line and reaction intensity on calendar day, miombo

3.4.4. Environmental Conditions

All fires were lit around 1330 hours (ranging from 1200 to 1330). Temperature at the time of burn averaged $24.7^{\circ}\text{C} \pm 3.0^{\circ}\text{C}$ in the dambo and $26.8^{\circ}\text{C} \pm 2.3^{\circ}\text{C}$ in the miombo. Relative humidity ranged from 10 to 41% between both sites. Wind speed ranged from 0.57 to 2.91 m s^{-1} in the miombo and from 1.15 to 2.29 m s^{-1} in the dambo. Winds were predominantly from the E-SE. Sky cover was clear. There was no precipitation recorded during the length of the study. However, there was often extensive dew in the dambo site in the early morning which disappeared shortly after sunrise. This may have affected the moisture content of the dambo grass through condensation in the morning; the effect of dew on the dambo grass is the potential focus of further research. It should also be noted that, at other dambo sites, night frost was evident during July. Although not evident at the study site, its effects at other dambos may be significant in

terms of seedling survival and moisture content equilibrium. These variables were not measured in this study.

3.5. DISCUSSION

3.5.1. Dambo

While this study attempted to witness a seasonal change in fire intensity as the season progressed, it also was apparent that these seasonal changes were made more complex by the heterogeneity of the fuel conditions, both between the miombo and dambo, and within each type of environment. For example, CF values of the fuels in the dambo did increase as the season progressed from 44% (on 6/14/96) to 98% (on 8/6/96) (See Table 2 and Figure 14). Live grass CF values ranged from 20% (on 6/26/96) to 90% (on 8/6/96). Dead fuel consumption ranged from 49% (on 6/14/96) to 100% for the last five burns. However, D207 is an anomaly in determinations of seasonal trends of increasing CF (see Figure 14). Its total CF is less than the burn previous to and following it. The reason for the anomaly is perhaps due to the fact that 31% of the total grass load was considered "live", which is much higher than for the burns preceding and following (23% on D190 and 20% for D218). However, despite the fact that D207 is an anomaly with regard to seasonal trends, it does not affect the strong negative correlation between proportion live and CF in a regression analysis ($\text{adj}R^2=.99$, $\text{SEE}=1.825$, $p=0.000$) (see Figure 15).

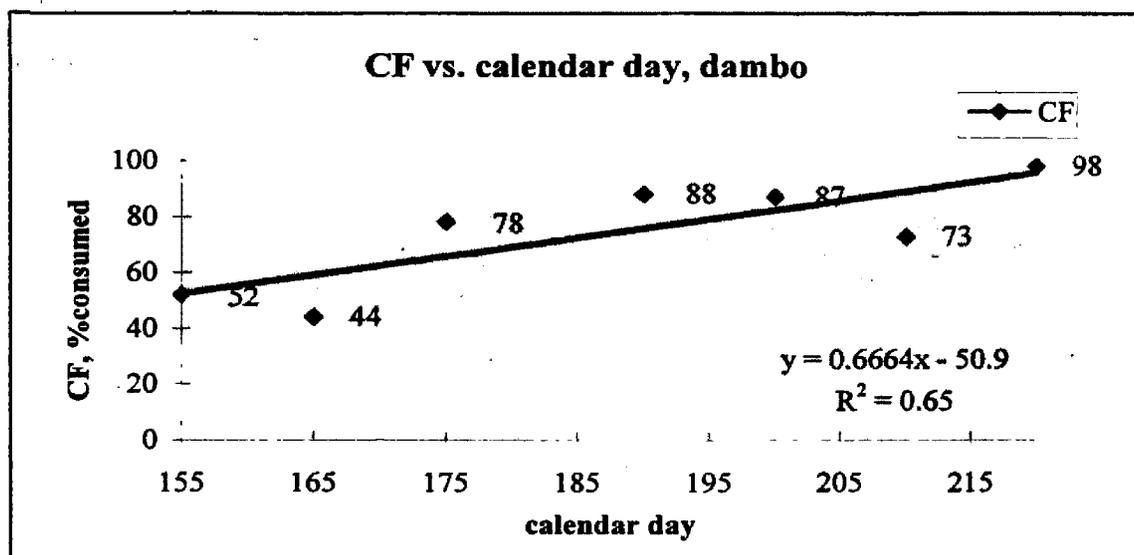


Figure 14: Linear regression of CF on calendar day, dambo

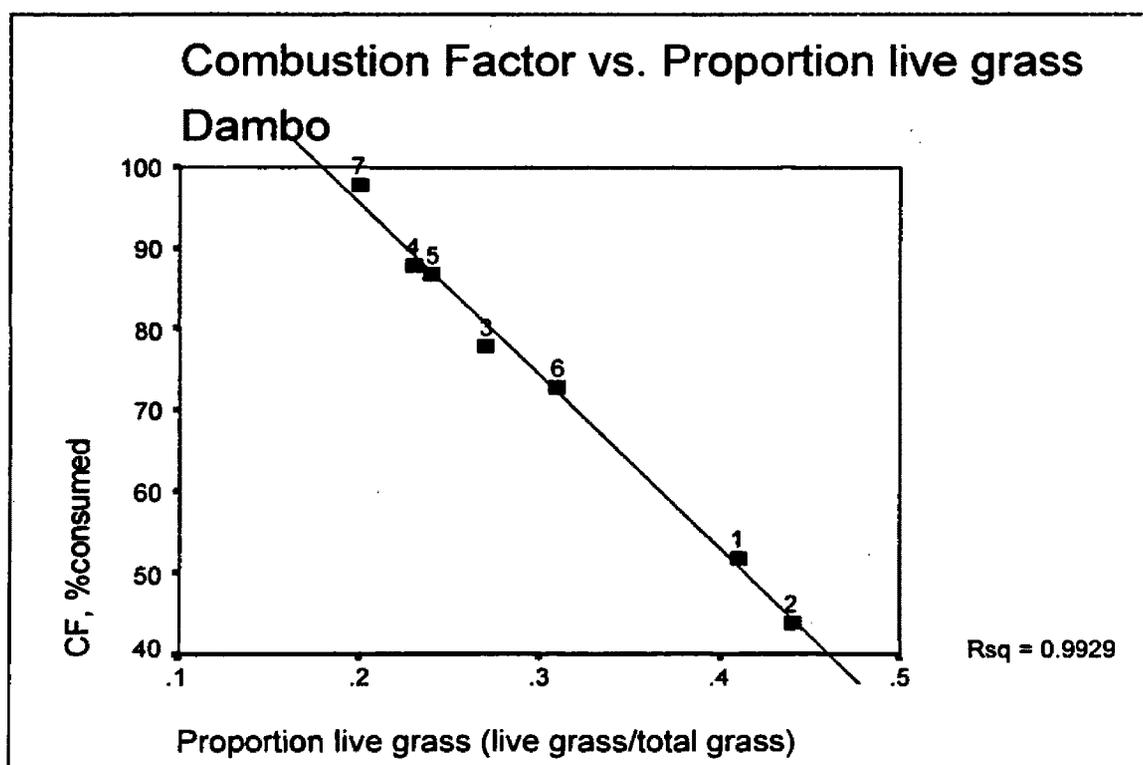


Figure 15: Linear regression of CF on proportion live grass, dambo

There was no statistically significant correlation between CF in the dambo and the average moisture content of the grass ($adjR^2 = 0.29$, $SEE = 16.626$, $p = 0.122$), the moisture

content of the live grass ($\text{adjR}^2=0.46$, $\text{SEE}=14.459$, $p = 0.055$), or the total fuel load ($\text{adjR}^2= -0.13$, $\text{SEE}=21.021$, $p = 0.608$). Regression of CF values in the dambo on the weighted average moisture content of the grass was slightly significant ($\text{adjR}^2= 0.50$, $\text{SEE} = 13.973$ $p = .046$) but did not significantly improve the model when proportion live was already in the model ($p = .086$). Therefore, the proportion of live grass is the variable that best predicts CF of the dambo fuels and indicates that early season CF values are influenced by biophysical variables reflecting an increased vegetation moisture. The studentized residuals are within two standard deviations of the mean and have no observable pattern (see Figure 16), so the assumptions of regression analysis have not been violated.

The model for the equation is:

$$Y = -213.086X + 138.211$$

which corroborates our hypothesis that the proportion of live grass (X) is negatively correlated with the CF ($b = -213.086$), i.e. that biophysical parameters of the early dry season will affect the CF of fires at this time in the dry season. With so few data points, though, reliability of the model must be explored further in future studies. Nevertheless, it indicates that there is very strong evidence of a negative linear relationship between the proportion of live grass and the CF ($p \leq .0001$, $\alpha = 0.05$).

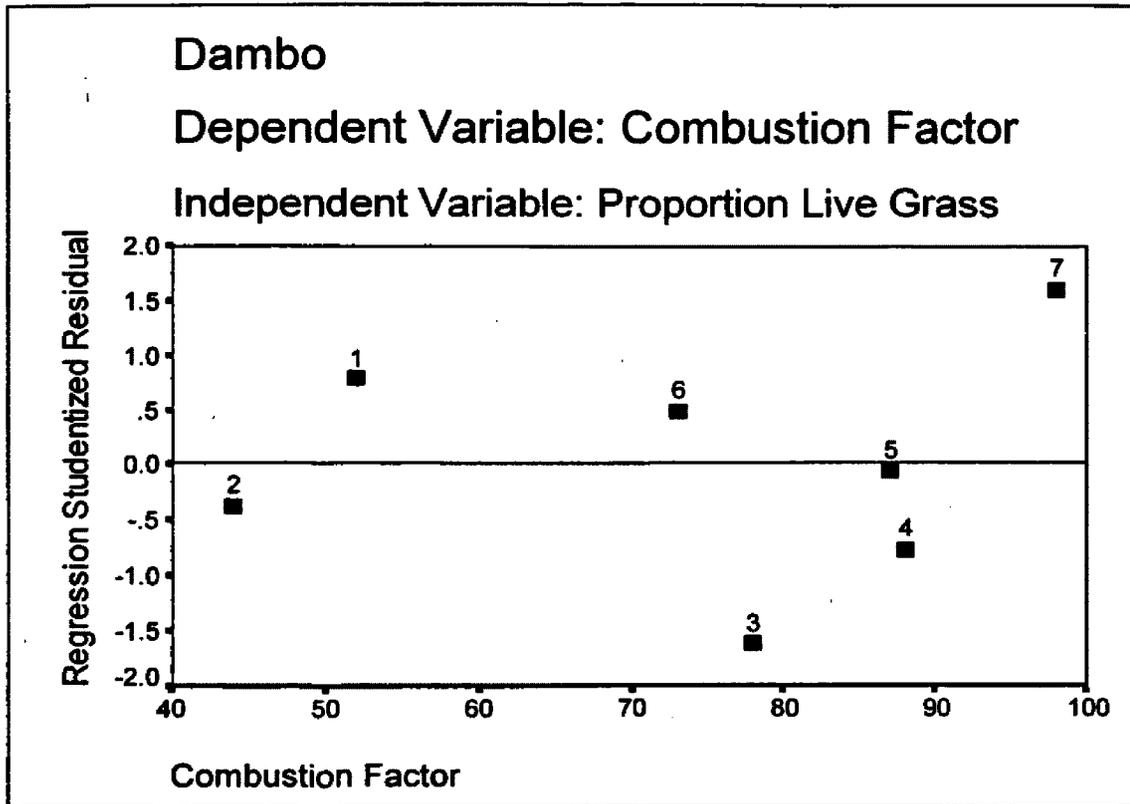


Figure 16: Regression studentized residuals of CF and proportion live grass, dambo

Correlation of fire line intensity and moisture content of live grass was not statistically significant ($\text{adjR}^2 = -0.099$, $\text{SEE} = 2081.54$, $p = 0.527$). Correlation of fire line intensity and the weighted moisture content of the grass was also not statistically significant ($\text{adjR}^2 = 0.15$, $\text{SEE} = 1831.22$, $p = 0.211$). But, fire line intensity was also negatively correlated with the proportion of live grass in the dambo ($\text{adjR}^2 = 0.57$, $\text{SEE} = 1295.97$, $p = 0.030$). Multiple linear regression of the proportion of live grass in the dambo and the total fuel load on the fire line intensity, however, was the most statistically significant result ($\text{adjR}^2 = 0.87$, $\text{SEE} = 714.43$, $p = 0.007$). The model for fire line intensity, Y , can be expressed as:

$$Y = 2.034(X_1) + -20279.5(X_2) + 2358.235$$

where

X_1 = Total fuel load

X_2 = Proportion of live grass

Therefore, I conclude that there is a strong negative relationship between the proportion of live grass and the total fuel load, with the fire line intensity. The higher the proportion of live grass, the lower the fire line intensity assuming fuel load remains fixed. This is again supporting the hypothesis that biophysical variables of vegetation moisture can be used to predict lower fire line intensity of early dry season biomass burning.

For reaction intensity, among the same variables with which correlations were attempted with fire front intensity, i.e. proportion of live grass, total fuel load, moisture content of live grass, and the weighted average moisture content, there were no statistically significant relationships in simple or multiple linear regression. Given this data, therefore, one cannot conclude that reaction intensity was linearly correlated with biophysical parameters of vegetation moisture content in the early dry season, i.e. proportion of live fuels, total fuel load, moisture content of live fuels, or weighted average moisture content of the fuels. The discrepancy between this conclusion and that which was reached with regard to fire front intensity, i.e. that early dry season biophysical variables, the combination of the proportion of fuel load and total fuel load, were linearly correlated with fire line intensity, cannot be fully explained, but may be due to sampling error of residence time measurements.

Fire line intensity is dependent on the ability of the fire to efficiently transfer heat between fuels to raise adjacent fuels above the moisture content of extinction and to

sustain rapid oxidation (Kaufman et al. 1992). Fine fuels, such as the grass found in the dambo, easily sustain rapid oxidation by efficient transfer of heat. Rapid oxidation also requires sufficient heat to accelerate pyrolytic reactions and volatilize gases from within the fuel surface (Ward et al. 1993). Therefore, dry fuels burn hotter than wet fuels because of lesser latent heat transfer, allowing facilitation of rapid oxidation (Robinson 1988; Kaufman et al. 1992; Rothermel 1983 in Ryan 1991. Trollope et al. (1996) reported that the most important factor influencing fire behavior and intensity in savanna burning is the amount of grass fuel available for combustion, especially when fuels are highly inflammable because of high moisture content. The high correlation obtained in this study for fire line intensity on the proportion of live grass and total amount of grass ($\text{adj}R^2 = 0.87$) supports this hypothesis.

3.5.2. Miombo

In the miombo, only 4 to 14% of the total fuel load was grass and therefore the fuel structure was more complex. The CF for the miombo increased from only 1% at M157 to 41% at M210 (see Table 3 and Figure 17). Changes in CF values were presumably due to a combination of factors including grass, wood, and litter consumption. Each plot was an individual experiment comprised of different fuel components, slightly different environmental conditions, and different levels of fuel loading and moisture content and only the latter is related to season. Differences can thus be attributed to a combination of these factors.

M157 burned substantially less efficiently than the other plots and this is evidenced by only 1% consumption of the total fuel load by the fire. M169, M186, and

M205 burned at the same level of efficiency in that the CF values were similar (17-21%). M197 burned slightly more efficiently than most, and M210 burned most completely (see Figure 17 and Table 3).

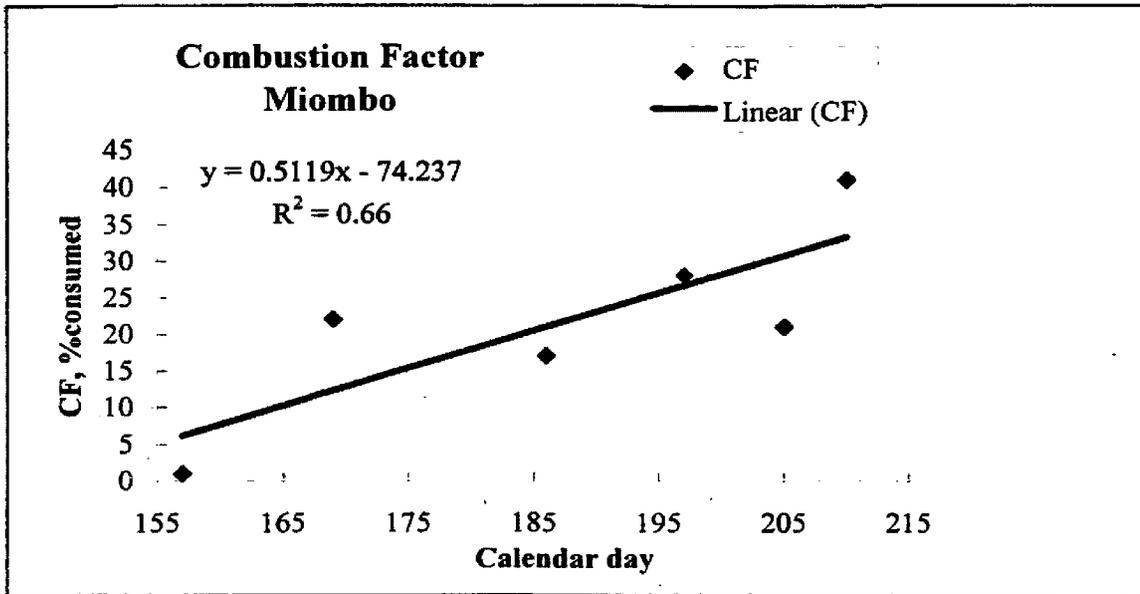


Figure 17: Linear regression of CF on calendar day, miombo

M210 had the highest litter and wood consumption (0-2.54 cm diameter), 52% for the litter and 46% for the wood. M210 consumption for downed wood (2.55-7.62 cm diameter) was also the highest, 37.26%. The only other plot with comparable downed wood consumption in the 2.55-7.62 cm diameter size class was M197 with 24.91%. The other plots had comparable wood consumption (1.82%-6.63%).

In describing the relationship between CF in the miombo and the biophysical characteristics of the early dry season miombo fuels, it was hypothesized that significant correlations would be found with the proportion of live grass, the total fuel load, the proportion of litter or wood, the moisture content of the live grass, or the weighted

average moisture content of all the fuels (weighted by the proportion of live or dead grass biomass). Of these variables, a high negative correlation was found between miombo CF and proportion live grass ($\text{adjR}^2 = 0.72$, $\text{SEE} = 6.925$) (see Figure 18).

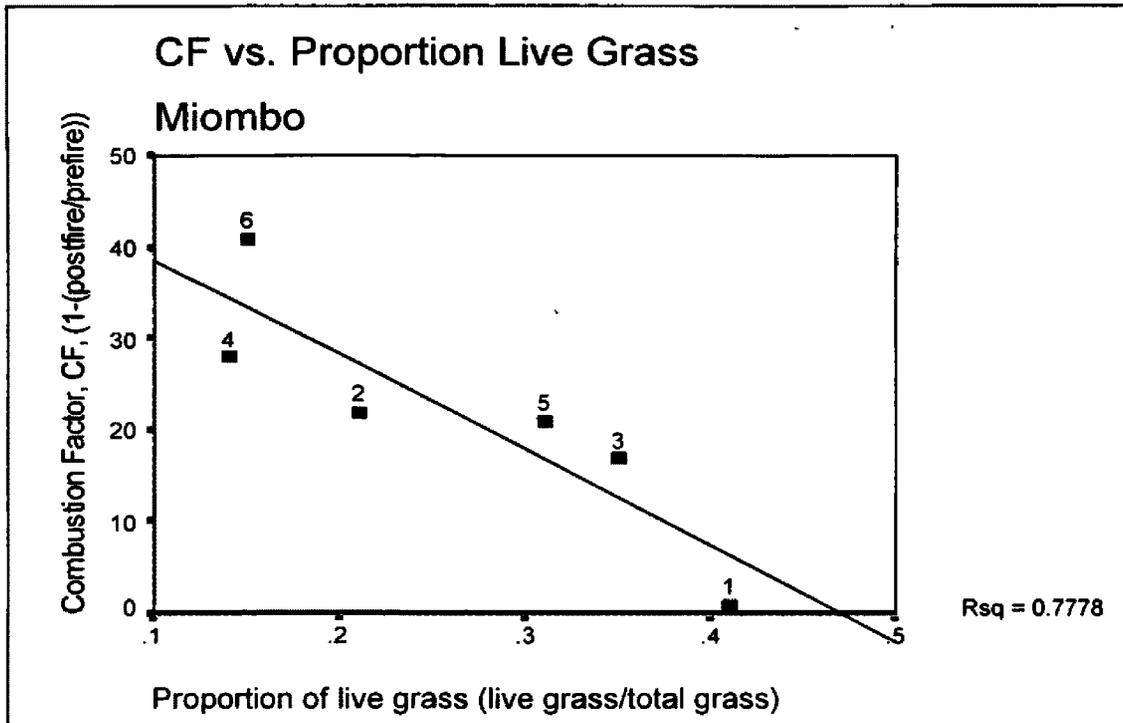


Figure 18: Linear regression of CF on proportion live grass, miombo

The relationship is statistically significant ($p \leq 0.020$, $\alpha = 0.05$) so we conclude that there is very strong evidence of a negative linear relationship between the proportion of live grass and the CF in the miombo. The residuals indicate no violation of regression assumptions (see Figure 19). However, the highest adjusted R^2 between miombo CF values and these biophysical variables was with the weighted average moisture content of the grass ($\text{adjR}^2 = 0.81$, $\text{SEE} = 5.723$, $p = 0.009$). Similarly high correlations were found with the moisture content of the live grass ($\text{adjR}^2 = 0.77$, $\text{SEE} = 6.276$, $p = 0.013$) and with the average moisture content of all the fuels ($\text{adjR}^2 = 0.80$, $\text{SEE} = 5.860$, $p = 0.010$). There was no significant linear relationship between the CF values and the proportion of woody

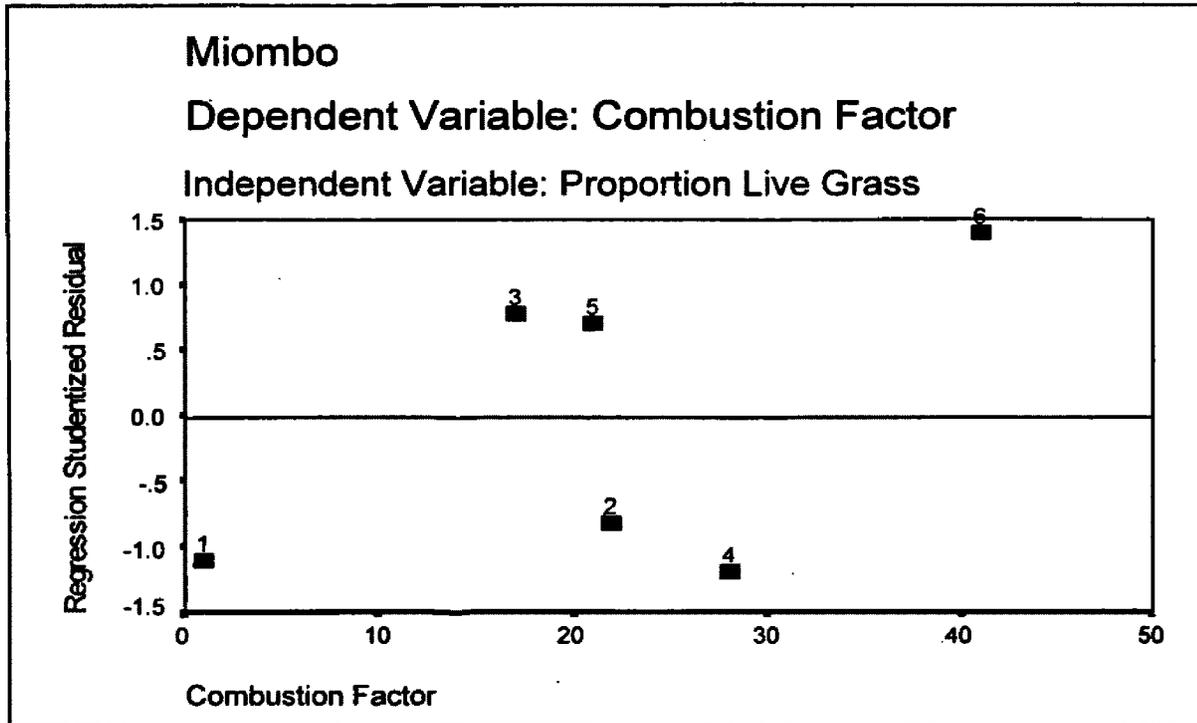


Figure 19: Regression studentized residual of CF and proportion live grass, miombo fuels to total fuel load ($adjR^2 = -0.14$, $SEE = 14.026$, $p = 0.567$), the proportion of litter ($adjR^2 = -0.22$, $SEE = 14.518$, $p = 0.772$), the proportion of leaves ($adjR^2 = 0.00$, $SEE = 14.689$, $p = 0.976$), or total fuel load ($adjR^2 = -0.14$, $SEE = 14.050$, $p = 0.57$). Multiple linear regression of the variables added no improvement to the model; no non-linear relationships were observed. Therefore, numerous models, based on variables which describe the moisture conditions of the fuels, seem to be able to predict the CF of the miombo in the early dry season.

Specifically, the models are described as follows:

for proportion of live grass, $Y = 48.88 + -104.00(X)$,

for the weighted average moisture content of the grass, $Y = 39.717 + -1.431(X)$

for the average moisture content of all the fuels, $Y = 92.121 + -1.709(X)$, and

for the moisture content of the live fuels, $Y = 49.448 + -0.387(X)$.

Based on the available data, all these models provide good predictive equations of CF in the miombo in the early dry season. Selection of the appropriate model to be used for future predictive modeling efforts should be based on available data and simplicity. All the models support the hypothesis that the moisture condition of the fuels is negatively correlated to the CF, thus predicting lower CF in the early dry season when vegetation has not completely cured.

Fire line intensity was most highly correlated with the moisture content of live grass ($\text{adj}R^2 = 0.70$, $\text{SEE} = 1421.50$, $p = 0.024$), and the average moisture content of all the miombo fuels ($\text{adj}R^2 = 0.75$, $\text{SEE} = 1277.94$, $p = 0.016$). Simple linear regression of the other biophysical parameters was not statistically significant. The regression model from the available data for predicting fire line intensity from the moisture content of live grass can be expressed as:

$$Y = 8203.152 + -73.105(X)$$

and for the average moisture content of all the miombo fuels as:

$$Y = 16472.2 + -327.754(X)$$

Multiple linear regression of these two variables was not significant ($p = 0.085$). Therefore, the data from this study indicates that there is a negative simple linear correlation between these two biophysical variables and fire line intensity, respectively, therefore indicating a relationship between vegetation moisture in the early dry season and fire line intensity.

Reaction intensity was also most highly correlated with the moisture content of the live grass ($\text{adjR}^2 = 0.58$) and the average moisture content of all the miombo fuels ($\text{adjR}^2 = 0.60$). However, these correlations were not statistically significant at $\alpha = 0.05$ ($p = 0.083$ and $p = 0.078$, respectively). The regression model of miombo reaction intensity on the moisture content of live grass is:

$$Y = 2428.304 + -22.377(X)$$

and for reaction intensity on the average moisture content of all fuels:

$$Y = 5386.302 + -109.465(X)$$

which indicates that the relationship between both measures of intensity (fire line and reaction) are negative ($b = -22.377$ and -109.465 , respectively). More research must be done to validate these relationships. Nevertheless, the models suggest that as the moisture content of the live grass increases, the intensities decrease, as we had hypothesized for early dry season fires.

Correlation between two of the response variables, CF and fire line intensity, gives a coefficient of determination of $R^2 = 0.69$ ($\text{adjR}^2 = .62$, $p = 0.021$) for the dambo, and $R^2 = 0.46$ ($\text{adjR}^2 = 0.33$, $p = .137$) for the miombo (see Figure 20 and 21). Correlation between CF and reaction intensity gives a coefficient of determination of $R^2 = 0.36$ ($\text{adjR}^2 = 0.15$, $p = .286$) for the dambo, and $R^2 = 0.22$ ($\text{adjR}^2 = -0.036$, $p = 0.42$) for the miombo. This indicates that fuel consumption is not well correlated with measures of intensity, although the relationship is better in the dambo where there is a continuous, homogenous fuel type.

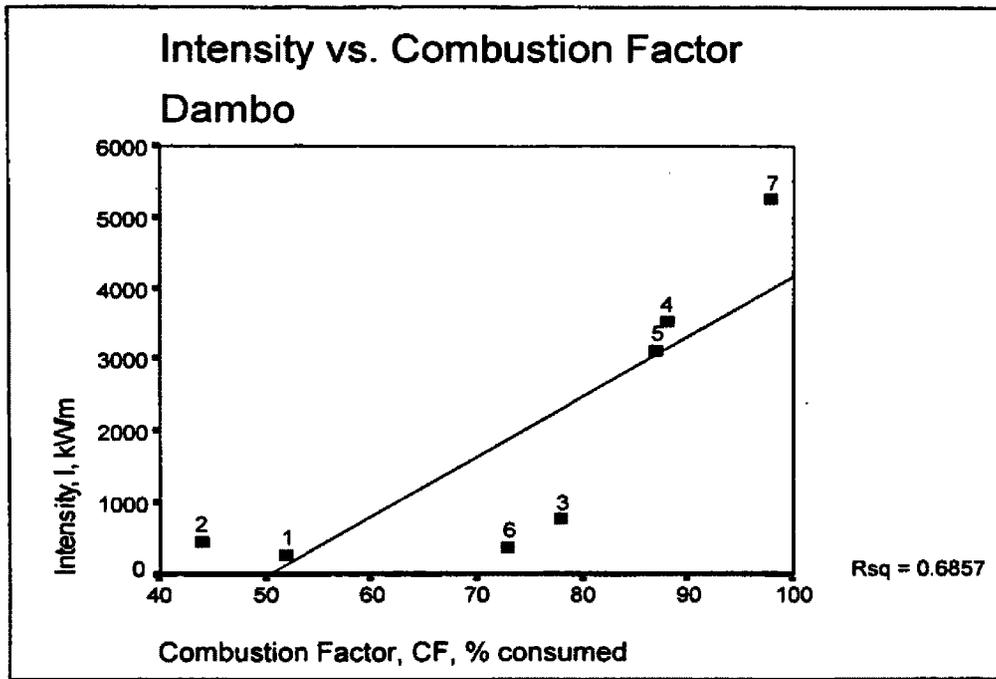


Figure 20: Linear regression of fire line intensity on CF, dambo

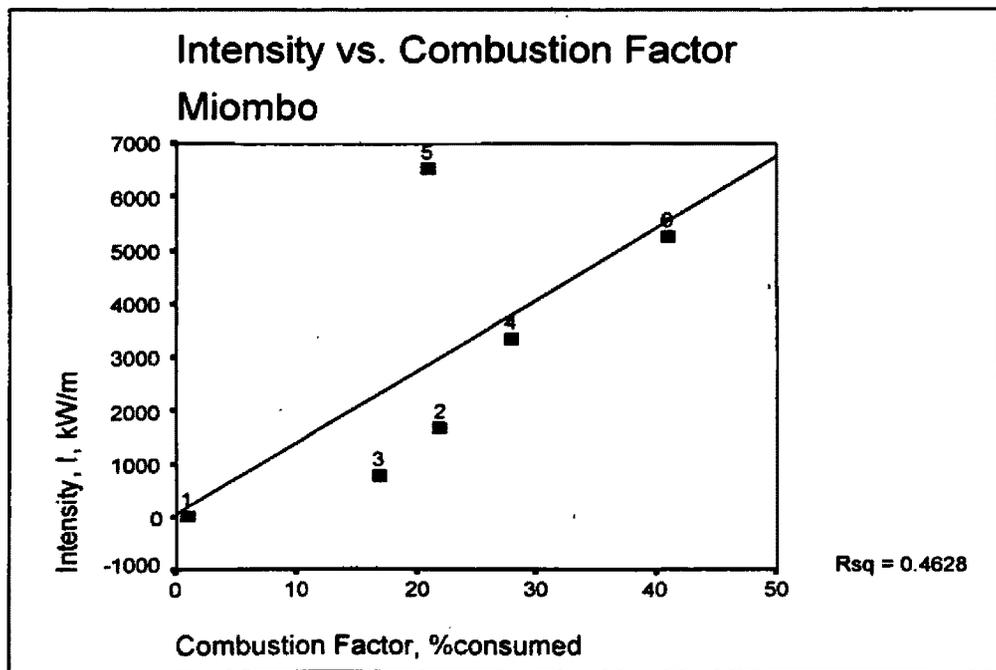


Figure 21: Linear regression of fire line intensity on CF, miombo

3.6. CONCLUSION

Results of this study indicate that the proportion of live grass to total grass is the critical variable in determining the percentage of fuel consumed by the burn (CF). The fact that fire line intensity was related to proportion of live grass and total fuel load in the dambo, versus simply the moisture content of live grass in the miombo, relates to the fact that the dambo consisted of a continuous, homogenous grass fuel layer. In the miombo, fuels were more heterogeneous and the variables (proportion live grass and total fuel load) were not as representative of the actual fuels that drove the fire line intensity.

The results do not strictly follow a seasonal gradient but indicate the necessity for individual evaluation of burn sites for accurate behavior predictions. High correlations between biophysical variables and high moisture content in the early dry season, e.g. the proportion of live grass to the total grass and the weighted average moisture content of the fuels, strongly suggests that there are general relationships of fire intensity related to seasonality which may affect emissions. At the plot level, seasonality will be relative to site conditions such as land use history, aboveground fuel loading, proportion of fine fuels, and previous environmental and edaphic conditions which will affect the moisture content of the fuels and the resultant fire behavior (Rothermel 1983). At the regional or global scale, however, estimates of general trends in vegetation moisture content, i.e. by remote sensing imagery, might be an effective way of approximating emissions. The regression models that have been provided by this study are the basis for algorithms that can be used by models to link vegetation phenology to emissions.

Particularly, this study suggests a strong negative correlation between the independent variables of proportion of live grass and moisture content of live grass with the dependent variables of consumption factors and intensity, but more data is necessary before regional estimates are attempted, given the limited number of fires in this study. Particularly, further work is needed to increase the number of sites used to evaluate early season burning, e.g. semi-moist miombo.

In these studies, it will be important to distinguish between total fuel consumption and fire line intensity and to control study sites for fuel heterogeneity. Since remote sensing platforms sense active fires based on temperature thresholds, fire counts are dependent on fire intensity. These fire counts are typically responsible for regional emissions estimates. However, it is necessary to judge whether it would be more appropriate to use scar areas in combination with active fire counts for assessment of fire emissions since this study alludes to a poor correlation between intensity and CF. This is an important consideration for assessing seasonal dynamics in the savanna fire regime across a multitude of ecosystems. It is also important to understand that fire is an integral part of indigenous agricultural practices of survival in an otherwise infertile landscape. Management guidelines which promote early burning must take into account seasonal crop plantings and shifting cultivation practices that are meant to coincide with the onset of the rains (see Chapter 2).

Chapter 4 is an extension of the results from this chapter. By using the same biophysical variables of early dry season vegetation, estimates of fire intensity are evaluated by the fire's combustion efficiency, i.e. the proportion of carbon dioxide

released as a proportion of carbon monoxide, which depends on the relative proportion of flaming and smoldering phases during the fire. A combination of CF and modified combustion efficiency measurements from early dry season fires is necessary to evaluate potential emissions.

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MODIFIED COMBUSTION EFFICIENCY OF EARLY SEASON BURNING IN ZAMBIAN SAVANNAS

Abstract: Carbon monoxide and carbon dioxide emissions from savanna fires in Western Province, Zambia, were investigated in the early dry season (late May to early August) 1996 to determine the effect of fuel moisture content on fire efficiency. Fourteen plots were evaluated, eight in a seasonally flooded grassland (dambo) and six in a semi-arid woodland (miombo). Fire carbon emissions were sampled through the early dry season, in combination with simultaneous fuel moisture and fire behavior measurements. In the miombo, modified combustion efficiency (MCE) was highly correlated ($\text{adj}R^2 = 0.61$) with the proportion of grass to the sum of litter and grass fuel loading and the moisture content of the litter. In the dambo, the weighted average moisture content of the grass singularly explained most of the variance ($\text{adj}R^2 = 0.85$). The difference between ecosystems can be explained by the homogeneity of fuels in the dambo grassland and the diversity of fuel types in the miombo. Future studies to evaluate seasonal trends in fire emissions for modeling or emissions studies must consider previous land use, fuel loading, and phenology.

4.1. INTRODUCTION

The exchange of carbon between land and atmosphere is small compared to the amount of carbon stored in sediments and the ocean (Stevenson 1986). To accurately isolate carbon pools and their sources and sinks, it is necessary to parameterize the rates of flux between systems. To theorize a northern hemisphere carbon sink, for example, the fluxes in the southern hemisphere must be modeled. Due to the understanding that anthropogenic forces have augmented the terrestrial release of carbon to the atmosphere, increasing attention has been placed upon the terrestrial biosphere-atmosphere carbon interaction. In particular, fires increase the rate of nutrient cycling between atmospheric CO_2 and biotic carbon pools by rapidly oxidizing organic carbon that would otherwise decompose more slowly through soil processes (Robinson 1988). Fossil fuels may emit 5200 Tg C/yr (Andreae 1991). Savanna biomass burning results in the emission of 1660 to 3690 Tg C/year (Hao et al. 1990; Crutzen and Andreae 1990). Hao and Liu (1994)

estimated that 2.0×10^9 tons of biomass were burned in Africa in 1990. In total, savanna fires may account for 25% of global biomass burning emissions, 50% of which come from Africa (Crutzen and Andreae 1990; Hao et al. 1990).

There has been little research to evaluate the carbon pool and carbon cycling pathways in miombo woodlands. These woodlands comprise a vast majority of southern African vegetation (Malaisse 1978). Only 10% of African savanna fires have been attributed to lightning (Frost 1996); the rest are anthropogenic. Reasons for burning include stimulation of regrowth of improved grass fodder for livestock, agricultural ash fertilization, agricultural land clearing, charcoal production, hunting, and clearance of village pathways. Aside from being beneficial to these processes, frequent fire may negatively affect organic matter production and thus soil stability, honey and fruit production, and the watershed capacity of dambo grasslands (Prior 1983). Fire frequency in savanna systems may be as high as once every one to two years (Ward et al. 1996; Chidumayo 1995).

Excluding water vapor, CO_2 accounts for half of the total increase in radiative forcing from all other gases combined (Houghton 1991). Ninety to ninety-five percent of the carbon released during biomass burning is accounted for by CO and CO_2 . It has been argued that the release of CO_2 from biomass burning does not contribute to this atmospheric buildup of CO_2 because of CO_2 uptake in vegetative regrowth, which sequesters carbon in the terrestrial system. However, Trollope et al. (1996) observed a mean standing crop fine fuel recovery of CO_2 equal to 105% of the original biomass one

year after experimental burns, indicating that savanna grassland fires do not contribute a net source of CO₂ to the atmosphere (Trollope et al. 1996). Understory fires in forested environments may also sequester CO₂ through grass regrowth if tree trunks, representing the fuel group with the largest carbon pool, are unaffected (Fearnside 1996 in prep.). Forested environments undergoing intense fires, however, may experience net carbon loss due to the conversion of a high biomass system to a low biomass system. Fearnside (1996 in prep.) has estimated a mean recovery time of 190 years for the return of original forest biomass in Brazil. Recovery times for the miombo woodlands of southern Africa are significantly less (18-50 years) due to the ability of most miombo species to produce coppice shoots (Trapnell 1959; Chidumayo 1993). However, there has been little research to assess long-term, site-specific succession of fire-hardy species after disturbance nor the resulting net carbon balance of African savannas experiencing frequent fire (Chidumayo and Frost 1996).

Carbon monoxide, on the other hand, is not directly reabsorbed by the terrestrial biosphere but reacts with OH radicals to affect methane concentrations. Methane is also produced in Zambia from the charcoal making industry, anaerobic dambos, ruminants, and termites (Scholes et al., 1996; Jones, 1990). It has been estimated that 14.9 - 145 Tg CO is emitted from savanna fires in Africa (WMO, 1995; Scholes et al., 1996). This upper amount is 30% of the release from industrial sources globally (WMO, 1995).

Results from recent international efforts to assess the effects of biomass burning have relied significantly upon quantitative expressions of the amount of area burned, the

amount of aboveground biomass consumed, and parameters defining the efficiency of the burn. There has been concern that improved combustion factors (the amount of fuel consumed by the fire), and combustion efficiency values are needed to enhance the prediction of trace emissions to the atmosphere from fires in the tropics (Ward et al. 1992; Kauffman et al. 1994). Most field studies have occurred in the late part of the dry season (August-September) in which most of the burning occurs. Estimates of early season burning have not been undertaken despite the numerous management guidelines which have prescribed early season burning to prevent ecologically damaging late season fires (Frost 1996; Chapter 2). Combustion efficiency may vary over a season, being lowest during the early dry season due to the high moisture content of the fuels (Hao et al. 1996). There have been no previous studies to evaluate this claim (Robinson 1988).

In this chapter, I present relationships between the fire combustion efficiency and fuel moisture content of early dry season biomass fires in two African savanna ecosystems. Specifically, the objectives of the study were to: 1) determine the MCE of burns in the early burn season, 2) correlate these parameters with the observed fire behavior and environmental conditions at the time of burn 3) determine whether there was an increase in intensity from the early to late season burns, due to decreasing moisture content of the vegetation, and 4) determine whether there was a difference with regard to the first three objectives between two ecosystems, a semi-arid miombo woodland and a seasonally flooded dambo grassland. Achievement of these objectives should provide a field-based link to remote sensing of fire potential based on vegetation

parameters, such as NDVI, providing a better prediction of fire emissions along a seasonal gradient and based on ecosystem heterogeneity.

4.1.1. Combustion Efficiency

Combustion efficiency is an essential parameter to assess variability in fire emissions based on the degree of oxidation and volatilization of fuel compounds due to influential ecosystem parameters. Combustion Efficiency (CE) was defined by Ward et al. (1992) as the percentage of fuel carbon emitted as CO₂, and by Ward and Hardy (1991) as the ratio of actual carbon contained in the emissions of CO₂ to the total amount of carbon released. Modified Combustion Efficiency (MCE) is defined as the molar ratio of CO₂ emitted to the sum of CO and CO₂ above ambient levels (Hao et al. 1996):

$$\text{MCE} = \frac{\text{CO}_2\text{-C}}{(\text{CO}_2\text{-C} + \text{CO-C})}$$

where C = mass of carbon.

The MCE factor should be used in preference to CO/CO₂ ratios and CE because of improved correlation with other products of incomplete combustion (Ward and Radke 1993). The effect of not including the carbon associated with particulate matter, methane, or NMHCs is less than 5% (Ward et al. 1992).

Fire oxidizes biotic carbon in massive, high temperature exothermic reactions. There are three stages of this combustion process: 1) volatilization of free water and low boiling point hydrocarbons, 2) flaming - pyrolyzation products of hemi-cellulose, cellulose, lignin and volatile hydrocarbons due to rapid oxidation, and 3) smoldering -

release of products of incomplete combustion due to a low oxygen-content environment (Ward and Radke 1993). The proportion of CO and CO₂ emitted from biomass burning is thus proportional to the efficiency of the fire. Combustion conditions that decrease the products of incomplete combustion simultaneously increase the production of oxidized components, such as CO₂ (Ward and Radke 1993). The efficiency of the fire is controlled by the moisture content of the vegetation, the chemical composition of the fuel complex, the distribution of the biomass between different size classes, the amount of available fuel, the density of the fuel bed, resulting in sufficient mixing of oxygen, and environmental conditions (Ward and Hao 1991). In savanna fires, 85% of fuel consumption typically occurs during flaming combustion, 15% occurs during smoldering (Ward et al. 1992; Ward et al. 1996).

Some emitted compounds can be attributed to flaming or smoldering combustion based on a linear correlation with the degree of oxidation and, thus, the production of CO and CO₂ (Yokelson et al. 1996). In this way, measurement of MCE contributes considerable predictive value to estimates of regional fire emissions for particular gas species. In particular, ratios of trace gases and particulate matter to the concentration of CO₂ is currently the method used for estimating these emissions (Ward et al. 1992; Babbitt et al. 1994).

CE during the flaming phase is 0.90-0.98. During smoldering, CE ranges 0.75-0.85. (Kaufman et al. 1994; Ward and Hao 1991). Tropical deforestation fires in Brazil during the BASE-A field campaign averaged a combustion efficiency of 0.91 ± 0.04 ; a

single cerrado fire was measured with a CE of 0.97 (Kauffman et al. 1992). Averages for several cerrado fires gave a CE of 0.94 (Ward et al. 1992). The average combustion efficiency for African savanna fires during the SAFARI-92 campaign was 0.93 ± 0.02 (n=13) (Hao et al. 1996). Savanna ecosystems are dominated by fine grass fuels which create a dominant flaming phase of combustion and produce a high combustion efficiency. Grassland fires therefore are predicted to release products of complete combustion and few products of incomplete combustion (Kaufman et al. 1994; Cofer et al. 1996). Grassland combustion also leads to emissions of nutrients with high volatilization temperatures, such as Ca, P, K (Kauffman et al. 1994).

4.2. METHODS

4.2.1 Site description

The field site was located approximately 7.5 km southeast of Kaoma, Western Province, Zambia in Kaoma Local Forest No. 310 (14°86' S, 24°82' E). Kaoma District averages 900 to 1000 mm rain/year, most during the wet season (late November-April). Average daily July temperatures (middle of the dry season) are 17.5 to 20°C. Elevation is approximately 1170 meters. Despite the fact that the site is a Protected Forest maintained by the Department of Forestry, both ecosystems are heavily utilized by local agriculturists and villagers for charcoal manufacturing, firewood collection, thatch harvesting, honey production, grazing, and agriculture. Local agricultural crops grown near the study site include cassava, groundnuts, maize, and sweet potatoes. The sites burn every 1-2 years to facilitate this production. Unlike the well-known chitemene cultivation in the Northern

province, agricultural fields are centered very near the village for proximity to markets. Much of the nearby land has been used for agricultural production, especially due to significant maize subsidies and credit incentives for agricultural development (Kydd, 1988). Local forests provide relatively intact forest available for grazing (especially in the dambo), honey harvesting, and illegal charcoal production. Agricultural clearing also occurs on some of the forest.

Fourteen sites were established between June 5 and August 6, 1996, six in a semi-deciduous, open canopy, semi-arid woodland (miombo) and eight in a seasonally flooded grassland (dambo). The ecosystems were separated by approximately 500 m and a dirt road. Chapter 3 describes the sampling of fuel biomass, moisture content, and soil parameters at each of these 2 hectare plots. Three Fire-Atmosphere Sampling System (FASS) towers (Ward et al. 1996) were spaced equally along the long axis of the plot, surrounded by a cluster design to sample fuel dry weights at 0.5 x 0.5 m subplots (see Figure 1). The sampling design was similar to that used by Shea et al. (1996) in Africa and by Kauffman et al. (1995) in Brazil. Fuel dry weight sampling is described in detail in Chapter 3. Fires were ignited alternately through the length of the study to capture the dry-down of the grass fuels.

4.2.2. Soil

Miombo woodland is generally coincident with planation surfaces of the Central African plateau (Cole 1986) yielding Precambrian granite and gneiss. Toward the west of the country, however, especially around the Zambezi River, these metasediments grade

into Paleogene sandstones, called the Kalahari sands upon weathering. Miombo woodland soils generally have low cation exchange capacities (CEC) and are low in total

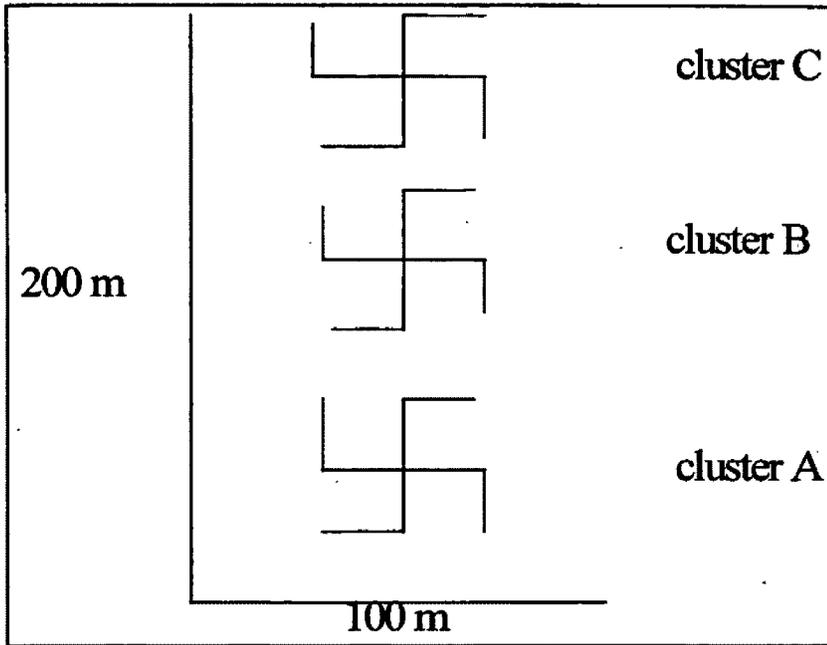


Figure 1: Cluster layout in a plot (see diagram 2 for details)

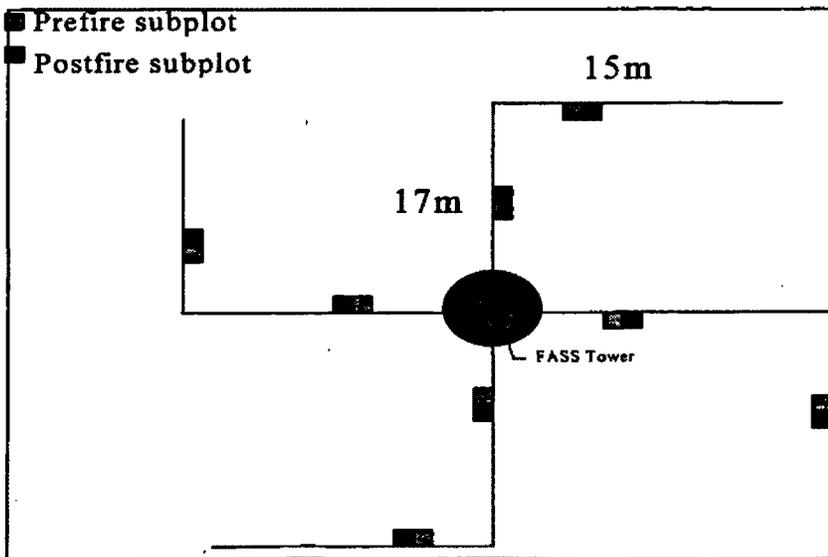


Figure 2: Subplot layout in one cluster

exchangeable bases, nitrogen, and extractable phosphorus (Cole 1986). The limited organic matter provides most of the CEC although clays augment this storage. On the sandy soils in Western Province which leach significantly during the wet season, there are considerable soil deficiencies limiting agricultural production. Fires assist fertilization of agricultural fields by increasing N and P availability, increasing mineral concentrations of Ca, K, and Mg, and raising pH (Andriessse and Koopmans 1984; DeBano 1990; Stromgaard 1988). There may also be considerable effects on microbial biomass and microbial N (Stromgaard 1988; Cook 1994). However, fires also decrease organic matter contents in the long term, decreasing soil CEC and increasing potential erosion, after the fertilization effect of the ash has diminished.

Soil pH, bulk density, and moisture content were measured during the early season in the dambo and miombo. pH ranged between 5.4 and 5.9 at each site. Bulk density averaged 0.79 ± 0.17 g/cc in the dambo and 1.43 ± 0.16 g/cc in the miombo with no significant change as the early season progressed. Dambo soil moisture content ranged from 4.50 to 7.92% (0-5 cm) and 6.08 to 11.16% (5-10 cm). Miombo soil moisture content ranged from 0.51 to 1.18% (0-5 cm) and 0.73 to 1.08% (5-10 cm). Moisture content for each plot was sampled at the burn date, providing potential evidence for a seasonal gradient. However, there was no significant seasonal trend in soil moisture content during the duration of our study indicating that soil moisture had decreased previous to our measurements.

4.2.3. Biomass

Fuel loads ranged from 1884 to 3314 kg ha⁻¹ in the dambo and 8953 to 13233 kg ha⁻¹ in the miombo. Dominant canopy species in the miombo study site were *Brachystegia bussei*, *Brachystegia longifolia*, *Pterocarpus angloensis*, *Monotes africanus*, *Diospyros batocana*, *Cryptosepalum exfoliatum*, and *Julbernardia paniculata*. The dominant understory shrubs were *Strychnos innocua* and *Diploryhnhos condylocarpon*. The dominant grass species most common in a dambo grassland are *Hyparrhenia* spp. and *Serrata* spp., 0.5 to 1.5 meters in height.

Moisture content of the live grass in the dambo ranged from 69% to 127%; moisture content of dead grass ranged from 13% to 38%. Live grass moisture content in the miombo decreased from 119% to 33% whereas for dead grass, the moisture content was relatively stable from 4% to 13% (see Figure 3 and Figure 4).

4.2.4. FASS system

Three sampling clusters were equally spaced along the long axis of each two hectare plot. The design was used to provide samples concentrated at Fire-Atmosphere Sampling System (FASS) towers which had been placed at the center of each cluster. The FASS tower is a self-contained monitoring package that collects real-time measurements of emissions fluxes, wind measurements, and particulate matter for each phase of combustion and thus is dependent on the amount of consumed biomass. For complete description of the FASS packages in Africa, refer to Ward et al. (1996). The FASS computers monitor the amount of fuel consumed for each phase of combustion. For this study, sampling from the flaming phase lasted 6 minutes, and 15 minutes for the smoldering phase. Each tower collected the gases from each of these two phases of

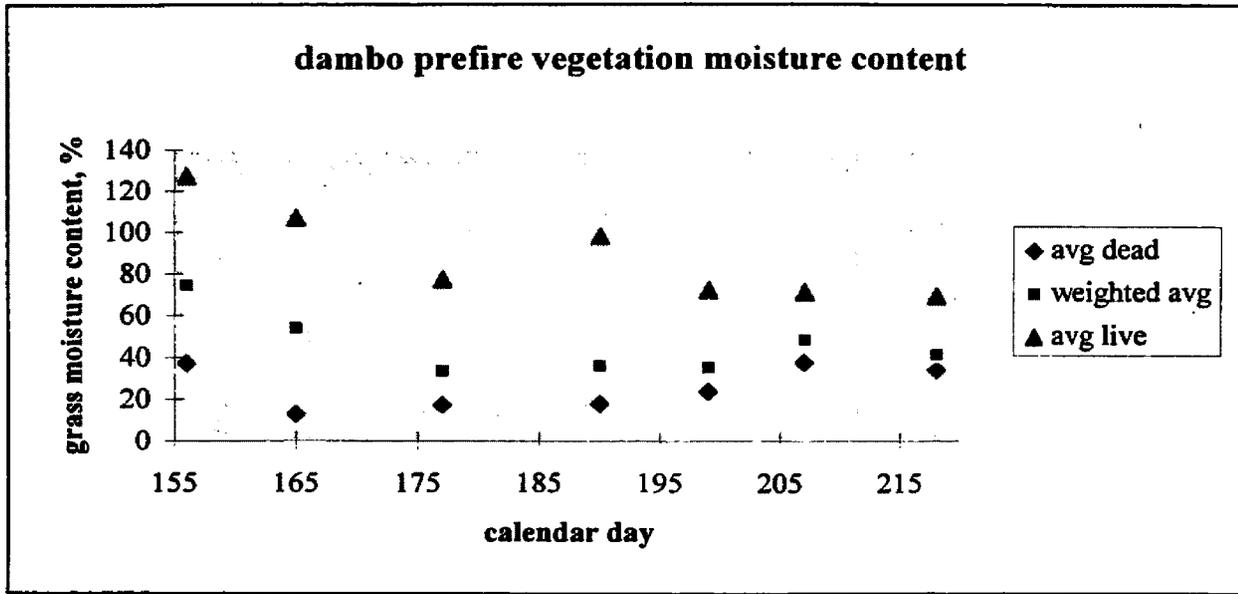


Figure 3: Biomass moisture contents, dambo

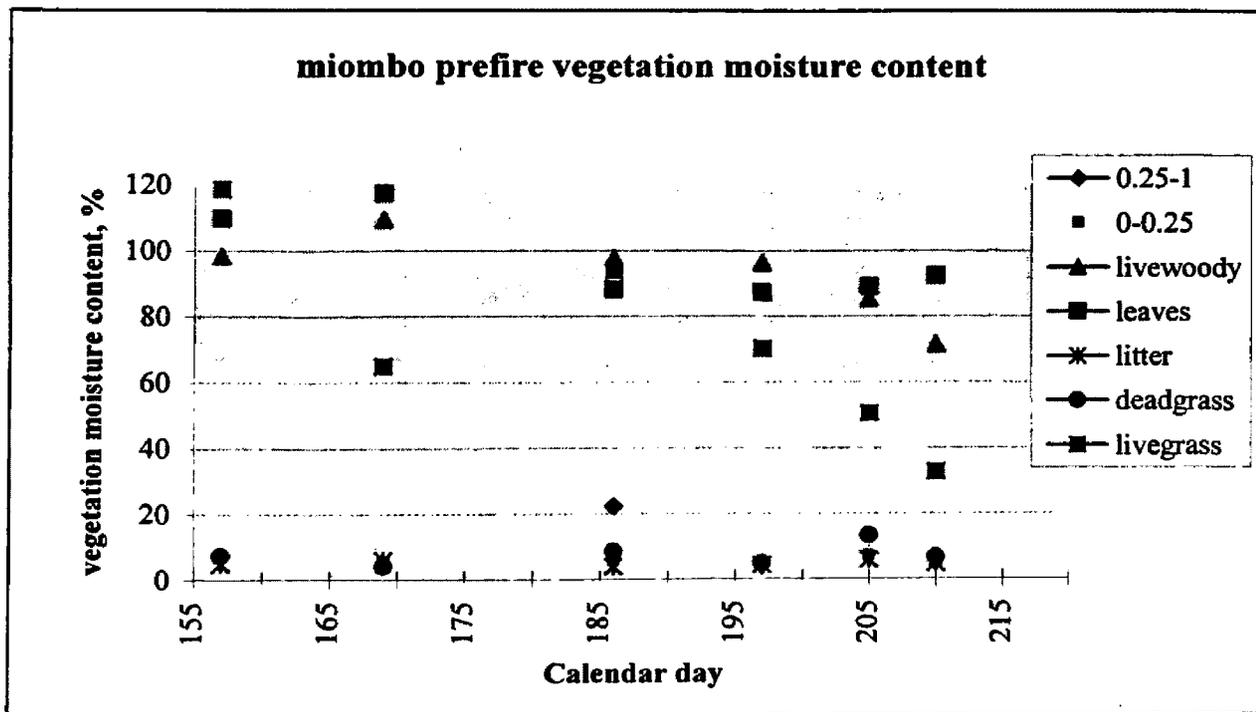


Figure 4: Biomass moisture contents, miombo

combustion separately in canisters specifically designed to prevent contamination. The canisters were analyzed at the Intermountain Fire Sciences Laboratory of the USDA Forest Service, Missoula, MT for concentrations of CO and CO₂. Ambient CO and CO₂ concentration values were then subtracted from the measured values and used in the equation for MCE defined by Hao et al. (1996). The MCE values for each phase of combustion were weighted by the amount of fuel consumption during each phase of combustion (Hao et al. 1996). Those values for which there was not valid fuel consumption data were weighted by assuming 85% of the fuel was consumed in the flaming stage and 15% in the smoldering phase (Ward et al. 1996). There was then a single MCE value for each tower. The MCE values from the towers at each plot were then averaged together to obtain a plot value to be used in the analysis.

4.3. RESULTS

4.3.1. Dambo

From Figure 5 it is clear that there is a dramatic increase in the MCE from D156 to D199. After this time, it appears that the MCE either slightly decreases or reaches a plateau. To determine the reason for this pattern, three variables were explored: the proportion of live grass, the moisture content of live grass, and the total fuel load. Simple linear regression between the moisture content of live grass and the MCE has a coefficient of variation of $R^2 = 0.35$ ($\text{adj}R^2 = 0.220$, $\text{SEE} = 0.028$, $p = 0.162$). Similar linear regression between the total fuel load and the MCE of the fire also showed no correlation ($R^2 = 0.03$, $\text{adj}R^2 = -0.17$, $\text{SEE} = 0.035$, $p = 0.736$) (see Figure 6). This graph

appears to conform to a curvilinear relationship. With so few samples, no nonlinear relationship was modeled because it is possible that D207, with such a low fuel load, is skewing the data. The box plots of the fuel load for the 24 subplots within each plot is displayed in Figure 7. From Figure 8, it is clear that D207 also had one of the highest values for proportion of live grass (0.31) (see Table 1). Only D156 and D165 had a higher proportion of live grass and they were burned in early June, whereas D207 was burned on 26 July. Therefore, D207 was not excluded from the analysis simply because of the lower fuel load. Alternatively, the curvilinear relationship that is alluded to by Figure 6 may be due to the fuel bed packing ratio. Packing ratio refers to the fraction of fuel array volume that is occupied by fuel (Rothermel 1972). Theoretically, there is an optimum packing ratio in which oxygen supply to the fuels to sustain combustion is

Table 1: Weighted MCE and proportion live grass for the dambo and miombo

| Site | Date | Weighted MCE | Live Grass/Total Grass |
|--------|-----------|--------------|------------------------|
| D156* | 05-Jun-96 | 0.883 | 0.41 |
| D165 | 14-Jun-96 | 0.911 | 0.44 |
| D177 | 26-Jun-96 | 0.954 | 0.27 |
| D190 | 09-Jul-96 | 0.966 | 0.23 |
| D199 | 18-Jul-96 | 0.964 | 0.24 |
| D207 | 26-Jul-96 | 0.909 | 0.31 |
| D212 | 31-Jul-96 | 0.958 | no data |
| D218 | 06-Aug-96 | 0.943 | 0.20 |
| | | | |
| M157 | 06-Jun-96 | 0.937 | 0.41 |
| M169 | 18-Jun-96 | 0.951 | 0.21 |
| M186 | 05-Jul-96 | 0.945 | 0.35 |
| M197 | 16-Jul-96 | 0.943 | 0.14 |
| M205 | 24-Jul-96 | 0.933 | 0.31 |
| M210 | 29-Jul-96 | 0.907 | 0.15 |
| Dambo | average | 0.94 | 0.30 |
| Miombo | average | 0.94 | 0.26 |

* D156 refers to Dambo plot burned on 5 June, 1996, Julian calendar day 156

** M157 refers to Miombo plot burned on 6 June, 1996, Julian calendar day 157

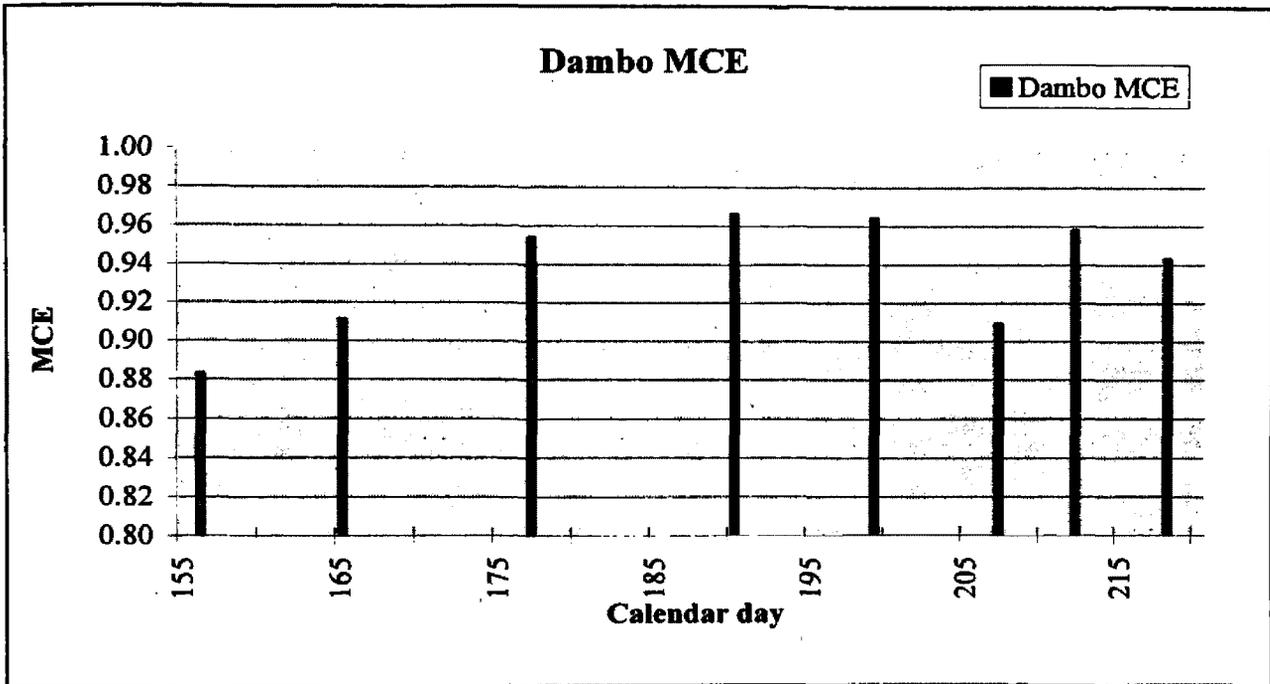


Figure 5: Histogram of dambo MCE by the date of burn, calendar day

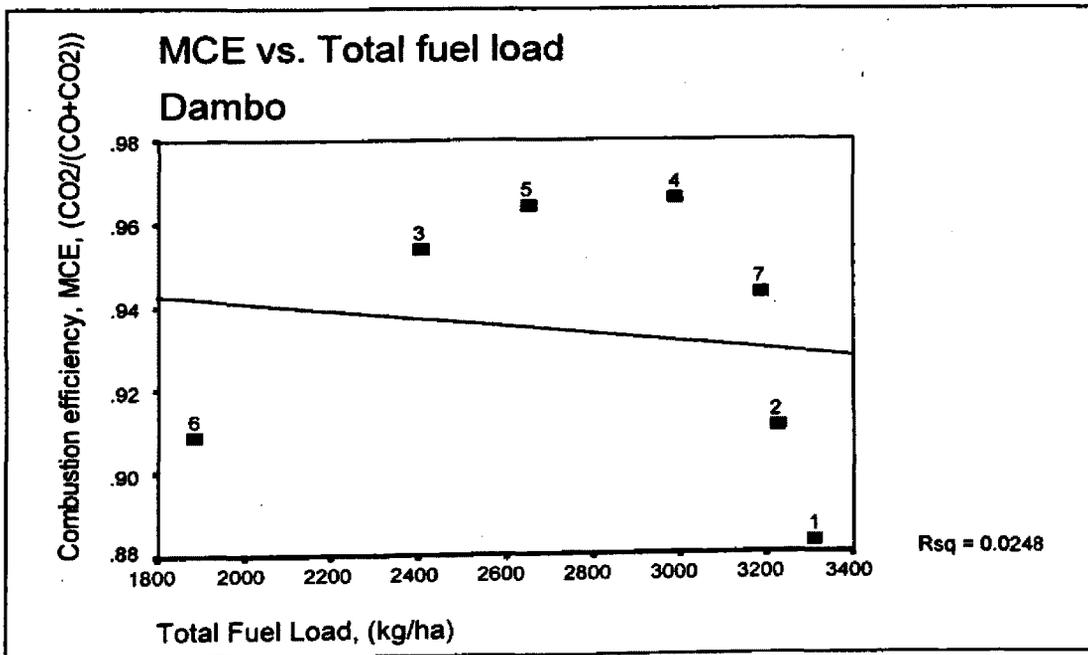


Figure 6: Linear regression of MCE on total fuel load, dambo

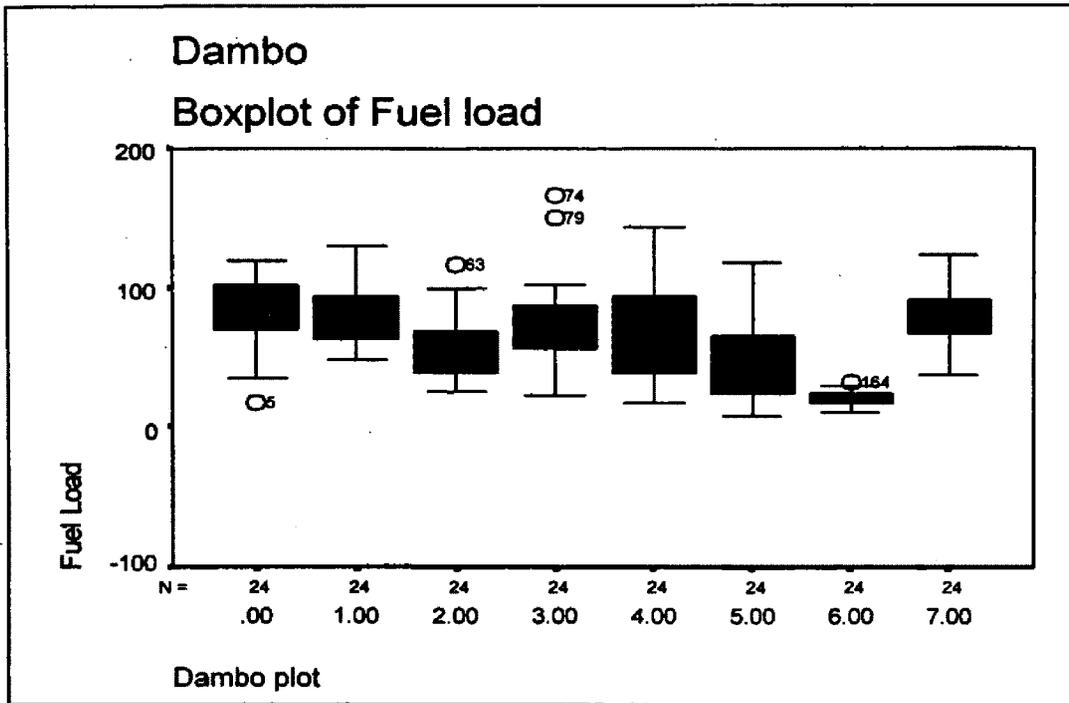


Figure 7: Box plot of subplot fuel loading, dambo

neither too limiting because of a dense packing ratio, or too dominant because of a sparsely packed fuel bed. This curve may depict that there is an optimum MCE at a fuel loading between 2800 and 3000 kg ha⁻¹. This hypothesis must be confirmed by work which more fully evaluates the fuel bed depths, fuel array bulk densities, and fuel particle densities in the miombo (Rothermel 1972).

Simple linear regression between the proportion of live grass and the MCE in the dambo had a significant negative linear correlation ($R^2=0.68$, $adjR^2 = 0.614$, $SEE = .020$, $p = 0.023$) (see Figure 8). The model for the regression line is:

$$Y = -.286(X) + 1.019$$

which supports the hypothesis that as the proportion of live grass increases, the MCE decreases ($b = -.286$). Studentized regression residuals are within 1.5 standard deviations

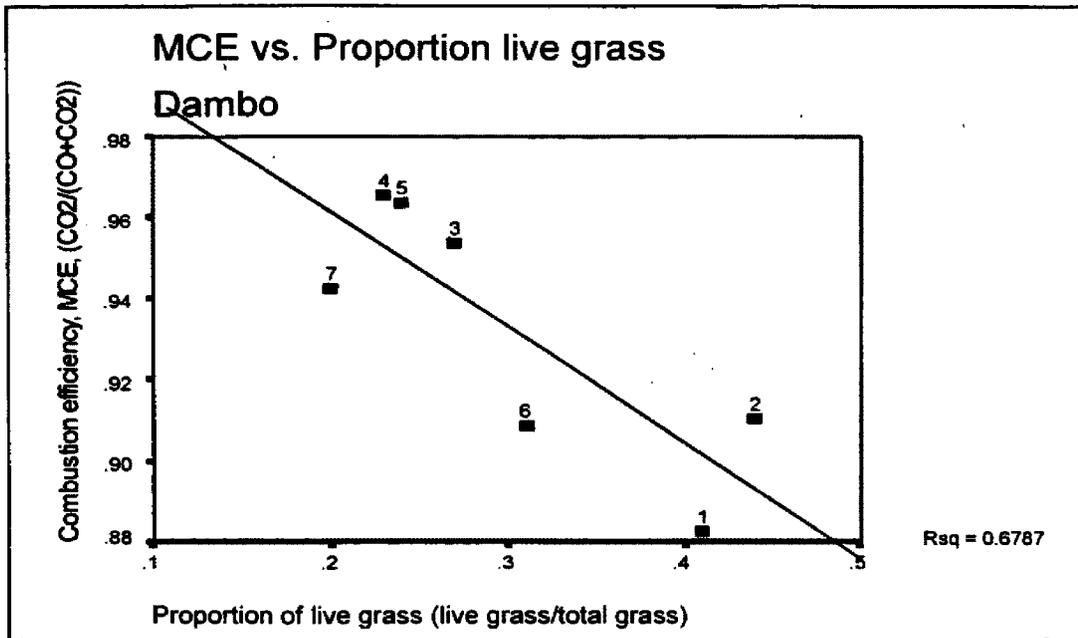


Figure 8: Linear regression of MCE on proportion live grass, dambo

from the predicted values and show no ordered pattern (see Figure 9). Therefore, the assumptions of regression analysis were not violated. Multiple linear regression between the proportion live and the moisture content of live grass or total fuel load was attempted but did not improve the explanation of variance.

Another variable that was used to describe the increased vegetation moisture content of the early dry season was the average moisture content of the grass, weighted by their fuel loading. This variable had the highest correlation with the modified MCE of the dambo ($R^2 = 0.88$, $adj R^2 = 0.85$, $SEE = 0.012$, $p = 0.002$) (see Figure 10). The studentized residuals (Figure 11) show no violation of the linear

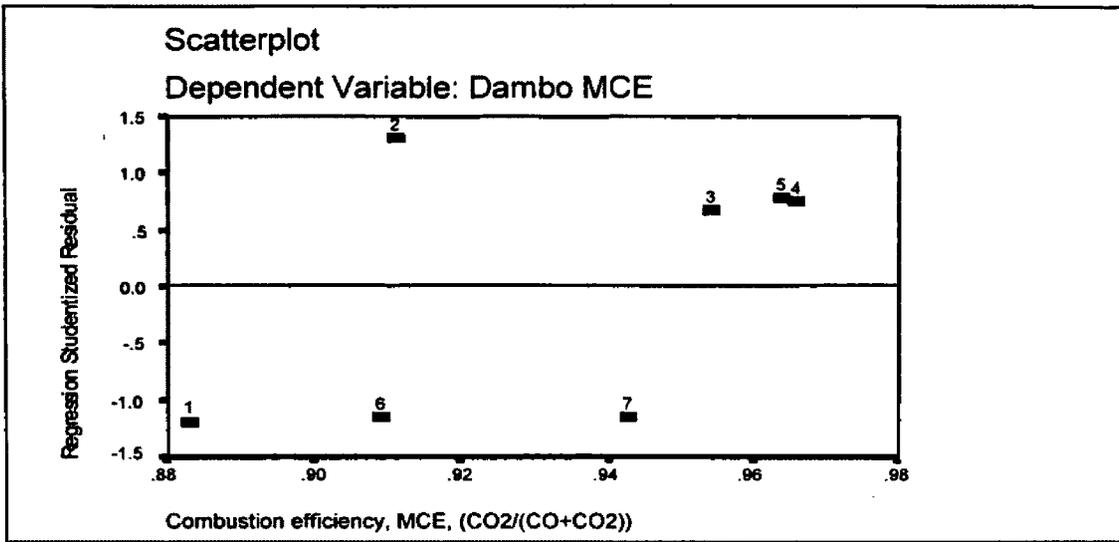


Figure 9: Regression studentized residuals of MCE and proportion live grass, dambo

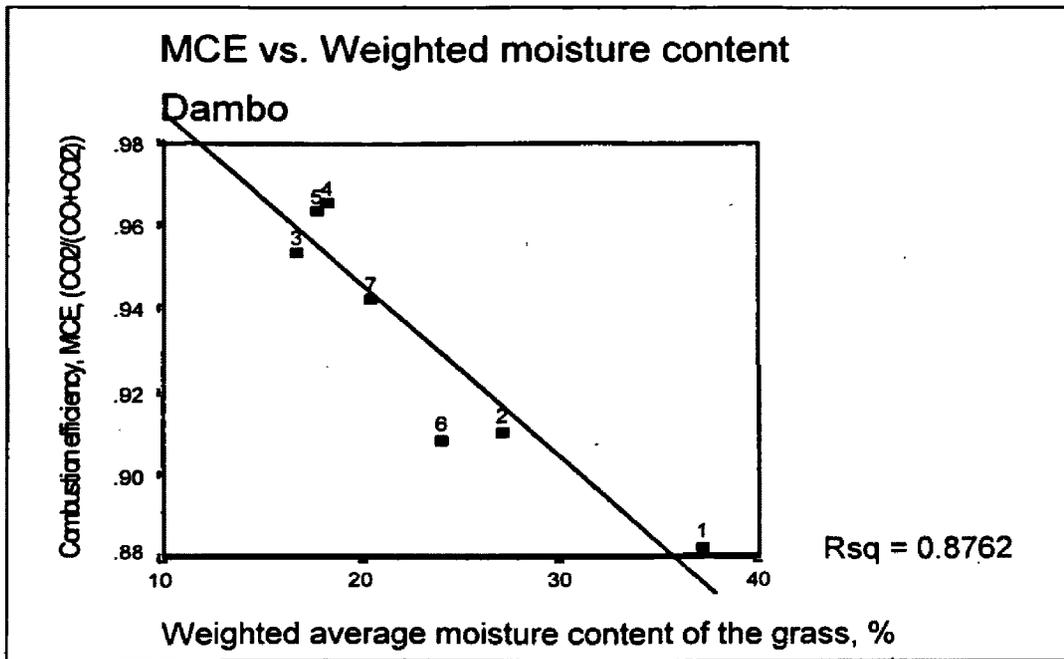


Figure 10: Linear regression of MCE on weighted average moisture content of the grass, dambo

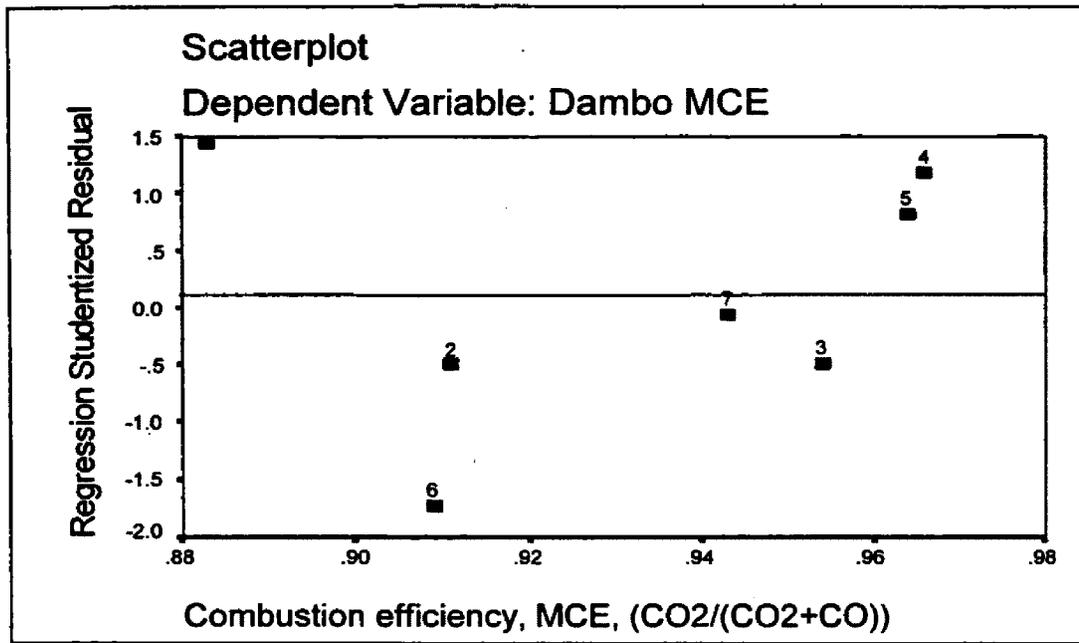


Figure 11: Regression studentized residual of MCE and proportion of live grass, dambo

regression assumptions. Therefore, the weighted moisture content of the live and dead grass in the dambo provides the best model for predicting the MCE of the early dry season fires. The model for the regression line of MCE (Y) on the average moisture content of the dambo grass, weighted by the relative fuel loading of the live and dead grass (X) is:

$$Y = 1.029 - 0.0041(X)$$

Therefore, based on the data from this study, the model previously defined for the proportion of live grass should only be used in deference to the latter model when the weighted moisture content of the fuels is not available. The statistically significant negative correlations of both models, however, support the hypothesis that the increased moisture content of the fuels in the early dry season decreases the MCE of fires at this time ($b = -0.286$, $b = -0.0041$, respectively).

4.3.2. Miombo

For the purpose of analyses it was assumed that the proportion of live grass or the weighted moisture content of the grass would similarly explain most of the variation in the miombo as it was assumed that the grass is responsible for carrying early season savanna fires. However, simple linear regression of the MCE against the proportion of live grass ($R^2=0.08$) efficiency (see Figure 12) or against the weighted moisture content of the grass ($R^2=0.109$), did not explain the variation in the observed MCE.

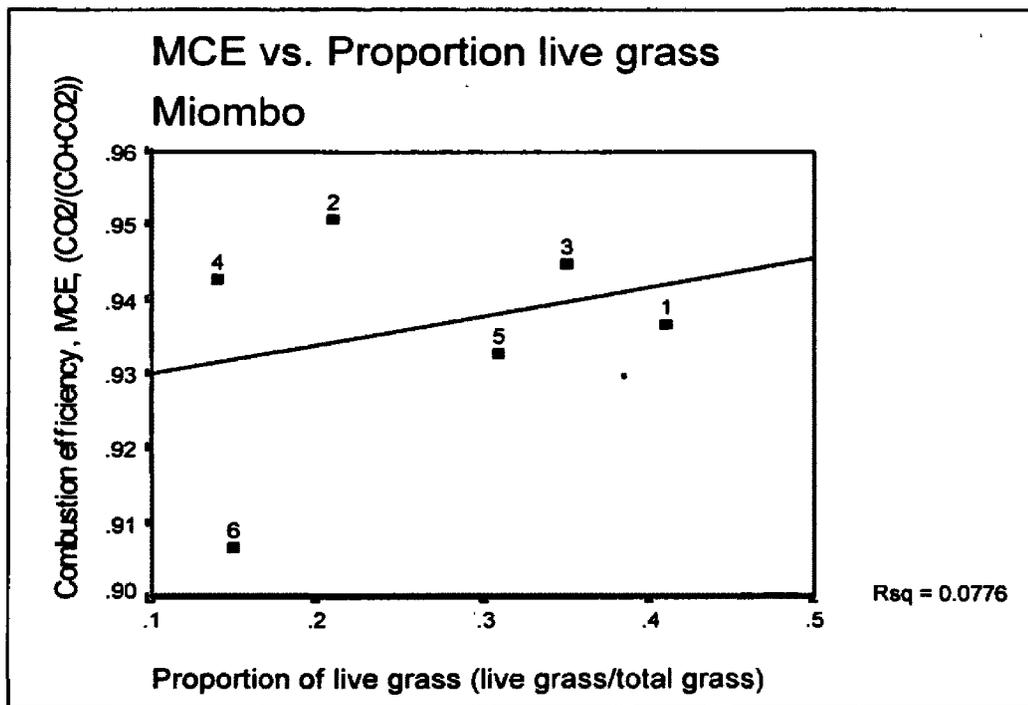


Figure 12: Linear regression of MCE with proportion of live grass, miombo

Similar to the dambo, though, there was no significant relationship between the total fuel load and MCE ($R^2 = 0.04$) or the moisture content of live grass and MCE ($R^2 = 0.31$). Yet, the MCE was certainly being affected by some variable different from that

which affected the dambo, as there was an observable *decrease* in MCE as the early dry season progressed (see Figure 13).

Therefore, it was presumed that the litter, which began to fall in the middle of July, affected the way the understory carried the fire. To test this hypothesis, simple multiple linear regression was carried out between the proportion of total grass to the sum of grass and litter ($G/(L+G)$) (see Table 2) and the MCE after Hao et al. (1996).

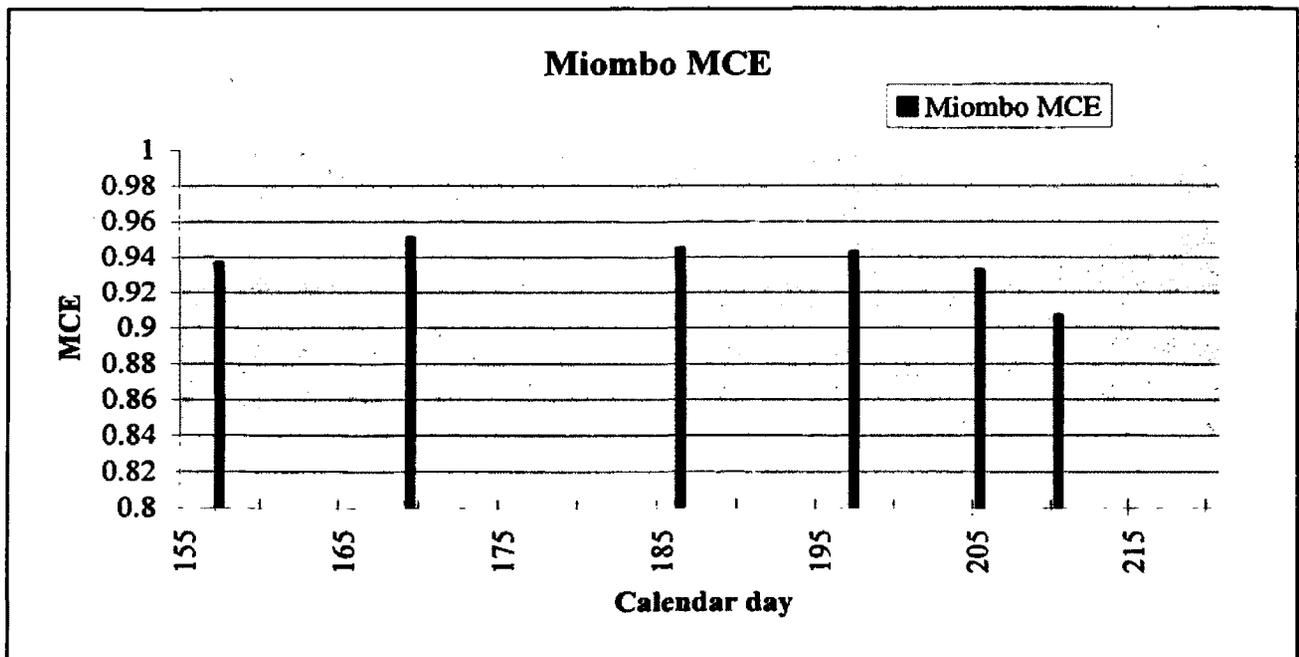


Figure 13: Histogram of MCE by the date of burn, miombo

The relationship was moderately significant ($R^2=0.58$, $adjR^2 = 0.47$, $SEE = 0.013$, $p = 0.080$) (see Figure 14). However, the ratio used by Hao et al. (1996) was based on late season fuel data. To evaluate the early season fuels it was hypothesized that the moisture content of the litter and the moisture content of the live grass might also affect the

strength of the relationship. The relationship was not significantly affected by multiple linear regression including the moisture content of the live grass ($adjR^2 = 0.51$). The coefficient of determination was improved, however, by multiple linear regression of $G/(G+L)$ and moisture content of the litter ($R^2=0.77$, $adjR^2 = 0.61$, $SEE = 0.010$).

Table 2: MCE and pre-fire biomass characteristics, miombo

| Site | Date | Weighted MCE | G/(G+L) | Litter %Moisture | Live Grass %Moisture |
|-------|---------|--------------|---------|------------------|----------------------|
| M157* | 6/6/96 | 0.937 | 0.23 | 4.86 | 118.58 |
| M169 | 6/18/96 | 0.951 | 0.20 | 6.01 | 64.92 |
| M186 | 7/5/96 | 0.945 | 0.33 | 3.88 | 93.82 |
| M197 | 7/16/96 | 0.943 | 0.30 | 4.21 | 70.14 |
| M205 | 7/24/96 | 0.933 | 0.24 | 5.82 | 50.54 |
| M210 | 7/29/96 | 0.907 | 0.09 | 4.57 | 32.75 |

* M157 refers to Miombo plot burned on 6 June, 1996, Julian calendar day 157

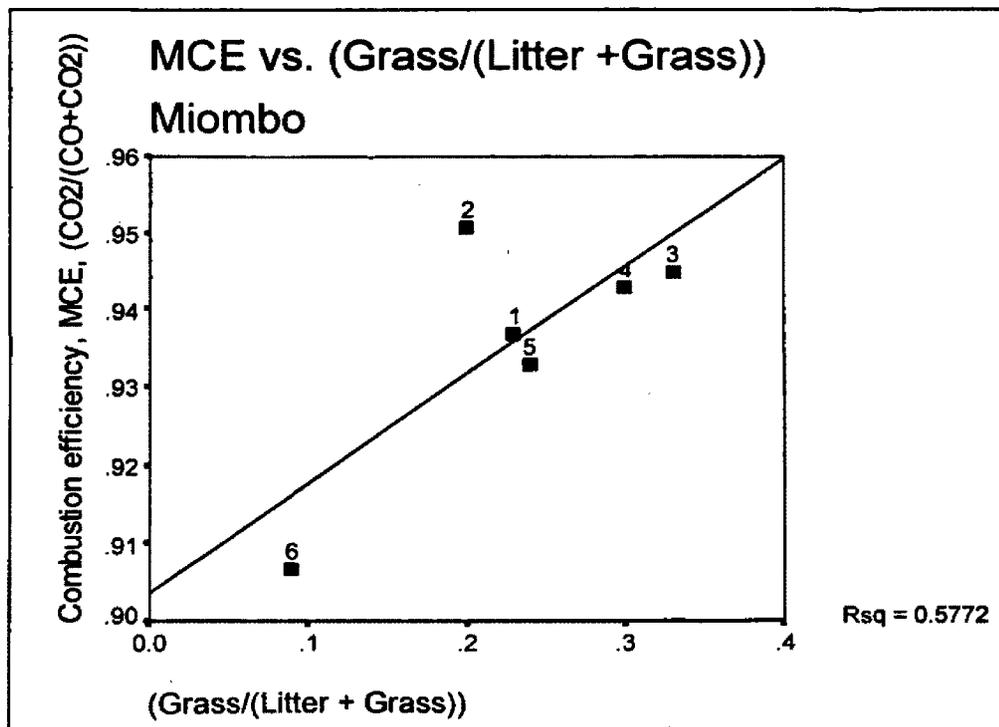


Figure 14: Linear regression of MCE with Grass/(Litter + Grass), miombo

The model for the regression line is:

$$Y = .171(X_1) + .0084(X_2) + .855$$

where:

X_1 = grass/ (litter + grass)

X_2 = moisture content of litter

The positive slopes of the regression line indicate that, as we would expect, the proportion of grass relative to the total amount of grass and litter provides a higher MCE ($b = .131$). Although the addition of the litter moisture content improves the R^2 (0.77, $\text{adj}R^2 = 0.614$), b_2 is not statistically significant ($p = 0.213$). Nevertheless, I have included it in the model equation in the hope that the statistical insignificance is due to the small number of experimental burns and that future studies will validate the practical significance of including moisture content variables into the assessment of early season fire efficiency studies.

4.4. DISCUSSION

The previous results verify two hypotheses: 1) there is significant ecosystem heterogeneity between the dambo and miombo, indicating that different parameters affect the fire MCE in different ways, and 2) the impact of fuel moisture content on the efficiency of the fire is significant in these two savanna systems. Thus, the hypothesis that burning in the early dry season will have a different effect on the quantity and type of emissions from savanna biomass burning is supported based on the assumption that different combustion efficiencies affect the products of complete and incomplete combustion. Further analysis to assess the specific impact of the early dry season fire

regime, i.e. with regard to aerosol production or trace gases, must take into account the ecosystem heterogeneity of the region.

Ward et al. (1996) used the ratio ($G/G+L$) to evaluate combustion efficiencies of late season fires in Zambia and South Africa as part of SAFARI-92. When their values are plotted with the values from this study (see Figure 15), there is an interesting relationship. Values from the Zambia 1996 miombo plots (this study) generally have a lower proportion of grass to total grass and litter than the South Africa sites. This is not unusual given that South Africa's Kruger National Park is predominantly a bushveld system. The miombo plots in Zambia, maintain an open canopy deciduous tree cover providing significantly more litterfall. The three miombo plots in the Zambia 1992 study are also quite distinct, correlating to different miombo types: fallow chitemene (ZFC), moist miombo (ZMM), and semi-arid miombo (ZSM). The Zambian dambo grassland site (ZDG), like all the grassland sites in this study, did not have any litter, and therefore had a $G/L+G$ ratio of 1.

All of the Zambia 1996 sites were from a semi-arid miombo system. Interestingly, they fall within a narrow band of $G/G+L$ values, but are distributed along a range of MCE values. They were burned in the early dry season versus in the 1992 study which took place during the late dry season. The difference between the two studies may be explained by different grass and litter loading on the two sites or, perhaps, by the different season of the burns. Indeed, it is interesting to note that the final miombo burn

in 1996 (M210) falls very close to the ZSM site, perhaps indicating that it equaled the value to be expected with a late season burn in a semi-arid miombo site in Zambia.

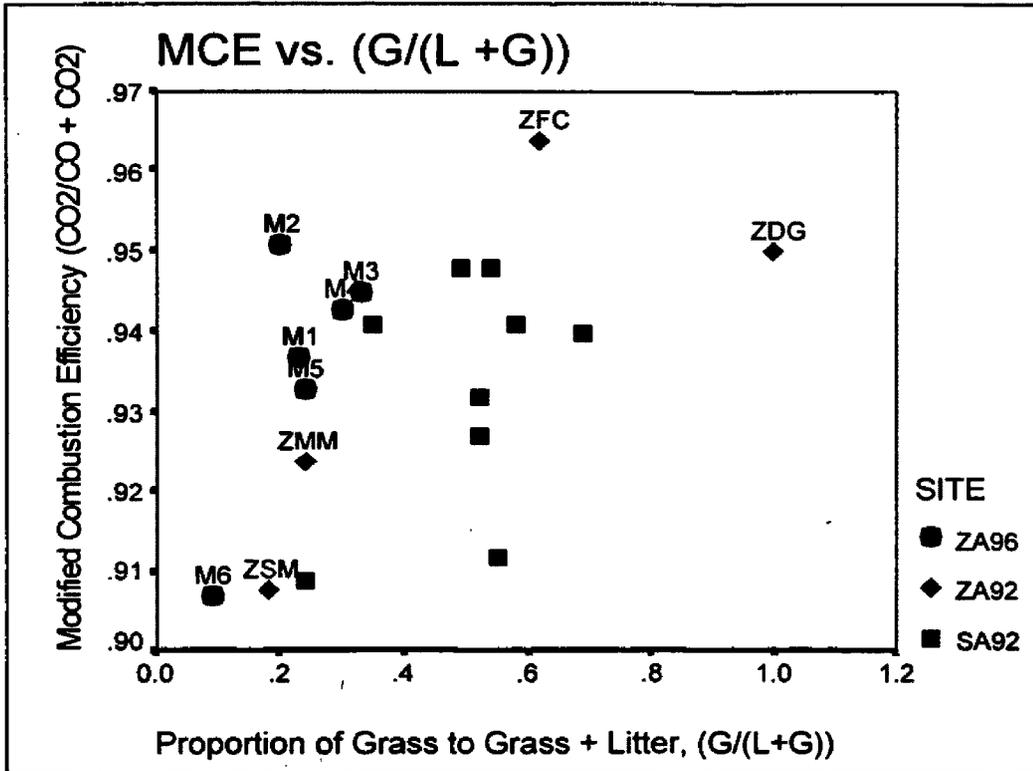


Figure 10: The response of MCE to the proportion of grass and litter

This would indicate that the dry-down of the vegetation was captured very well in this study, and that the other plots (having similar fuel loading) would have approached this value if they had burned later in the year. The MCE values from the earlier miombo plots, therefore, simulate the relative efficiency of early season fires.

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DISCUSSION

5.1. INTRODUCTION

Fire in African savannas is a significant force that changes global atmospheric chemistry by augmenting emissions of CO₂, aerosols, and trace gases, and that affects local vegetation patterns. Within the United States, fire management plans often emphasize the need to understand ecosystem response to anthropogenic fire suppression. In the African savannas, however, the ubiquitous and traditional use of fire requires different management which aims to conserve natural resources and ecosystem heterogeneity. Particularly, this has translated into directives to encourage early dry season burning to prevent potentially destructive late season fires (Chidumayo et al. 1996; Cook 1994; Harris 1980). There has been little research to evaluate the effect that an early burning regime has on tropical biomass burning emissions. The results and discussions of the preceding chapters were a collective effort to evaluate the efficiency of fires during this time of year, indicating the potential impacts of the fire emissions. It has been postulated that early season fires will result in emissions derived from incomplete combustion because of the higher moisture content of the vegetation (Hao et al. 1996). Toward this end, I have evaluated the completeness of the burn (combustion factors), the efficiency of the fires (modified combustion efficiency), and the behavior of the fire (through estimates of fire front intensity and reaction intensity). These parameters are needed to understand the amount of fuel consumption, the oxidation potential of the fire (proportion of products from incomplete versus complete combustion), and the quantity of the resultant emissions fluxes, as they might be affected by the moisture content of the

vegetation. Results indicate that there is a different response to fires in the early season. The completeness of the burn, early in the dry season, is significantly less. The combustion efficiency increases as the season progresses but is mediated by the effect of litter fall in the woodland system. Thus, products of incomplete combustion are more likely to be expected during this time of the year, which may have an effect on global trace gas estimates from tropical biomass burning.

However, to fully understand the seasonal dynamics of early season burning so as to apply estimates to modeling efforts or to make long term predictions, it is necessary to simultaneously evaluate the socio-economic and political forces influencing burning practices and which may ultimately control the magnitude and duration of early season burning, and to evaluate the ecological ramifications of such management. Such socio-economic critique is lacking in a majority of the scientific literature on biomass burning despite the fact that predictive modeling efforts and/or ecological and land use management depends on the ability to define the duration, magnitude, and effects of biomass burning in the past, present, and future. To blame indigenous cultures (i.e. overpopulation) or practices (i.e. shifting cultivation) as the cause of increased biomass burning emissions ignores the importance of co-evolutionary relationships between the environment and indigenous cultures, and the increasingly significant role that national and international policy (i.e. modernization) exert on encouraging the use of fire. While I have made a preliminary attempt at understanding this dynamic (Chapter 2), it is a complex topic and requires the attention of future independent research initiatives.

Early dry season burning management necessitates recognizing the links between the socio-economic, cultural, and biophysical conditions that affect savanna ecology, and mediating global concerns of emissions. One such link lies in an assessment of fire effects on soil biochemistry and how such interaction affects agriculture and land use.

5.2. SOIL BIOCHEMISTRY

Scholes and Walker (1993) saw three trends in savanna research: 1) responses of the global savanna system on geologic time scales to natural changes in rainfall, temperature, and nutrient cycling, and how these interface with anthropogenic activity and disturbance, 2) individual plant response to environmental change, and 3) spatial patterns in savanna ecosystem function. Savanna biogeochemistry is currently a subject of much interest as it is critical to an understanding of these research initiatives. In light of recent estimates that indicate the severity of anthropogenic influence, recent efforts have focused on disturbance effects on savanna biogeochemistry (Jones, 1990). Particularly, soil processes are potentially greatly effected by biogenic fire emissions (Shea et al. 1995; Cook 1994; Ojima et al. 1994). Moreover, the effects of fire on soil processes may be influenced by seasonal dynamics of fire intensity, changes in land use, and ecosystem heterogeneity. The understanding of the interaction of these factors will determine the magnitude at which soil processes control savanna vegetation structure and species composition in response to fire disturbance.

Several studies in the United States have led to an understanding of fire effects on soil biochemistry (Stark 1977; DeBano 1990; Ojima et al. 1994; Hobbs and Schimel 1984). Work in tropical systems has been scant, particularly because there is very little

knowledge of baseline processes and thus very little method of detecting disturbance effects. However, there is evidence to believe that temperature and chemical changes from fires affect plant nutrient availability, that ash provides initial nutritive value, and that nitrogen and carbon cycling are significantly altered by a continuous fire regime.

Stromgaard (1988) argued that chitemene agriculture combines the effects of heat and ash to provide an effective agricultural system. Particularly, he proposes that heat from fires kills nitrifying bacteria, inhibiting conversion to nitrite and nitrate, thus preserving nitrogen in the ammonium form so that nitrogen is not leached through the growing season but rather, remains plant-available. This is in contrast to studies in which microbial activity is enhanced through fire (Britton 1979; Delmas et al. 1995; Srivastava and Ambasht 1994). On the other hand, inhibition of nitrifiers might be due to a release of toxins by plant roots (Delmas et al. 1995; Stromgaard 1988).

Further, chitemene agriculture depends on the phosphorus and calcium provided by the ash which improves the physical condition of the soil, increases alkalinity, and provides phosphorus in an otherwise P-limited system (Moore and Vaughan 1994; Stromgaard 1988; Frost, 1996). Fire also increases the concentration of potassium, and other base cations, perhaps by releasing the nutrients stored in the organic matter (Kauffman et al. 1994; Andriessse and Koopmans 1984; Tveitnes 1983). Studies have shown that because potassium is highly mobile, the initial increase after fire will eventual decrease shortly thereafter (Stromgaard 1988). Nevertheless, sequestration of elevated concentrations of nutrients in the ash component does occur in miombo systems (Trapnell 1959; Lawton 1978). Stromgaard (1984) found that chitemene ash contained $44 \text{ kg ha}^{-1} \text{ N}$,

1 kg ha⁻¹ P and 219 kg ha⁻¹ K. There is a positive correlation between the amount of ash used and the yield of finger millet, for example, perhaps indicating the nutritive effects of fire for agricultural production (Araki 1992).

Losses of nutrients through of fire, directly via fire emissions, or through fire effects, can be significant in the long term. Determination of N/C ratios for burned ecosystems is essential since lack of such knowledge is one of the problems associated with global source estimates (Lobert et al. 1991). Oxidation of soil carbon may equal 17% of the net soil flux to the atmosphere (0.3 Pg C/year) (Houghton 1991) although this estimate is highly dependent on microbial activity. On the contrary, Crutzen and Andreae (1990) proposed that at least this same amount of carbon is converted to inert carbon, in the form of charcoal, via biomass burning, perhaps accounting for a part of the terrestrial carbon sink (Houghton 1991). In fact, 70% of all the black inert carbon that is produced is produced in Africa (Kuhlbusch et al. 1996). Yet, it has now been suggested that the amount of charcoal accumulation is smaller than previously thought (Fearnside 1996 in prep.; Kuhlbusch et al. 1996).

The effect of biomass burning on nitrogen cycling is even less clear. In fact, 60-70% of the nitrogen emissions are unknown (Andreae 1991). Emissions from savanna soils are strongly dependent on the soil water content, the soil nitrogen status, and temperature (Parsons et al. 1996; Srivastava and Ambasht 1994). Nitrogen emissions from fire are further dependent on the nitrogen content of the fuels (Ward 1990). Hobbs and Schimel (1984) suggested that fire increased the rate of N mineralization but that the N losses that occurred through fire were potentially not compensated for by N fixation.

Ojima et al. (1994) incorporated combustion losses of aboveground C, N, and P into the CENTURY model (Parton et al. 1987). From field experiments in the tallgrass prairie of the western U.S., they determined that: 1) nitrogen mineralization was enhanced by increasing soil temperatures, 2) nitrogen availability was increased because non-symbiotic N-fixing bacteria were stimulated by ash phosphorus, and, finally, 3) that most of the significant N losses occurred via combustion rather than by leaching or denitrification pathways. These simulations also showed that increased plant production after fire was due to an increase in nitrogen use efficiency (NUE), i.e. that greater carbon was gained per unit of nitrogen utilized, rather than because of a greater total nitrogen availability. Ojima et al. (1994) postulated that this could explain a mechanism by which C₄ species, with high NUE, could persist by outcompeting C₃ species despite recurrent N losses from fire. This might also be a reason for C₄ grass predominance over woodlands in savanna fire ecosystems, versus the increase in wooded patch communities in fire-exclusion areas (Ojima et al. 1994; Archer 1988).

There needs to be work to evaluate these claims in the early season burning regime. It is possible that higher soil moisture before the fire might increase NO_x emissions. Further, burning before the litter falls means that the soil has a different nutrient content than later in the season. Therefore, the microbial response might be different. Also, there needs to be a more detailed evaluation of the internal nutrient cycle (within-plant) of the miombo species such that external nutrient cycles (plant-litter-soil) can be contrasted. What kind, and how much of within-plant nutrients are recycled prior to senescence and what effect does this have on the litter nutrient pool (Frost 1996)?

How do we account for ecosystem heterogeneity? Does the lower intensity of the burns in the early dry season, as has been suggested with this research, affect the soil biochemistry or the nitrogenous emissions? How does this affect the nitrogen fixation potential of woodland areas (miombo) versus grassland systems (dambo) and their relative dominance? Finally, and perhaps most important from a social and management context, do the agricultural benefits associated with burning (i.e. fertilization inputs) differ between the early and late dry season burns?

5.3. MANAGEMENT

Early burning is a more practical management technique for promoting both tree growth and species conservation in the miombo without increasing the risk of fierce accidental late season fires. However, the fire regime is complex. Fire influences climate through atmospheric emissions but it also influences vegetation through natural selection. The fuel properties of the vegetation, in turn, also affect the type of fire. Climate affects fire through the control of weather (relative humidity, wind) and through the control of water and energy supplies to the vegetation on a seasonal basis (Ryan 1991). And, as previously mentioned, soil factors will intervene at many levels of this cycle. Therefore, to properly manage a fire regime, it is necessary to understand these interactions such that a desired goal is achievable.

In Zambia, much of the woodlands are under communal forms of utilization. There will thus be different utilization of the woodland areas. For example, people involved in livestock production will want to burn as soon as possible to stimulate

nutritive grass regrowth; they will continue to burn for regrowth late into the season. There have been early burning guidelines for grazing management and restriction of stocking rates following a burn to prevent erosion in dambo systems (Prior 1983) but it is unclear that these guidelines are enforced. However, if wood is a desired product of the woodlands, for poles or timber, for example, then early burning should be encouraged so as to protect trees and saplings from damaging late season fires (Chidumayo et al. 1996). Those involved in charcoal production may not take ecological considerations into account as much as farmers who depend on fertile soils for agricultural productivity. In addition, burning too early may induce grass growth which exhausts soil water reserves until the rains begin again (San José and Medina 1975).

Therefore, an integrated fire management program must be developed that defines the threshold between desired and undesired effects of biomass burning. These effects must weigh the global ramifications of early season burning, i.e. with regard to quantity of burned biomass and trace gas emissions, as they may affect global climate change, and the regional and local ramifications of economic well-being, development, and agricultural production. The regional and local ramifications must further take into account the differing reasons for savanna use by different constituents within a society. All management guidelines must also appreciate the significant historical fire use for both survival and cultural purposes, and ecological adaptations to continual fire use that have already occurred. Managers must expect that fire will continue to be an integral part of development and must prepare the local forests against fierce accidental fires through firebreaks and fuelbreaks (Goldammer and Manan 1996). There must also be significant

involvement of local communities in endeavors such that community values that already enforce woodland protection are augmented and supported, and that local people are involved in conservation efforts. Similar efforts have proven successful in wildlife conservation (Kelso 1993). Before early burning management is enforced, it is strongly urged that social studies are undertaken to evaluate the traditional use of fire and traditional fire management practices to determine the effectiveness of creating new management objectives.

5.4. CONCLUSION

This study was an attempt to evaluate emissions from early season burning in an African savanna. As such, scientific and social consideration were taken into account. There were several limitations to this study, however. For example, numbers taken from the literature, e.g. value for heat yield (H) used in the equation for fire line intensity (Trollope 1983), must be validated with other studies in other parts of Africa. Sampling error would be minimized if more care were taken in paired plot preparation of pre-fire and post-fire subplots because of the heterogeneity of miombo woodlands. Also, the small number of plots used to evaluate fire efficiency and combustion completeness limited the statistical power of the results. This does not detract from the clear trends that are suggested by this work, but does illicit caution in extrapolating this study to regional or global scales.

Many more studies are needed in other semi-arid miombos and dambos. Further, more studies are needed to evaluate the emissions from other types of systems, with

different moisture regimes, vegetation loading and structures. This work might be facilitated by remote sensing analyses of Zambia which aim to classify fire potentials based on moisture regimes or vegetation type and which identify sites for further field work. Given limitations of scale and cost, remote sensing applications for early season biomass burning evaluation might be most beneficial in interannual determinations of relative greenness based on seasonal precipitation variability. Particularly necessary is a discretization of different land uses within the miombo and dambo to delineate the reasons for fire use and their regional extent to both target management policies and evaluate emissions potentials. Remote sensing could be particularly helpful in this effort.

To conclude, early season emissions appear to be affected by the moisture content of the vegetation such that early season burning may have a different effect on global estimates of tropical biomass burning when seasonal dynamics are incorporated, e.g. by increasing estimates of trace gas emissions. Early burning is a small but significant part of the fire regime in Zambia. The Zambian fire regime is, in itself, a small but significant player in global climate change. Yet, as more is discovered about the biogeochemistry of savanna systems, it appears fire management has the potential to moderate global emissions and reinforce natural ecosystem dynamics. Evaluation of early season burning is an important research objective to assist in the determination of long term effects of a disturbance regime on a savanna system at global and local scales.

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