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FUEL CHARACTERISTICS AND EMISSIONS FROM BIOMASS BURNING AND LAND-USE CHANGE IN NIGERIA

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Abstract. Nigeria is one of the 13 low-latitude countries that have significant biomass burning activities. Biomass burning occurs in moist savanna, dry forests, and forest plantations. Fires in the forest zone are associated with slash-and-burn agriculture; the areal extent of burning is estimated to be 80% of the natural savanna. In forest plantations, close to 100% of litter is burned. Current estimates of emissions from land-use change are based on a 1976 national study and extrapolations from it. The following non-carbon dioxide (CO_2) trace gas emissions were calculated from savanna burning: methane (CH_4), 145 gigagrams (Gg); carbon monoxide (CO), 3831 Gg; nitrous oxide (N_2O), 2 Gg; and nitrogen oxides (NO_X), 49 Gg. Deforestation rates in forests and woodlands are 300×10^3 ha (kilohectare, or kha) and 200 × kha per year, respectively. Trace gas emissions from deforestation were estimated to be 300 Gg CH_4, 2.4 Gg N_2O, and 24 Gg NO_X. CO_2 emissions from burning, decay of biomass, and long-term emissions from soil totaled 125 561 Gg. These estimates should be viewed as preliminary, because greenhouse gas emission inventories from burning, deforestation, and land-use change require two components: fuel load and emission factors. Fuel load is dependent on the areal extent of various land uses, and the biomass stocking and some of these data in Nigeria are highly uncertain

1. Introduction

The ecoclimatic zones in Nigeria range from the very humid freshwater and mangrove swamps in the south to the semiarid Sahelian zone in the north (Keay, 1959). The most extensive vegetation zones are forests and savannas. Savanna, a seasonal tropical vegetation type in which there is a closed or nearly closed groundcover of grasses that have flat, cauline leaves and are at least 80 centimeters (cm) high, comprises close to 80% of Nigeria's area of 924 000 square kilometers (km^2). Trees and shrubs are most often present in savanna, and they burn periodically (Sanford and Isichei, 1986).

Savannas can be divided into two broad groups: moist (humid) and dry (subhumid). Most burning takes place in the moist savannas, where the moisture-indexed length of the growing season is between 151 and 270 days and the rainfall/evapotranspiration ratio is between 0.4 and 1.0. This zone is described as subhumid (ILCA 1979). In terms of vegetation classification, the savanna area includes the derived (Transition), southern guinea, and northern guinea zones, or the guinea-congolian mosaic of lowland rainforest; *Isoberlinia* woodland and secondary grassland; and Sudanian woodland with abundant *Isoberlinia* (White, 1983; Keay, 1959).

Nigeria has a population of 88 million people and is one of the most densely populated countries in Africa. Most of the country is suitable for agriculture, and land use is largely driven by fiber, fuel, and food production. Fire is used extensively for bush clearing and

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weed control in the widely practiced subsistence agriculture, and as a range management tool in livestock systems. Fire use in vegetation systems is human-related, but natural fires caused by lightning have been reported in savannas (Menaut *et al.*, 1985). Fires are so intimately associated with savannas that they are regarded as fire climax ecosystems. Fire is more essential to savanna maintenance than a humid climate. Fire frequency decreases with decreasing rainfall, from virtually annually in humid savannas to occasional and irregular fires in arid regions (once in 20 years) (Walker, 1985; Skarpe 1992). All plant species in the humid savanna communities are adapted to fires, without which the grass sward degenerates through the accumulation of senescent material and death of tillers. Savanna fires are generally restricted to the herbaceous layer, and crown fires are infrequent. In humid savannas the fuel load and intensity of the fires are such that the vegetation develops into a mosaic of open grassland with clumps of closed woodland and forest. Derived, or transition, savanna in West Africa converts back to forest if it remains unburned for some time.

Extensive wildfires are rare in the forest zone except in dry forests and plantations that suffer ground (litter) fires (Delmas *et al.,* 1991). Fires in the forest zone are associated with slash- and-burn agriculture, charcoal production, and conversion of forest to other permanent land uses, such as plantations of crops and exotic trees. One of the effects of forest fires is the transformation of dry forests into savanna. Once established, such savannas are maintained by fires (Swaine, 1992). Whether burned directly or converted, the loss of tropical forest cover has negative consequences for future global climate (Brown *et al.,* 1993).

Dry forest fires combust forest floors and litter and often smolder rather than burn openly. Small plants, including juvenile trees, suffer the greatest mortality, and large trees suffer bole damage and may die within 2 to 4 years after the fire. Opening the forest canopies allows the germination of certain herbaceous and perennial shrubs, especially plants in the family *Zingiberaceae,* and the shrub *Chromolaena odorata*, which is the best indicator of disturbed humid vegetation in West Africa (Keay, 1959).

Humid savanna fires mostly occur when vegetation is not completely dry. Delmas *et al.* (1995 a,b) report a grass moisture content of 7% to 8% in the dry season in the humid Lamto savanna in Côte d'Ivoire, as compared with 4.2% at Nylsvley in South Africa (Frost, 1985). Thus, only leaves, which are drier than stems, burn in early savanna fires. In dry forests where *Chromolaena* dominates, only the leaves burn. In humid savannas, up to 80% of the vegetation cover may burn, whereas in the Sudan zone only 25% to 50% (Delmas *et al.,* 1991) burns. An even lower proportion of litter burns in the Sahel.

The burning of savanna is linked to vegetation phenology. Savanna plant growth starts with the sprouting or regrowth (flushing) from rhizomes whose tops had been burned the previous season (Afolayan, 1978). Flushing can start as early as January (the middle of the dry season) and is a major reason why nomadic herdsmen burn savannas, the new flush being rich in nutrients (Collins, 1977). Germination of annual grasses starts with the rains, which in the Nigerian savanna begin between April and late May. Grasses attain their peak growth in October-November, after which they start senescing and drying up.

Burning can start in mid-December and by the end of January, most burning has taken place. The longer the burning is delayed into the dry season, the more intense the burn and the less the nutrient content of the grasses (due to translocation of some nutrients to belowground parts) (Isichei, 1983). Most West African savanna trees shed their leaves and flush new growth between February and May so that only a small proportion of savanna leaf litter is burned in annual fires (Collins, 1977).

Forest plantation fires (especially *Tectona grandis* and *Gmelina*) also occur in December-January. Plantation fires are more intense because the trees are completely deciduous and litter production is abundant (Akeredolu and Isichei, 1991). Leaf shedding occurs over a short time in December-January concomitant with occurrence of fires. Up to 100% of the litter is burned in some forest plantation fires.

Nigeria is reportedly one of the 13 major sources, by country, of greenhouse gas emissions (Marland, 1991). Not only are large quantities of natural gas flared in Nigeria but there is also extensive biomass burning, especially in the savanna zones. While reporting on the acidification potential in the Nigerian environment as part of the SCOPE Project, "Acidification in Tropical Countries," we had the opportunity to assess the contributions of emissions from biomass burning and energy use to acidification in Nigeria (Isichei and Akeredolu, 1988). We have also reported on the emissions of carbon (C), nitrogen (N), and sulphur (S) from biomass burning in Nigeria (Akeredolu and Isichei, 1991). For some aspects of these studies we had relied on earlier studies of N cycling in savanna ecosystems that had reported herbaceous biomass production and N content; the role of burning in N cycling in savannas was also assessed (Isichei and Sanford, 1980). For the present study of the fuel load characteristics for biomass burning assessment and emissions from burning, updated data from earlier studies (Isichei, 1983; Isichei, 1994; Isichei and Akeredolu, 1988; Isichei and Sanford, 1980) and more recent information from the literature were used to compile emissions of the greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2), carbon monoxide (CO), and other nitrogen compounds (NO_x), and nonmethane volatile organic hydrocarbon compounds.

2. Methodology of assessment of fuel load for biomass burning and resulting emissions

2.1. Savanna Burning

Most of the Nigerian savanna is burned annually. An estimated 20 700 × 10^3 ha (kha) of savanna is assumed to be subjected to annual fires. This is approximately half the area described as moist savanna. ERGO (1994) identified nine land-use types in its assessment of land-use change in Nigeria between 1976 and 1990. The categories were bare ground, grassland, scrub-shrubland, woodland, forest, mangrove, open water, cultivation, and settlement. The combinations of land-use types that are associated with savanna burning are farmland-woodland/shrub/grassland, wooded shrub grassland/woodland transition, and grassland wooded shrub.

FAO (1981) states that guinea savanna occupies 376 070 square kilometers (km^2), and the transition zone 41 560 km^2. These two zones, totalling 417 630 km^2, cover approximately 45% of Nigeria's land area. Our estimate of the annually burned area is approximately half the size of the guinea and transition zones. The ERGO land-use categories that burn annually are estimated to be 42 108 × kha. When farmland categories (22 246 × kha, according to ERGO) are subtracted from this area (farmlands are not burned annually), 19 863 × kha remain, similar to our estimate of 20 700 × kha.

A value of 3 Mg of dry matter per hectare (Mg dm ha^{-1}) was arrived at after considering the grass production figures shown in Table I. De Leeuw (1978) suggested a predictive relationship between total annual rainfall and maximum annual herbage standing crop. Thus: grassland primary production (kg ha^{-1}) = 2.36 × annual rainfall (mm) + 34.7. Most moist savanna locations would fall into the 3 Mg dm ha^{-1} yr^{-1} category if this equation were used. The fraction of total biomass actually burned is based on the results of Isichei and Sanford (1980) and Menaut *et al.* (1993).

Grasses, both annuals and perennials, are the dominant life form in the herb layer in moist savanna. Because they decline at the end of the season they are considered dead at the time of burning (Collins, 1977). When burning occurs before the grasses dry, only the leaves burn in some species. The proportion of leaves to other plant parts varies widely depending on the grass species. No data are available on the proportions of plant parts (Delmas, 1995 a,b).

The proportion of biomass oxidized based on the observations of Isichei (1994) was estimated to be 0.80. The observation was derived by burning grass in an aluminum tray and weighing the "ash" after burning and cooling. The mean weight of ash was 20% of the oven dry weight. A value of 0.47 as C fraction in biomass was adopted in this analysis (Susott *et al.*, 1995).

The N:C ratio was estimated to be 0.0007 (Isichei, 1994). There have been extensive analyses of N in Nigerian savanna grasses (Isichei, 1983). Mean dry season N concentration is approximately 0.35%, giving an N:C ratio of 0.007. The International Panel on Climate

TABLE I

Grass production figures for Nigeria

Grass standing crop at peak standing crop (Mg dm ha^{-1})	Reference
3.04	Isichei & Sanford (1980) (mean value for 9 sites)
0.8–6	Usman (1981)
1.5–7	Afolayan (1978)
2.01–4.5	De Leeuw (1976)
5.7–6.8	Hopkins (1966)
2.21–3.16	Muoghalu & Isichei (1991)

Note: Mg dm ha^{-1} = megagrams of dry matter per hectare.

Change (IPCC) default values for trace gas emission factors (for example, NO_x) and emission ratios do not differ significantly from the estimates of Delmas *et al.* (1995, this volume).

Burning is much less extensive in the Sudan region of Nigeria relative to the more humid savanna zones. However, there are no precise data on the areal extent of savanna burning in the Nigerian Sudan zone. We have adopted a value of 30% as the proportion of savanna burnt annually (Delmas *et al.,* 1991), and a herbaceous production figure of 2 Mg dm ha^{-1} yr^{-1}. Burning of agricultural residues is not common in Nigeria, as they are in great demand as livestock feed and construction material (Bayer and Otchere, 1985).

2.2 Land-use Change and Forestry

2.2.1. Forest clearing: CO_2 release from burning aboveground biomass on- and offsite
FAO (1986) reported an annual rate of deforestation of 300 000 ha for Nigeria, and this value was adopted in this analysis. The current extent of forests and plantations was obtained from NEST (1991) and Ojo (1994). For woodlands, deforestation was estimated to be 200 000 ha annually based on the observations of ERGO (1994). In their study, woodlands decreased from 44.63% to 41.3% between 1976 and 1990. When this decrease is converted to land area and divided by 15 years, a value of about 205 000 ha per year is obtained.

An average of 250 Mg dm ha^{-1} is used as forest dry matter, based on forest aboveground biomass of 229 Mg dm ha^{-1} for an undisturbed forest in southwestern Nigeria (Okali and Ola-Adams, 1987). Assuming a higher standing crop value for the more humid forests of southeastern Nigeria, a value of 250 Mg ha^{-1} was employed for undisturbed forests. For woodlands, a value of 50 Mg dm ha^{-1} was adopted based on prior estimates by Isichei (1994).

It is assumed, based on the work of Okali and Ola-Adams, that all fruit (0.4% of biomass), leaves (3%), and branches (33.3%) and 50% of stems (29.5% of biomass) are burned in savanna fires. The IPCC combustion default value of 0.9 was adopted for logged forest, because only branches and wood not considered useful are left behind, and these burn easily (UNEP *et al.,* 1995). Further, the IPCC value of 0.9 as fraction of biomass oxidized offsite was adopted, with most of the material used mainly for firewood. Approximately 24% of dry matter is assumed left to decay onsite. This includes tree stumps and large woody material not suitable for use as firewood and timber (which we assume constitute 10%). For the logged forest, a fraction of 0.1 was adopted, because 0.9 is assumed to be oxidized onsite.

Bebwa and Lejoly (1993) obtained a surface soil total C content of 16 Mg ha^{-1} in a 6-year fallow in Zaire. The value reported for the moist Lamto savanna in the Côte d'Ivoire was 17.8 Mg (Hall *et al.,* 1994). If a soil density of about 1 and an organic matter content of 3% (surface soil, 15-centimeter (cm) depth) for forest are assumed (Müller-Sämann and Kotschi, 1994), then a soil C content of 30 Mg ha^{-1} would be obtained.

2.2.2. Land-use change

ERGO (1994) reported that 2.3% of Nigeria's land area (920 000 km^2) is converted from grassland to cultivated land each year. This proportion equals 42 320 × kha, a value adopted as total conversion of grassland to cultivation over a 20-year period. A value of 15 Mg ha^{-1} was adopted as soil C content of grasslands (Müller-Sämann and Kotschi, 1994). The IPCC value of 2% was used in our analysis. Jones and Wild (1975) estimate an annual C mineralization rate of 4% in the savanna zones of West Africa, but this estimate is considered too high (see Müller-Sämann and Kotschi, 1994).

3. Results and discussion

3.1. Biomass Burning

Tables II and III show the stepwise estimates of emissions of C and non-CO_2 trace gases from biomass burning in Nigerian savanna. One crucial factor in making these estimates is the areal extent of biomass burning in Nigeria. Tekie (1989) estimates that up to 80% of natural savanna is burned in annual fires. The areal extent of burning savanna varies from year to year and from one location to the other, depending on such factors as land use and seasonality. Better estimates of the areal extent of savanna burning are now available (Scholes, this volume, and it is becoming clear that burning may have been overestimated in the past. Brustet *et al.* (1991) estimated CO_2 emissions from the burning of 180,000 km^2 of moist savanna in Côte d'Ivoire as 90 × 10^6 Mg for the months of December, January, and February. Using the same area estimate extent as in this study, Akeredolu and Isichei (1991) reported a CO_2 emission of 37 teragrams (Tg), 1.6 Tg of CH_4, and 0.0018 Tg of NO_X. Interpolation of Nigeria's latitude and longitude coordinates from the gridded emission data of Crutzen *et al.* yields a figure of 35 Tg CO_2 for savanna burning. These values are higher than those reported here, and it needs to be stated that estimates are improving as more refined estimates of savanna area burned, fraction of biomass burned, and emission ratios are available. Andreae *et al.* (1995) have concluded that N emissions from savanna burning are in the range of 14 – 33 kg ha^{-1}, corresponding to 60% of the aboveground N pool. Remote sensing offers the best method of estimating the areal extent of burning, both on a year-to-year basis and averaging over a number of years.

The season of burning, vegetation type and phenology are especially important because they affect the quantity of trace gases emitted from fires. Nutrients, especially the N content of savanna grass, drop exponentially toward the end of the growing season. As more areas become exotic tree plantations, more detailed information on the extent of each tree type and the frequency of fires under each species will be needed. Litter production under the various plantations is well known, but again, the areal extent of various plantation species such as *Gmelina, Tectona grandis, Eucalyptus,* and *Pinus* etc. are not exactly known.

TABLE II

Carbon released from biomass burning in Nigerian savanna

Biomass type	Area burned (kha)	Biomass density (Mg dm ha^{-1})	Fraction burned	C released[1] (Gg)
Humid savannah herbaceous layer	20 700	3	0.3	23 350
Humid savannah litter	20 700	2	0.2	3 892
Plantation	43	7	0.9	127
Total C released				27 369

[1]Assumes biomass is 47% carbon

TABLE III

Non-CO_2 trace gases released from biomass burning in Nigerian savanna

Trace gas	Emissions (Gg)
CH_4 (emission ratio = 0.004, Molar ratio = 16/12)	145
CO (emission ratio = 0.06, Molar ratio = 28/12)	3 831
N_2O (emission ratio = N:C ratio = 0.007, Molar ratio = 44/28)	2
NO_x (emission ratio = 0.12, Molar ratio = 30/14)	49

3.2. Land-use Change and Forestry

3.2.1. CO_2 release from forest and woodland clearing

The relationships between forest clearing, forest and woodland burning on- and offsite, and C and CO_2 release are shown in Tables IV through VI. An estimated 125 561 Gg CO_2 is released from burning of cleared forest, delayed emissions from decay, and long-term emissions from soil in Nigerian forests and woodlands (Table VII).

3.2.2. CO_2 release from conversion of grassland to cultivated land

An additional 46 552 Gg CO_2 is estimated to be released from a 20-year conversion of grassland to cultivated land (Table VIII). This demonstrates the importance of fallow land, which is often not given as much attention as mature, preserved forests and woodlands in ecological studies.

Based on an N:C ratio of 0.005 (Isichei, 1994) in wood, 300 Gg CH_4, 4375 Gg CO, 2.4 Gg N_2O, and 24 Gg NO_X are estimated to be released from the burning of cleared forests and woodlands (Table IX).

TABLE IV

Biomass cleared annually from Nigerian forests and woodlands

Forest type	Area cleared (kha)	Biomass before (Mg dm ha^{-1})	Biomass after (Mg dm ha^{-1})	Annual loss (Gg dm)
Undisturbed	300	250	5	73 500
Logged	300	200	5	58 500
Woodland	200	50	3	9 400

TABLE V

Carbon released from onsite burning of biomass cleared from Nigerian forests and woodlands

Forest type	Biomass burned (Gg dm^{-1})	Fraction oxidized	C released[1] (Gg)
Undisturbed	18 375	0.66	5 700
Logged	14 625	0.9	6 186
Woodlands	2 350	0.8	884
Total C released			12 770

[1]Assumes biomass is 47% carbon

TABLE VI

Carbon released from off-site burning of biomass cleared from Nigerian forests and woodlands

Forest type	Biomass burned (Gg dm^{-1})	Fraction oxidized	C released[1] (Gg)
Undisturbed	7 350	0.9	3 109
Logged	5 850	0.9	2 474
Woodlands	940	0.9	398
Total C released			5 981

[1]Assumes biomass is 47% carbon

TABLE VII

CO_2 emissions from forest and woodland clearing in Nigeria

C from burning (Gg)	C from decay (Gg)	C from soil (Gg)	CO_2 from clearing[1] (Gg)
18 751	10 993	4 500	125 561

[1]Conversion ratio 44/12

TABLE VIII

CO_2 emissions from conversion of grassland to cultivated lands in Nigeria

A 20-year total conversion of grasslands to cultivation (kha)	B Soil carbon content of grasslands (Mg C ha^{-1})	C Annual rate of carbon release from soil	D Total annual soil carbon release from grassland conversion (Gg C)	E Total CO_2 released from historic conversion over 20 years (Gg CO_2)
			D=(AxBxC)	E=(Dx[44/12])
42 320	15	0.02	12 696	46 552

TABLE IX

Non-CO_2 trace gases from burning of biomass cleared from forests and woodlands in Nigeria

A Carbon Released (Gg C)	B Nitrogen-Carbon Ratio	C Total nitrogen Released (Gg N)		D Trace Gas Emission Ratios	E Trace Gas Emissions (Gg C)	F Conversion Factors	G Trace Gas Emissions From Burning Cleared Forests (Gg CH_4, CO)
					E=(A × D)		G=(E × F)
18 751	0.005	94	CH_4	0.012	225	16/12	300
			CO	0.1	1 875	28/12	4 375
					Gg N		Gg N_2O, NO_x
		C=(AxB)			E=(C × D)		G=(E × F)
			N_2O	0.007	0.658	44/28	2.4
			NO_x	0.121	11	30/14	24

4. Conclusion

The IPCC reporting format (UNEP *et al.*, 1995) requires a reliable national database of land-use emissions, which is absent for Nigeria. Most of the earlier estimates of emissions from burning and land-use changes are largely based on extrapolations (Crutzen *et al.*, 1990). Our emission values are lower, but are based on more recent and detailed information (Isichei, 1994).

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