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Above-Ground Biomass and the Fate of Carbon after Burning in the Savannas of Roraima, Brazilian Amazonia

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SUMMARY

Above-ground biomass (live + dead), was estimated pre- and post-burn in eight types of savanna ecosystem in Roraima, in the extreme northern part of the Brazilian Amazon. The objective was to investigate the stock of pre-burn above-ground carbon and its fate after experimental fires that were set during the dry season (December-March). The total biomass in each ecosystem was divided into two groups (“fine fuels” and “trees and shrubs”), and the combustion factor and the concentration of carbon were determined for of each of the biomass components within these groups. The ecosystems with the lowest biomasses were the grasslands (1627 to 4045 kg ha^{-1}), followed by parkland (6127 kg ha^{-1} to 8038 kg ha^{-1}) and open woodland savanna (10,246 to 11,731 kg ha^{-1}). The percentage of “live biomass” was higher in the open woodland vegetation types (77.1 to 85.6%), and lower in the grassland and parkland types (11.4 to 51.4%). The total emitted carbon (“presumed release”) in each ecosystem varied from 551 to 1474 kg C ha^{-1}. These results differ from those observed in the savannas of central Brazil (2909 kg C ha^{-1} emitted), which were used as the standard in the Brazilian national inventory of greenhouse-gas emissions for the burning of non-anthropic savannas. This suggests that the calculations of Brazilian emissions for savannas should be disaggregated by region instead of using standard national values. Savanna ecosystems in Amazonia, although defined phytoecologically in the same way as those of central Brazil (despite being separated by great geographical distances), possess fire dynamics of their own, implying differences in the emissions of greenhouse gases.

Keywords: Amazonia, biomass, carbon, cerrado, savanna, savannah

1. INTRODUCTION

Biomass and carbon contained in the different components of the vegetation are key parameters for the calculation of the emission of particulates and greenhouse gases from fires in savannas (IPCC/OECD, 1994; Cachier et al., 1995; Liousse et al., 1997; IPCC, 1997; Ferek et al., 1998). These parameters have been determined for different types of savannas in various parts of the world, the largest number of studies being in Africa (Crutzen and Andreae, 1990; Scholes, 1995).

In Brazil, studies to quantify plant biomass and carbon stocks in savanna ecosystems (also called “*cerrado*” in Brazil, see Eiten, 1982), have recently begun to receive greater attention. Most of the studies in Brazil have been done in the central part of the country, such as the studies by Ward et al. (1992), Kauffman et al. (1994), Miranda et al. (1996a; 1996b), Silva et al. (1996), Sato & Miranda (1996), Abdala et al. (1998), Castro and Kauffman (1998), Miranda and Miranda (2000) and Ottmar et al. (2001). Such studies are lacking in the Amazon region, even though Amazonian savannas also are affected by frequent burning, contributing to the net emission of particulate material and greenhouse gases to the atmosphere (Nepstad et al., 1997; Barbosa and Fearnside, 2005). Although Amazonian savannas have their own dynamics in the event of fire, floristic and structural criteria lead to these emissions being estimated in the general calculations of the National Inventory of greenhouse gas emissions from burning of non-anthropic savannas (Brazil, MCT, 2002) by use of proxy values from central Brazil that are not appropriate for the Amazon region. The present study fills this lacuna by evaluating the above-ground biomass (pre and post-burn) and the fate of the carbon (both the stock and the release) in eight types of open (low biomass) savanna located in the Brazilian Amazon.

2. STUDY AREA

The study area is the largest continuous block of savannas in northern part of the Brazilian Amazon. The savanna area covers approximately 40,000 km^2; including islands of forest and agricultural areas. This savanna area is located in the State of Roraima, approximately between 2^o 30' N and 5^o 0' N and 59^o 30' W and 61^o 30' W (Fig. 1). It is a large mosaic of ecosystems of open vegetation that is part of the "Rio Branco-Rupununi" complex, located between Brazil and Guyana (Eden, 1970; Sarmiento and Monasterio, 1975). According to Brazil, Projeto RADAMBRASIL (1975), the vegetation types in this mosaic can be divided into two landscape groups, taking into account their position with respect to altitude, pedology and geomorphology: (1) “savannas” (S)–located in the low and mid-altitude relief (< 600 m) of the Boa Vista and Surumu Formations, predominantly on latosols and podzolic soils (Oxisols and Ultisols), and (2) “steppe-like savannas” (T)–located in the high-altitude relief of the Roraima Group (> 600 m), established on sandy and stony soils. In both cases, vegetation types range from grassland to open woodland, according to the classification of Brazil, IBGE - Brazilian Institute of Geography and Statistics (1992), together with the definitions adopted by Coutinho (1978) and Ribeiro and Walter (1998) (Table 1). We disaggregate the data so that they can be interpreted both in terms of the IBGE vegetation code and in terms of the *campo limpo* (grassland) or “clean field” (CF) and *campo sujo* (grassland with scattered small trees) or “dirty field” (DF) distinction often employed in ecological studies of the *cerrados* (savannas) of central Brazil.

The climate of the area is Awi under the Köppen classification, with 1100-1700 mm of rainfall and 100-130 days with rain per year (Lameira and Coimbra, 1988; Barbosa, 1997). The driest months are between December and March, and the peak of the rainy season is between May and August. The relief that supports this landscape rises in altitude as one moves from the center-south to the north-northeast, beginning at an altitude of approximately 80-100 m in the Boa Vista Formation and increasing to over 600 m in the Roraima Group (Brazil, Projeto RADAMBRASIL, 1975).

[Figure 1 and Table 1 here]

3. MATERIAL AND METHODS

Fieldwork was carried out between January 1995 and January 1998. The methodology used to identify and to quantify the above-ground plant biomass, and the corresponding carbon for each of the ecosystems studied was based on inventories that contained biomass components with the greatest uniformity possible, together with procedures of direct (cutting and weighing) and indirect analysis (by means of regression), as described below.

3.1 Total above-ground biomass

For purposes of the calculations in this study, “total above-ground biomass” refers to all plant matter (live or dead) that is present above the surface of the soil; this is the biomass that is exposed to fire. For all of the ecosystems, the total biomass of each vegetation type was divided into two groups: (1) fine fuels (including ashes and particulate material) and (2) trees and shrubs. In all vegetation types, the two groups were measured before and after the burn, thus allowing comparisons of mass loss between the two measurement stages as well as allowing calculation of the “combustion factor” (% of the biomass eliminated by the fire) and of the fate of the carbon, both for each component and for the total. The method employed for each biomass group is given below.

3.1.1 Fine-fuel biomass (direct method)

Fine-fuel biomass is composed of components such as herbs and dead leaves with little resistance to fire, as well as ashes and particulate material generated by the fire. The components considered were:

(1) *Live*: Poaceae, Cyperaceae, herbs (woody and non-woody) and tree seedlings (arborous-bushy individuals with diameter at the base of less than 2 cm, measured approximately 1 cm above the ground).

(2) *Dead*: fallen leaves (herbs and trees) and “litter” (fragmented organic material).

(3) *Ashes-particulates*: a mix of inert material (ashes) and carbon particles (particulate material, as defined by Kuhlbusch and Crutzen, 1995 and Andreae et al., 1998), that are deposited on the soil immediately after the passage of the fire (only

collected in the post-burn phase).

All components in this group were sampled using a 1-m^2 movable metallic square to delimit the sample space where the components of the biomass were cut at the soil surface using either knives or small pruning shears. The initial point of the sampling was established randomly in each of the ecosystems. In each sequence, all of the quadrats were established at intervals of 20 m in a line moving to the north as a standard direction and zig-zagging by 90^o after each fifth sample. A total of 100 measurements were made in the pre-burn phase and 100 in the post-burn phase, distributed over the following ecosystems (cf. Table 1): Sg CF (30 pre / 30 post), Sg DF (35 / 35), Sp (20 / 20), Tg CF (5 / 5) and Tg DF (5 / 5) and Tp (5 / 5). The fine-fuel biomass of the Sa and Ta ecosystems was not sampled directly, being estimated indirectly based on the results of the parkland and dirty field ecosystems. The live components of Poaceae, Cyperaceae and "herbs" were assumed to have the lowest mean values from the sample quadrats in the parkland and dirty field ecosystems, while the dead "litter" and "leaves" components, together with the "tree seedlings" component, were assumed to have the highest values. This is believed to be realistic because Ta and Sa are the ecosystems that are most densely stocked with trees, resulting in a greater proportion of the ground being shaded and reducing the abundance of Poaceae, Cyperaceae and "herbs" (all heleophyllic), as compared to other ecosystems in the area, such as "clean field." The fine-fuel components were therefore considered that were most similar to the Sa and Ta ecosystems and that were measured in other vegetation types included in this study.

In both the pre- and post-burn phases, the total wet weight was measured for each sample in the quadrat, as well as the wet weight of a sub-sample that, in general, varied from 1 to100 g depending on the amount and the type of the component collected. Of the collected components, only "ashes-particulates" in the post-burn phase was given a different treatment. This component was collected immediately after the passage of the fire in order to avoid losses due to strong winds, forming a single bulked sample (ashes + particulate material) collected in a sub-quadrat measuring 22 × 22 cm, always in the lower right-hand corner of the1-m^2 quadrat, due to difficulty of collecting this material over a larger area. In the laboratory, the "litter" and "ashes-particulates" components underwent a process of decontamination to remove plant fragments and soil aggregates so as to avoid overestimation of the final result.

All of the sub-samples were taken to the laboratory for drying in an oven at 80^{o}C to constant weight for the determination of the individual humidity (%) and, soon after, of the dry weight per unit of area. After this procedure, the material was double ground and passed through a Number 30 mesh sieve for analysis of carbon concentration (%C). A LECO CR-412 carbon analyzer was used, following the "dry path" procedures of Cerri et al. (1990). A total of 568 samples were obtained for determining the carbon concentration in the biomass of the fine-fuel group.

3.1.2 Tree and shrub biomass

Tree and shrub biomass was defined as that composed of all the species of trees and bushes (live and dead) with base diameter ≥ 2 cm (independent of height). Two methods were used for this calculation:

3.1.2.1 Direct method

A total of 130 individuals were used (live) for the direct method (cutting and weighing), distributed among the eight ecosystems studied. This was necessary to obtain a mathematical relationship between each individual's allometric parameters and its biomass (dry weight). For this purpose, the following independent variables were measured for the 130 individuals: (1) the base diameter (Db), (2) the diameter of the crown (Dc) - calculated by the average between the largest and the smallest distance and (3) the total height (Ht) - from the surface of the soil to the top of the crown of the tree. Each individual was measured and, soon after, cut and partitioned into the categories used for weight determination: (1) leaves, (2) twigs (wood pieces with diameter (d) < 5 cm), (3) branches ($5 \leq d < 10$ cm) and (4) logs ($d \geq 10$ cm). For the wood pieces, a sample in disk form (50-200 g) was taken of each division for estimating dry weight, carbon concentration (estimated in the same way as for fine-fuel biomass), and the basic density (g cm^{-3} - dry weight/saturated volume) for each live tree or shrub individual, as presented in Barbosa and Fearnside (2004). For the leaves, the range of sample weights was 25-100 g, the same procedure being followed for obtaining %C. A total of 388 samples were taken for all tree and shrub categories.

The choice of the species and the allocation of the collection effort was based on the approximate density of each species (or of its associated group) as indicated by the available inventories in the open savannas of Roraima (Dantas and Rodrigues, 1982; Sanaiotti, 1996; Miranda, 1998). The greatest effort was allocated to *Byrsonima crassifolia* (L.) Kunth. in H.B.K. and *Byrsonima coccolobifolia* Kunth. in H.B.K. (these two species together totaled 56 individuals), *Curatella americana* L. (31 individuals), *Byrsonima verbascifolia* (L.) Rich. ex A. Juss. (12), *Himatanthus articulatus* (Vahl.) Woods. (9), *Bowdichia virgilioides* Kunth. (9) and an “others” category for seven additional species found in the local savannas (*Antonia ovata* Pohl., *Roupala montana* Aubl., *Xylopia aromatica* (Lam.) Mart., *Byrsonima* cf *intermediata* A. Juss., *Miconia rubiginosa* (Bonpl.) DC., *Genipa americana* L. var *caruta* (H.B.K.) and *Palicourea rigida* Kunth) with a total of 13 individuals.. Taken together, the species sampled represent the great majority of individuals in the open savannas of Roraima, almost always encompassing > 90% of all individuals present (Barbosa, 2001).

Trees were selected in the field in 12 locations distributed over the eight ecosystems: Sg CF (8 individuals), Sg DF (35), Sp (25), Sa (32), Tg CF (2), Tg DF (2), Tp (11) and Ta (15). The collection of individuals was done over a randomly placed path, beginning at any given point in the landscape, and thereafter always proceeding in a northerly direction. The size of the sample (n=130) was determined by means of two preliminary surveys (the first with 30 and the second with 60 individuals) that were used for statistical selection of sample size (Brower et al., 1998; p. 10), assuming a standard error of the estimate of 20-30% for the sampling. The preliminary inventories served to provide a basis for assessing the need for complementing the species and individuals in order to adjust the sampling as a whole.

3.1.2.2 Indirect method

Once the direct procedure was completed, a regression model was derived from the trees and shrubs (n=130) harvested as part of the direct method to represent the relationship between the dry biomass of an individual (dependent variable) and the independent variables (base diameter, crown diameter and height). Within this universe, trees and bushes that were sampled varied from 2 to 40 cm in diameter at the base (mean ± standard deviation = 8.0 ± 6.1 cm), from 0.17 to 8.23 m (1.75 ± 1.46 m) in crown diameter and from 0.25 to 7.0 m in height (2.27 ± 1.62 m). The regression equation was developed from these variables using computational analysis in decimal and logarithmic form (natural and base ten). This allowed a larger range of options for analyzing the parameters for evaluation of the precision: R^2 (coefficient of determination) and S_{xy} (standard error of the estimate).

With this last task concluded, 378 quadrats were established, each measuring 4 × 20 m, distributed randomly over all of the ecosystems: Sg CF (121 quadrats), Sg DF (77), Sp (40), Sa (14), Tg CF (42), Tg DF (12), Tp (38) and Ta (34), the sample area totaling 3.024 ha. Starting from these quadrats, the same independent variables were collected (Db, Dc and Ht) for all "live" tree and shrub individuals with base diameter ≥ 2 cm. The reason for distributing several small quadrats among the different ecosystems, instead of a single large quadrat in each one, was to try to encompass the natural variability of trees and shrubs in these vegetation types.

To quantify the biomass (wood) of the “dead” individuals, two methodologies were used taking advantage of the same quadrats: (1) “standing” individuals (same method as for the live individuals, discounting the percentage of leaves not present) and (2) “fallen” individuals (fallen pieces, with measurement of length and mean diameter of each piece for calculation of the volume and, later, of the biomass using the basic density of each species, as presented by Barbosa and Fearnside, 2004).

3.1.3 Combustion factor for tree and shrub biomass

The combustion factor is the percentage of the biomass eliminated by the fire event. Determination of the components of the trees and shrubs group (leaves, live wood and dead wood) followed a different path from the fine-fuel components due to the different behavior of this group with respect to fire. To determine how much was eliminated by the fire (physical damage) in the elements of this group, 127 live individuals of different species and base diameters were analyzed (Db ≥ 2 cm), distributed among the Sg DF, Sp and Sa vegetation types. The sampling was carried out starting from four linear transects of 200 m each, always in the north–south direction, and having as the starting point for observations the following geographical coordinates (Datum SAD 69): (1) 2^o 42' 31" N and 60^o 50' 10" W, (2) 2^o 57' 58" N and 60^o 44' 27" W, (3) 2^o 54' 12" N and 60^o 54' 35" W, and (4) 2^o 44' 09" N and 60^o 33' 24" W. For each observed individual, measurements were taken of diameter at the base, crown diameter and height, in order to allow estimation of the mean damage for each species and diameter class. Extension of the results to the other vegetation types that had not been sampled was accomplished using the density of each tree and shrub species in the vegetation type in question.

The first step in this stage of the work was to estimate visually, for each live individual, the percentage of leaves that (1) remained green (live), (2) dried and fell (dead intact) and (3) burned (dead eliminated). The analysis was always made 3-5 days after the fire in order to avoid distortions with respect to distinguishing green and dry leaves. This provided an estimate of the mean combustion factor of the leaves and of the percentage of the mass of foliage that remained green and present on each individual after the passage of the fire. In the same sampling, the percentage of burns was determined for the “live” woody biomass (wood) through observation of the lateral extent of the crowns of the large trees and of the trunks of the trees growing in the transects. To estimate the loss of the “dead” woody biomass (“fallen” and “standing”) from regular burning, the experimental data on combined disappearance (natural decomposition and fire) were used for the tree and shrub biomass described in Barbosa (2001).

3.1.4 Prescribed burns

The experimental burns in each of the ecosystems studied were timed in accord with the same weather factors that the local inhabitants use in burning savannas. Burns are carried out from December to March between 11:00 and 15:00 h, with direct sun and with wind (normal at this time of year), although wind spread cannot be controlled.

3.1.5 Data analysis

After completing the foregoing stages, data on both of the biomass groups (fine fuels / trees and shrubs) were tabulated and converted to above-ground biomass (live and dead) for each savanna ecosystem. The values were computed for biomass pre- and post-burn (components and total), with their respective combustion factors. The biomass data were then transformed into mass of carbon by multiplying by the carbon concentration (%C) for the corresponding biomass component. The results were divided by 100 to obtain the carbon stocks (per component and total). This was done in order to account for the fate of the carbon after the burn, the following pathways being taken as the base: (1) live biomass (green vegetation, still photosynthesizing), (2) dead biomass (already dead or having entered into the decomposition process), (3) ashes-particulates (long-term carbon stocks) and (4) presumed release (emitted to the atmosphere in the form of gases).

4. RESULTS

4.1 Regression model

The regression model $\ln(Bd) = a + b.\ln(Ht) + c.\ln(Db) + d.\ln(Dc)$ best represented the relationship between the live above-ground biomass (dry weight), and the independent variables measured for the 130 sampled individuals in the tree and shrub category, as indicated by the coefficient of determination (R^2) and the standard error of the estimate (S_{xy}). The multiple regression model and its coefficients are presented in Table 2.

[Table 2 here]

4.2 Biomass

For each ecosystem, the total above-ground biomass (pre- and post-burn) considering the live and dead components of the trees and shrubs and fine fuels groups), is presented in Tables 3 and 4. The proportion of the pre-burn biomass represented by trees and shrubs was smaller for the ecosystems with low densities of trees (Sg CF = 0.01 and Tg CF = 0.06), and larger for the open woodland ecosystems (Sa = 4.5 and Ta = 3.8). Because the “ashes-particulates” component (analyzed separately) was discounted, the live biomass was always much larger in the pre-burn phase than in the post-burn phase for all vegetation types. The ecosystems with highest total above-ground biomasses (mean ± SD) in the pre-burn phase were open woodlands (Sa = 11,731 ± 1,118 kg ha^{-1} and Ta = 10,246 ± 262 kg ha^{-1}), while those with lowest biomasses were grasslands (Sg DF = 3258 ± 711 kg ha^{-1} and Tg CF = 1627 ± 425 kg ha^{-1}). The same situation was found in the post-burn phase. In the two groups of ecosystems (“savannas” and “steppe-like savannas”), the tree and shrub biomass in the pre-burn phase of the open woodland systems (Sa and Ta) represented approximately 80% of the observed total, while in the other vegetation types this value varied from 1.4% (grassland) to 48.0% (parkland). In the post-burn phase these numbers were always above 90% (after discounting “ashes-particulates”) for Sg DF, Tg DF, Sp, Tp, Sa and Ta, and were less than 37% in the Sg CF and Tg CF vegetation types due to the lower density of tree and shrub individuals in these two ecosystems.

The combustion factor (%) for all biomass (total) was always larger for those ecosystems with the highest concentrations of fine-fuel biomass, such as Sg CF (81.9%) and Tg CF (87.6%), and smallest for ecosystems with high concentrations of trees, such as Sa (16.3%) and Ta (18.7%). The combustion factor for the fine-fuel biomass group was above 80% in all ecosystems, while for the trees and shrubs group this value was below 5%. Considering the total for the post-burn biomass, the percentage of “ashes-particulates” was larger in the ecosystems with large amounts of fine fuels (Sg CF combustion factor = 45.0% and Tg CF combustion factor= 37.8%), and smaller in the open woodlands (Sa = 4.6% and Ta = 5.4%).

[Tables 3 and 4 here]

4.3 Carbon

The carbon stocks in each ecosystem are presented in Tables 5 and 6. As with biomass, the open woodlands had the largest amounts of total above-ground carbon in the pre-burn phase (Sa = 5217 ± 525 kg C ha^{-1} and Ta = 4400 ± 111 kg C ha^{-1}), while the smallest amounts were in the grasslands in the post-burn phase (Sg CF = 249 ± 90 kg C ha^{-1} and Tg CF = 92 ± 19 kg C ha^{-1}), after discounting the “ashes-particulates” component. The mean concentration of carbon (%C) in the “savannas” group (43.0 to 46.3%), as a weighted average over all components (pre and post-burn) except for “ashes-particulates”, was larger than the concentration in the “steppe-like savannas” (42.8 to 44.9%). Mean %C values for the trees and shrubs components were always larger than those of the fine-fuel components. The “ashes-particulates” component had the lowest concentration of carbon of all components analyzed, with values varying from 14.4 to 19.5% for all ecosystems. Ashes-particulates represented 1.8 to 6.4% of the total carbon in the post-burn phase in parkland and open woodland areas and 7.4 to 27.7% in the grassland ecosystems.

[Tables 5 and 6 here]

4.4 Fate of the carbon (stock and release)

The fate of the carbon present in the pre-burn phase, measured soon after the passage of the fire (post-burn) is presented in Table 7 for all ecosystems studied. In general, most of the “live” pre-burn biomass of the grassland vegetation types (Sg and Tg) entered non-living categories in the post-burn phase (“dead biomass”, “ashes-particulates” and “presumed release”), leaving only 12 to 37% of the initial total carbon as post-burn live biomass. The parkland and open woodland maintained a percentage between 41 and 86% of “live” biomass. Most of the pre-burn carbon in the parkland vegetation types (Sp and Tp) was emitted (“presumed release”) to the atmosphere (1300-1500 kg C ha^{-1}), while the open woodland ecosystems (Sa and Ta) emitted smaller amounts, between 600 and 700 kg C ha^{-1}, similar to the values for the Sg (CF and DF) and Tg (CF and DF) vegetation types (560-850 kg C ha^{-1}). The simple average of long-term carbon (“ashes-particulates”) formed in the burn was 67.7 kg C ha^{-1} (1.6 to 8.0%) for the “savannas” group and 56.6 kg C ha^{-1} (1.7 to 3.2%) for the “steppe-like savannas” group.

[Table 7 here]

5. DISCUSSION

5.1 Biomass

Our results for savanna biomass are in accord with existing measurements in Roraima. Siqueira et al. (1994) quantified the average biomass of “grass” (Poaceae) over the 1992-1993 period, which was 2097 kg ha^{-1} at a site close to Igarapé Água Boa (Sg), in Roraima. This value is similar to the value determined in the present study for the same component of the Sg CF (2066 kg ha^{-1}) and Sg DF (2128 kg ha^{-1}) vegetation types, which represent the same type as that sampled by Siqueira and collaborators. Santos et al. (2002), based on the work of Xaud (1998) and Santos et al. (1998), determined averages of 4.23 to 9.92 Mg ha^{-1} for the total above-ground biomass in areas of “shrub and/or tree savanna” (like savanna park) located in a contact zone (savanna-forest ecotone) in Roraima. This range of values is consistent with the mean determined in the present study for Sp (8.04 Mg ha^{-1}). Although there are similarities among the means from the few existing studies in the region, we emphasize that differences could exist among locations, and that they are result of different definitions of the ecosystems or different sampling methodologies (for example giving emphasis to the spatial distribution of the natural variation or using a measurement from a single point or area as the result for each ecosystem).

Our individual values of total above-ground biomass for the savannas of the northern part of Amazonia are smaller than those observed in recent studies in central Brazilian savannas, even taking into consideration (1) our adaptations to the different Brazilian classifications and (2) the methodologies for determination of the biomass of trees and shrubs (Table 8). The implication of this for calculation of emissions of carbon and greenhouse gases to the atmosphere can be seen when the results for the corresponding vegetation types are compared. For example, our estimate of the pre-burn total in Sg CF was between 1.7 and 2.2 times less than the values determined for clean field (the corresponding category in central Brazil for grassland) by Castro and Kauffman (1998) and by Kauffman et al. (1994), respectively.

[Table 8 here]

In the same way, the absolute mean concentration of carbon contained in Sg CF (43.0%) and Tg CF (42.8%) was about 4 percentage points (47.5 and 47.8%, representing approximately a 10% difference) below that of the structurally equivalent type (clean field) listed by Kauffman et al. (1994). These differences create distortions in the calculations if the values for central Brazilian ecosystems are transferred to the Amazonian savannas. The results also show that the biomasses of the savannas of northern Amazonia are closer to the values for similar ecosystems in Africa, such as the “grassland” and “woodland” savannas of Zambia (see Hoffa et al., 1999), and some “parkland” ecosystems in South Africa (see Shea et al., 1996; Ward et al., 1996). The Venezuelan results, such as those of Bilbao and Medina (1996), are also close to those observed in Roraima. However, this is a comparison with little utility because, in addition to not having had the trees and shrubs component measured, the terminology does not match well enough for a valid comparison. In addition, although the savannas of Venezuela have the same general origin as the savannas of Roraima, the Venezuelan savannas can be influenced by differences in factors such as anthropogenic fire, soil fertility and other aspects linked to wind currents and rain from the Caribbean Sea and the Atlantic Ocean. These factors can cause differences in the general aspect of the landscape, as pointed out by Goodland (1966), Cooper (1981) and Huber (1987).

Due to the vast distances between different parts of Brazil (especially with respect to Amazonia), each savanna location represents an ecoregion that is quite different from the others, undergoing burning that is regular but distinct from that in the other locations. This differs from what is usually found in the general calculations of greenhouse-gas emissions, for which point measurements are extrapolated to all of a given landscape type. In addition, the exclusion of some portions of the total biomass (*e.g.*, trees) per unit of area from the general survey distorts the pre-burn stock of carbon and its destination after the fire event. We emphasize the importance of including this component in the general calculations. Where the results of this study differ from those of other studies, mainly in the mean concentration of carbon and the combustion factor, the results obtained are functions of the weighted distribution that this sampling employed when considering all of the components present in the two biomass groups.

In the context of debates about global responsibilities for emissions of pollutant gases, Brazil could review its official calculations in the national inventory for burning in savannas (see Brazil, MCT, 2002) through regional approaches. From the methodological point of view, it would be much more advantageous to use regional values than to use either national “default” values or those provided for Tropical America by the Intergovernmental Panel on Climate Change (IPCC, 1997, p. 4.25). These values do not match the different regional characteristics. For example, the mean value suggested by the IPCC for above-ground biomass is 6.6 Mg ha^{-1} for savanna environments that are converted to agricultural use. This result was taken from Hao et al. (1990, p. 451) who, in turn, had used an average of two studies in Venezuela and one in Brazil (see Coutinho, 1982). The report in the Brazilian inventory of greenhouse-gas emissions from burning in non-anthropic savanna ecosystems (Brazil, MCT, 2002) adopts data of H. S. Miranda (unpublished), from work in the IBGE (Brazilian Institute of Geography and Statistics) Ecological Reserve near Brasília, as standard values for the more than 2.0×10^6 km^2 of different types of *cerrado* in Brazil. Only the biomass values for the fine fuels (herbs, leaves, etc.) are used in the emissions inventory calculations. In addition, the "*cerradão*" (dense *cerrado*) vegetation type is included in the general calculations, although this vegetation is considered to be a forested form of savanna and the Brazilian reports on deforestation (Brazil, INPE, 2004) classify it as "forest", instead of "non-forest", as suggested by Brazil, MCT (2002). This can lead to double counting in the general calculations of Brazil's emissions of greenhouse gases. Our above-ground (live + dead) biomass data range from 3.2 to 11.7 Mg ha^{-1}, and help to represent the different savanna ecosystems located in the northern portion Amazonia, which also have annual emissions of greenhouse gases from anthropogenic fires in Brazil.

The combustion factor is another key parameter for which the IPCC "default" value is based on African data, although studies are available from central Brazil (Ward et al., 1992; Kauffman et al., 1994; Miranda et al., 1996; Castro and Kauffman, 1998) that apply to the same theme. In addition, the number suggested by the IPCC (85-100%) only takes into account the combustion of the fine-fuel biomass, excluding the tree and shrub biomass from the final result. This is done due to the fact that the fine-fuel biomass is the most vulnerable to fire because of the low amount of water in its tissues during the dry season, and because of the amount of effective heat to which this biomass is exposed from the flames (even if only for a short time). However, the tree and shrub biomass also suffers damage, mainly from the burning and/or drying in the "leaves" component and in the less-vulnerable woody tissues such as small twigs and the tips of branches that are beginning to senesce. Our results indicate that the combustion factor for "live" leaves can lie between 4.7 and 22.9% (see Tables 3 and 4), and the combustion factor for wood (live) is close to 0.01% (a low combustion factor). Depending on the structure of the ecosystem, the tree and shrub biomass components taken together can emit between 0.2 and 22.6 kg C ha^{-1}, which is not included in the general calculations. Although the value per unit of area is small in absolute terms, this value becomes significant when considered in light of the thousands of square kilometers of Amazonian savannas that are burned annually (Barbosa and Fearnside, 2005). It is important that the data used for calculating the emissions of a country of continental dimensions like Brazil follow the current level of knowledge of the regional context. Otherwise, the calculations can represent a multiplication of errors due to the distortions of values adopted in the tabulations of each study or of the general national inventory.

5.3.2 Fate of the Carbon

Reorganization (%) of the pre-existing carbon after burning was a function of the structural composition of each savanna studied. In ecosystems with large amounts of fine-fuel biomass (*e.g.*, Sg and Tg), a greater proportion of the carbon (> 55%) is emitted to the atmosphere ("presumed release"). That is, the larger the proportion of fine-fuel biomass, the larger the percentage of the carbon that is emitted to the atmosphere. On the other hand, the larger the concentration of tree and shrub biomass in an ecosystem, the less will be the percentage emitted and, consequently, the larger will be its stock of “live” and “dead” biomass (remainder) (*e.g.*, Sa and Ta, both > 77%).

In general, ecosystems with large amounts of components that are sensitive to fire (grass and fine litter) release more carbon to the atmosphere, although this does not mean that there is a net emission due to the fast growth cycle that these components possess. The tree and shrub biomass as here defined (base diameter ≥ 2 cm) represented from 1.4 to 97.3% of the total mass of each ecosystem, and was responsible for almost the entire stock of remaining carbon in the post-burn phase for most of the vegetation types. Of all the carbon in this phase for all ecosystems (except Sg CF and Tg CF), more than 90% belonged to the tree and shrub component (dead + live).

Although 12-83% of the total carbon present in the pre-burn phase is released to the atmosphere with the passage of the fire, most will come back in the following growth period due to the type of plant material that undergoes effective combustion - mostly fast-growing components, such as grass (Menaut et al., 1991) and new leaves (Sarmiento, 1984). However, although most of the CO_2 released is sequestered in the following growth period, a portion of this gas stays as a net addition to the atmosphere because it is not reabsorbed by the plant tissues of the trees that would be growing if fire were not present. In the case of savannas, the annual net entrance of the trace gases (CH_4 and N_2O) in the atmosphere contributes to global change due to the high global warming potentials of these gases as compared to CO_2 (Ramaswamy et al., 2001, p. 388). The amount of burning and consequent trace-gas releases depends on the climatic conditions (successive dry years can accelerate this process). In addition, there is a delay in the rate of tree growth in areas with high frequency of burning that, in turn, perpetuates the landscape of savannas that we now have (Lamotte, 1985; San José and Montes, 1997; Barbosa, 2001). This “landscape stability” proportionate to the frequency of burning maintains the current pattern of carbon partitioning.

Of the total gross emission of carbon in the form of gases at the time of burning, the figure of 562-1474 kg C released per year for each hectare affected by fire in Roraima is larger than the overall average used for West African savannas (540 kg C ha^{-1} $year^{-1}$) in estimates of carbon and trace-gas emissions by Menaut et al. (1991). However, the emission is smaller than those inferred by Kauffman et al. (1994) for different types of savannas (*cerrados*) in central Brazil, with gross emissions of 1550-3180 kg C ha^{-1} at the time of burning (without counting the trees and shrubs group). Similarly, the values calculated here are lower than the values estimated in the study by Castro and Kauffman (1998) with instantaneous emissions above 2500 kg C ha^{-1}, also in central Brazilian savannas. A value of 2909 kg C ha^{-1} was applied to all Brazilian savanna areas was estimated in by national inventory of greenhouse-gas emissions for the burning of non-anthropic savannas (Brazil, MCT, 2002), based on a single study (see above) and including the *cerradões* (a type of forest, rather than savanna) in the calculations. These differences can indicate different interpretations of plant life forms and different methods of calculation. However, all suggest high instantaneous (gross) emissions of carbon to the atmosphere because of the extensive areas that are affected by fire in savannas throughout the World.

Another important factor in the analysis is the high relative amount of carbon in the form of ashes and particulate material ("ashes-particulates") that are perpetuated as a long-term carbon stock. Delmas (1982) found absolute values ranging from 66 to 85 kg C ha^{-1} in the ashes of two burned savanna areas in the Ivory Coast, producing numbers that fall within the range found in the present study (20.9-95.6 kg C ha^{-1}). Although with almost twice the (average) amount of above-ground biomass per unit of area, the low concentration of carbon in the ashes in the Ivory Coast (8-15%C) had the effect of making the emissions results close to those found for Roraima. Hurst et al. (1994a, 1994b), determined, that of all the carbon burned in an experiment in Australian savannas, 3.7% was present in the ashes. This value is within the range obtained in the present study (1.6-8.0%) for the fate of carbon in the post-burn phase. In contrast, a study in the Ivory Coast by Menaut et al. (1991) found a value for this carbon stock (3 kg C ha^{-1}) far below the values obtained in the present study.

The concentrations and the total for carbon contained in the ashes of four savanna ecosystems studied by Kauffman et al. (1994) in central Brazil (22-53%C or 80-1130 kg C ha^{-1}), are several times higher than the results presented here. Different methods for separating and cleaning the samples of the post-burn "ashes-particulates" component might have provoked these more accentuated differences. In addition, these values are naturally very variable because they depend basically on the amount of pre-burn biomass and on the humidity of the material that burned. If burned at the beginning of the dry season, fires tend to produce low values because the complete combustion (flaming) phase is less intense than in the fires burning in the middle of the dry season (Korontzi et al., 2003). In the present study, we carried out the experimental burning at the peak of the dry season (January to March).

According to Vogl (1974), mentioned by Seiler and Crutzen (1980), the particulate material in savannas is formed more by burning of grass than by the combustion of more resistant elements such as logs, branches or twigs. This can carry a larger amount of particulate material in the burned zones of savannas than in forests (Allen and Miguel, 1995). In Roraima, we observed that the wind and the first rains carry a part of this material into nearby water courses, which are fringed with the "buriti" palm (*Mauritia flexuosa* L.). This is soot composed of charcoal (black carbon) that, over the course of time, ends up being deposited in the fluvial sediments (Kuhlbusch and Crutzen, 1995; Kuhlbusch et al., 1996). Even though this represents only a small absolute amount in comparison with the total amount of pre-burn carbon, it indicates that burning can result in storing carbon over the long term in the form of particulate material, as emphasized by Canut et al. (1996).

We also observed that part of the particulate material formed by the local fires is transported by clouds of smoke and by wind. Due to the difficulty of separating different components, the carbon contained in these aerosols ends up being counted in a mistaken way as carbon released in the form of gas instead of as particulate material, as demonstrated in the examples of distribution of the "affected carbon" by Lobert et al. (1991) and Cachier et al. (1995). These long-lived aerosols reside in the atmosphere for variable lengths of time and have a very active role in dispersing solar radiation and in cloud micro-physics (Leslie, 1981; Crutzen and Andreae, 1990; Jacobson, 2001). These aerosol emissions can change the radiative balance and the hydrological cycle of tropical areas (Andreae et al., 1998, 2004). These particles are directly related to negative radiative forcing and can result in a significant temperature decrease (Houghton et al., 1995; Reid and Hobbs, 1998). We do not have an estimate of how much of the carbon that is defined as “presumed release” is emitted in the form of particulate material and is transported by wind in clouds of smoke.

6. CONCLUSIONS

(1) Most of the biomass eliminated by the fire in the savannas studied in Roraima is in the fine-fuel component (grasses, herbs, dry leaves, etc.), which, in turn, is responsible for most of the gross release of carbon to the atmosphere in all of the ecosystems studied.

(2) Tree and shrub biomass has a low combustion factor and, therefore, little net release of carbon to the atmosphere with the burning. However, it should be included in the general calculations of emissions of greenhouse gases due to the multiplicative effect of the vast expanses of area that are burned annually.

(3) The biomass and the total above-ground carbon, estimated for the savannas of Roraima are smaller than the values observed in central Brazil, indicating differences in the structure of ecosystems that fall under the same phytoecological definition indicated by IBGE (1992).

(4) “Ashes-particulates" produced by combustion of plant material in savannas constitutes an important long-term reservoir in the general calculations of carbon balance, in addition to having a strong influence on global atmospheric chemistry.

(5) The use of regionally disaggregated values for partitioning the carbon in the calculations of greenhouse-gas emissions is methodologically more advantageous than the use of “default” values currently employed in Brazil. Structural differences provide differentiated values of biomass and carbon in each of the various savanna ecoregions.

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FIGURE LEGEND

Figure 1 - Eight savanna types studied in Roraima: “Savannas” / “Steppe-like savannas” – (A / E) open woodland, (B / F) parkland, (C / G) grassland (dirty field) and (D / H) grassland (clean field).

Table 1 - Caracterization of the ecosystems studied in Roraima.

Group(1)	Ecosystem	Structural Type	Crown Cover (%)	Tree Stratum (Height)	Estimated Area(2)	
					(km^2)	(%)
Savanna						
	Sg (grassland)	Clean field	0	Absent	7929	31.0
	Sg (grassland)	Dirty field	< 5	Minimal	5759	22.5
	Sp (parkland)	Parkland cerrado	5-20	2-4 m	11350	44.4
	Sa (open woodland)	Typical cerrado	20-50	3-6 m	547	2.1
Steppe-like savanna						
	Tg (grassland)	Clean field	0	Absent	198	2.9
	Tg (grassland)	Dirty field	< 5	Minimal	343	4.9
	Tp (parkland)	Parkland cerrado	5-20	2-4 m	5730	82.6
	Ta (open woodland)	Typical cerrado	20-50	3-6 m	666	9.6

(1) **Savanna** = vegetation situated at altitudes below 600 m, occupying a mosaic of Ultisol and Oxisol soils; **steppe-like savanna** = vegetation situated at altitudes above 600 m in litholic soils, including milk quartz.

(2) Only natural ecosystems (excluding anthropogenic and agricultural areas). Estimated by Barbosa & Fearnside (2002) based on vegetation maps (1:250,000) in Brazil, Projeto RADAMBRASIL (1975).

Table 2 - Multiple regression model indicating the relationship of live above-ground tree and shrub biomass (dry weight) to allometric parameters (diameter at the base, height and crown diameter) in the open savannas of Roraima.

Regression Model (1)	Coefficient	Value of the Coefficient	Standard error	R^2	Standard error of the Estimate (%)	Significance level (“p”)
ln(Bd) = a + b.ln(Ht) + c.ln(Db) + d.ln(Dc)	a	4.501	0.277	0.984	27.7	< 0.0001
	b	0.459	0.076			< 0.0001
	c	1.589	0.091			< 0.0001
	d	1.025	0.098			< 0.0001

(1) Bd = dry biomass (kg); Db = diameter at the base measured 1 cm above the ground (m); Ht = total height (m); Dc = crown diameter (m).

Table 3 - Above-ground biomass (pre- and post-burn) and combustion factor (%) in open savannas in Roraima (SD in parentheses).

"SAVANNA" Group component (kg ha^{-1})	Sg CF			Sg DF			Sp			Sa (1)		
	Pre- burn	Post- burn	Combustion factor (%)	Pre- burn	Post- burn	Combustion factor (%)	Pre- burn	Post- burn	Combustion factor (%)	Pre- burn	Post- burn	Combust factor (%
FINE FUELS												
Live												
Poaceae	2065.8	149.3	92.8	2128.1	35.2	98.3	3289.9	150.7	95.4	*1152.3*	*103.8*	*91.0*
	(470.0)	(120.0)		(1031.9)	(70.1)		(938.7)	(144.0)		*(514.2)*	*(57.0)*	
Herbs	23.4	2.9	87.6	148.4	4.2	97.2	75.1	14.3	80.9	*89.5*	*43.8*	*51.1*
	(13.9)	(5.4)		(532.2)	(5.4)		(118.3)	(21.5)		*(36.5)*	*(47.2)*	
Cyperaceae	624.3	286.4	54.1	14.2	0.6	95.5	105.5	3.0	97.2	*93.7*	*12.7*	*86.4*
	(639.1)	(357.2)		(15.8)	(1.2)		(130.2)	(5.3)		*(74.1)*	*(12.3)*	
Tree seedlings	57.6	23.2	59.6	21.8	0.1	99.6	183.2	17.2	90.6	*189.3*	*24.5*	*87.1*
	(141.0)	(78.5)		(108.6)	(0.2)		(209.6)	(32.3)		*(172.1)*	*(42.3)*	
Subtotal live	2771.1	461.8	83.3	2312.5	40.1	98.3	3653.7	185.2	94.9	*1524.8*	*184.8*	*87.9*
	(497.4)	(264.3)		(984.9)	(62.1)		(861.9)	(121.9)		(416.6)	(49.7)	
Dead												
Leaves	19.6	9.6	50.8	41.1	-	100.0	182.4	4.8	97.4	*166.3*	*4.9*	*97.1*
	(29.2)	(24.8)		(97.4)	-		(195.1)	(11.7)		*(83.8)*	*(4.7)*	
Litter	471.0	82.4	82.5	198.1	40.9	79.3	341.5	77.3	77.4	*442.3*	*75.7*	*82.9*
	(253.1)	(176.8)		(167.2)	(30.7)		(111.5)	(96.3)		*(150.6)*	*(46.9)*	
Subtotal dead	490.6	92.0	81.2	239.1	40.9	82.9	523.9	82.2	84.3	*608.6*	*80.6*	*86.8*
	(244.4)	(160.9)		(155.2)	(30.7)		(140.6)	(91.3)		*(132.4)*	*(44.3)*	
Total Fine Fuels	3261.7	553.8	83.0	2551.6	81.0	96.8	4177.7	267.4	93.6	*2133.4*	*265.4*	*87.6*
	(459.3)	(247.1)		(907.1)	(46.2)		(771.4)	(112.5)		*(335.5)*	*(48.1)*	
TREES AND SHRUBS												
Live												
Leaves	8.0	6.1	22.9	84.6	79.1	6.5	355.7	337.7	5.1	831.0	790.2	4.9
Wood	27.9	27.9	0.02	514.7	514.7	0.01	3288.2	3288.0	0.01	8728.0	8727.6	0.005
Subtotal live	35.9	34.1	5.1	599.3	593.8	0.9	3643.8	3625.7	0.5	9559.1	9517.8	0.4
	(1.1)	(1.1)		(13.5)	(13.5)		(161.7)	(161.7)		(1297.7)	(1297.7)	
Dead												
Standing wood	10.6	10.4	1.8	30.1	29.5	1.8	136.3	133.2	2.3	27.3	26.6	2.3
	(0.5)	(0.5)		(1.1)	(1.1)		(13.5)	(13.5)		(3.6)	(3.6)	
Fallen wood	0.7	0.6	18.4	77.4	63.1	18.4	79.8	61.6	22.8	11.2	8.7	22.8
	(0.1)	(0.1)		(8.3)	(8.3)		(4.5)	(4.5)		(1.2)	(1.2)	
Subtotal dead	11.3	11.0	2.9	107.5	92.7	13.8	216.1	194.8	9.9	38.5	35.3	8.3
	(0.5)	(0.5)		(8.5)	(8.5)		(16.3)	(16.3)		(4.1)	(4.1)	
Total Trees and Shrubs	47.2	45.0	4.6	706.8	686.5	2.9	3859.9	3820.5	1.0	9597.5	9553.1	0.5
	(1.0)	(1.0)		(12.7)	(12.8)		(153.6)	(154.3)		(1292.5)	(1292.9)	
TOTAL Savanna	3308.9	598.8	81.9	3258.5	767.5	76.4	8037.6	4087.9	49.1	11730.9	9818.5	16.3
	(452.8)	(228.6)		(711.0)	(19.8)		(469.8)	(150.1)		(1118.5)	(1259.3)	
ASHES-PARTICULATES	-	490.6	-	-	237.8	-	-	327.3	-	-	*473.2*	-
	-	(1053.1)		-	(178.8)		-	(239.5)		-	*(46.6)*	

Table 4 - Above-ground biomass (pre- and post-burn) and combustion factor (%) in open steppe-like savannas in Roraima (SD in parentheses)

"STEPPE-LIKE SAVANNA"	Tg CF			Tg DF			Tp			Ta (1)		
Group component (kg ha^{-1})	Pre-burn	Post-burn	Combustion factor (%)	Pre-burn	Post-burn	Combustion factor (%)	Pre-burn	Post-burn	Combustion factor (%)	Pre-burn	Post-burn	Combust factor (%
FINE FUELS												
Live												
Poaceae	1175.8	13.6	98.8	2083.1	26.5	98.7	2990.3	39.3	98.7	*1152.3*	*103.8*	*91.0*
	(565.0)	(19.9)		(1087.2)	(32.9)		(1609.5)	(46.0)		*(514.2)*	*(57.0)*	
Herbs	66.4	72.6	-9.3	74.9	55.3	26.2	83.4	38.0	54.4	*89.5*	*43.8*	*51.1*
	(48.4)	(88.3)		(89.1)	(79.5)		(129.8)	(70.8)		*(36.5)*	*(47.2)*	
Cyperaceae	111.0	0.0	100.0	91.6	1.8	98.0	72.1	3.6	95.0	*93.7*	*12.7*	*86.4*
	(105.7)	(0.0)		(145.1)	(5.5)		(184.4)	(11.0)		*(74.1)*	*(12.3)*	
Tree seedlings	31.0	15.2	51.0	26.3	13.0	50.7	21.5	10.7	50.2	*189.3*	*24.5*	*87.1*
	(69.3)	(34.0)		(62.3)	(26.2)		(55.4)	(18.5)		*(172.1)*	*(42.3)*	
Subtotal live	1384.2	101.4	92.7	2275.8	96.5	95.8	3167.3	91.6	97.1	*1524.8*	*184.8*	*87.9*
	(492.3)	(71.0)		(1004.6)	(58.2)		(1527.5)	(51.7)		*(416.6)*	*(49.7)*	
Dead												
Leaves	30.0	0.0	100.0	82.0	2.5	96.9	133.9	5.0	96.3	*166.3*	*4.9*	*97.1*
	(67.1)	(0.0)		(120.3)	(7.1)		(173.5)	(14.1)		*(83.8)*	*(4.7)*	
Litter	124.2	12.0	90.4	272.1	34.4	87.4	420.0	56.8	86.5	*442.3*	*75.7*	*82.9*
	(63.3)	(18.3)		(207.6)	(48.5)		(351.8)	(78.8)		*(150.6)*	*(46.9)*	
Subtotal dead	154.2	12.0	92.2	354.1	36.9	89.6	553.9	61.8	88.8	*608.6*	*80.6*	*86.8*
	(64.1)	(18.3)		(187.4)	(45.7)		(308.7)	(73.6)		*(132.4)*	*(44.3)*	
Total Fine Fuels	1538.4	113.4	92.6	2629.8	133.4	94.9	3721.2	153.4	95.9	*2133.4*	*265.4*	*87.6*
	(449.3)	(65.4)		(894.6)	(54.8)		(1346.1)	(60.5)		*(335.5)*	*(48.1)*	
TREES AND SHRUBS												
Live												
Leaves	7.9	7.5	4.8	127.3	117.7	7.5	241.1	229.1	5.0	550.0	524.2	4.7
Wood	78.1	78.1	0.005	1194.6	1194.5	0.01	2075.5	2075.4	0.01	7089.5	7089.2	0.005
Subtotal live	86.0	85.6	0.4	1321.9	1312.2	0.7	2316.6	2304.4	0.5	7639.6	7613.4	0.3
	(8.1)	(8.1)		(207.6)	(207.6)		(83.9)	(83.9)		(253.1)	(253.1)	
Dead												
Standing wood	3.0	3.0	1.8	16.2	15.9	1.8	59.6	57.7	3.2	440.6	426.6	3.2
	(0.2)	(0.2)		(1.7)	(1.7)		(3.1)	(3.1)		(73.0)	(73.0)	
Fallen wood	-	-	-	77.3	63.0	18.4	29.5	20.1	31.8	32.1	21.9	31.8
	-	-		(16.4)	(16.4)		(1.4)	(1.4)		(3.1)	(3.1)	
Subtotal dead	3.0	3.0	1.8	93.5	79.0	15.6	89.1	77.8	12.7	472.7	448.5	5.1
	(0.2)	(0.2)		(16.1)	(16.1)		(3.5)	(3.5)		(72.9)	(72.9)	
Total Trees and Shrubs	89.1	88.6	0.5	1415.5	1391.2	1.7	2405.8	2382.3	1.0	8112.3	8061.9	0.6
	(7.8)	(7.8)		(194.9)	(196.7)		(80.9)	(81.3)		(242.6)	(243.1)	
TOTAL Steppe-like savanna	1627.4	202.0	87.6	4045.3	1524.6	62.3	6127.0	2535.7	58.6	10245.7	8327.3	18.7
	(425.2)	(40.1)		(649.8)	(184.3)		(849.3)	(80.0)		(261.9)	(236.9)	
ASHES-PARTICULATES	-	122.7	-	-	324.6	-	-	526.4	-	-	*473.2*	-
	-	(39.7)		-	(284.9)		-	(530.1)		-	*(46.6)*	

(1) numbers in italics represent estimated values, as specified in the text.

Table 5 - Above-ground carbon in open savanna in Roraima ((% and stock, pre- and post-burn; SD in parentheses).

"SAVANNA" Group component (kg ha^{-1})	Sg CF				Sg DF				Sp				Sa [(1)]			
	Pre-burn	%C	Post-burn	%C	Pre-burn	%C	Post-burn	%C	Pre-burn	%C	Post-burn	%C	Pre-burn	%C	Post-burn	%C
FINE FUELS																
Live																
Poaceae	756.6	36.6	56.5	37.9	762.0	35.8	13.3	37.9	1286.6	39.1	64.1	42.5	*428.4*	*37.2*	*40.9*	*39.4*
	(172.1)	(2.5)	(45.4)	(10.7)	(369.5)	(2.7)	(26.6)	(3.0)	(367.1)	(2.4)	(61.3)	(3.3)	*(191.2)*	*(2.5)*	*(22.5)*	*(5.7)*
Herbs	9.1	38.9	1.1	39.1	59.4	40.0	1.6	37.6	32.9	43.8	6.4	44.5	*36.6*	*40.9*	*17.7*	*40.4*
	(5.4)	(2.2)	(2.1)	(2.7)	(213.1)	(4.5)	(2.0)	(5.5)	(51.8)	(2.1)	(9.6)	(2.9)	*(15.0)*	*(2.9)*	*(19.1)*	*(3.7)*
Cyperaceae	220.9	35.4	106.8	37.3	4.8	33.8	0.3	41.1	41.8	39.6	1.4	45.9	*34.0*	*36.3*	*5.3*	*41.4*
	(226.1)	(3.2)	(133.2)	(3.0)	(5.4)	(8.0)	(0.5)	(4.2)	(51.5)	(4.3)	(2.4)	(0.5)	*(26.9)*	*(5.2)*	*(5.1)*	*(2.5)*
Tree seedlings	22.3	38.7	9.8	42.3	9.2	42.1	0.04	42.1	84.1	45.9	7.2	41.8	*80.0*	*42.2*	*10.3*	*42.0*
	(54.6)	(3.0)	(33.2)	(0.2)	(45.7)	(2.1)	(0.1)	(2.1)	(96.3)	(2.8)	(13.5)	(3.0)	*(72.7)*	*(2.6)*	*(17.8)*	*(1.8)*
Subtotal live	1008.8	36.4	174.2	37.8	835.4	36.2	15.2	38.0	1445.4	39.6	79.0	42.7	*579.0*	*38.1*	*74.2*	*40.2*
	(179.8)	(2.7)	(98.2)	(4.0)	352.7	4.2	23.5	3.7	(335.0)	(2.9)	(51.7)	(2.4)	*(154.0)*	*(3.3)*	*(19.8)*	*(3.4)*
Dead																
Leaves	8.3	42.5	4.3	44.2	17.3	42.0	-	-	73.3	40.2	2.3	48.4	*69.1*	*41.6*	*2.3*	*46.3*
	(12.4)	(1.7)	(10.9)	(2.2)	(41.0)	(4.0)	-	-	(78.4)	(5.9)	(5.6)	(0.1)	*(34.9)*	*(3.9)*	*(2.2)*	*(0.7)*
Litter	154.8	32.9	49.3	59.9	58.8	29.7	15.8	38.6	110.8	32.4	36.3	46.9	*140.1*	*31.7*	*36.7*	*48.4*
	(83.3)	(3.1)	(105.8)	(10.1)	(49.6)	(4.4)	(11.8)	(9.4)	(36.2)	(4.6)	(45.2)	(16.9)	*(47.7)*	*(4.1)*	*(22.7)*	*(12.1)*
Subtotal dead	163.2	33.4	53.6	58.6	76.1	32.5	15.8	38.6	184.1	35.5	38.6	47.0	*209.2*	*34.9*	*39.0*	*48.3*
	(79.7)	(2.3)	(98.3)	(6.7)	(47.7)	(4.2)	(11.8)	(9.4)	(53.0)	(5.3)	(42.8)	(8.3)	*(43.4)*	*(4.0)*	*(21.5)*	*(6.6)*
Total Fine Fuels	1172.0	36.0	227.8	42.7	911.4	35.9	31.0	38.3	1629.5	39.2	117.7	44.1	*788.2*	*37.2*	*113.1*	*43.0*
	(165.9)	(2.5)	(98.2)	(5.7)	(327.2)	(4.2)	(17.6)	(6.6)	(303.2)	(4.0)	(48.8)	(5.5)	*(124.7)*	*(3.6)*	*(20.4)*	*(5.1)*
TREES AND SHRUBS																
Live																
Leaves	4.0	50.3	3.1	50.3	42.3	50.0	39.5	50.0	171.5	48.2	162.8	48.2	385.2	46.3	366.3	46.3
	-	(2.7)	-	(2.7)	-	(3.3)	-	(3.3)	-	(3.6)	-	(3.6)	-	(4.0)	-	(4.0)
Wood	12.9	46.3	12.9	46.3	237.2	46.1	237.2	46.1	1518.8	46.2	1518.7	46.2	4024.7	46.1	4024.5	46.1
	-	(2.7)	-	(2.7)	-	(2.5)	-	(2.5)	-	(1.8)	-	(1.8)	-	(2.0)	-	(2.0)
Subtotal live	16.9	47.3	16.0	47.1	279.5	46.7	276.7	46.6	1690.3	46.4	1681.5	46.4	4409.9	46.1	4390.8	46.1
	(0.5)	(2.7)	(0.5)	(2.7)	(6.3)	(2.9)	(6.3)	(2.9)	(75.0)	(2.8)	(75.0)	(2.8)	(598.7)	(3.0)	(598.7)	(3.0)
Dead																
Standing wood	4.9	46.8	4.8	46.8	13.7	45.7	13.5	45.7	64.7	47.5	63.2	47.5	13.5	49.7	13.2	49.7
	(0.2)	(1.9)	(0.2)	(1.9)	(0.5)	(1.8)	(0.5)	(1.8)	(6.4)	(1.9)	(6.4)	(1.9)	(1.8)	(1.6)	(1.8)	(1.6)
Fallen wood	0.3	47.6	0.3	47.6	36.1	46.6	29.4	46.6	39.1	49.0	30.2	49.0	5.5	49.1	4.3	49.1
	(0.03)	(1.5)	(0.03)	(1.5)	(3.9)	(1.4)	(3.9)	(1.4)	(2.2)	(1.4)	(2.2)	(1.4)	(0.6)	(2.2)	(0.6)	(2.2)
Subtotal dead	5.3	46.9	5.1	46.8	49.9	46.4	42.9	46.3	103.8	48.0	93.4	48.0	19.1	49.5	17.5	49.5
	(0.2)	(1.7)	(0.2)	(1.7)	(3.0)	(1.6)	(2.8)	(1.6)	(4.8)	(1.7)	(5.0)	(1.7)	(1.5)	(1.9)	(1.5)	(1.9)
Total Trees and Shrubs	22.2	47.2	21.2	47.0	329.3	46.6	319.7	46.6	1794.1	46.5	1774.9	46.5	4429.0	46.1	4408.3	46.1
	(0.5)	(2.2)	(0.4)	(2.2)	(5.8)	(2.3)	(5.8)	(2.3)	(71.0)	(2.2)	(71.3)	(2.2)	(596.1)	(2.4)	(596.3)	(2.4)
TOTAL Savanna	1194.2	36.2	249.0	43.0	1240.8	38.7	350.7	45.9	3423.6	43.0	1892.6	46.3	5217.2	44.8	4521.4	46.1
	(162.8)	(2.3)	(89.9)	(3.8)	(241.9)	(3.1)	(6.9)	(4.2)	(181.5)	(3.0)	(69.9)	(3.8)	(524.9)	(3.0)	(581.9)	(3.7)
ASHES-PARTICULATES	-	-	95.6	19.5	-	-	36.3	15.3	-	-	56.7	17.3	-	-	*82.1*	*17.4*
	-	-	(205.1)	(2.5)	-	-	(27.3)	(3.1)	-	-	(41.5)	(4.9)	-	-	*(8.1)*	*(3.5)*

(1) numbers in italics represent estimated values, as specified in the text.

Table 6 - Above-ground carbon in open steppe-like savanna in Roraima (% and stock, pre- and post-burn; SD in parentheses).

"STEPPE-LIKE SAVANNA"	Tg CF				Tg DF				Tp				Ta (1)			
Group component (kg ha^{-1})	Pre-burn	%C	Post-burn	%C	Pre-burn	%C	Post-burn	%C	Pre-burn	%C	Post-burn	%C	Pre-burn	%C	Post-burn	%C
FINE FUELS																
Live																
Poaceae	480.4	40.9	6.1	44.6	851.1	40.9	11.8	44.6	1182.4	39.5	16.2	41.3	*463.2*	*40.2*	*44.5*	*42.9*
	(230.8)	(0.9)	(8.9)	(0.0)	(444.2)	(0.9)	(14.7)	(0.9)	(636.4)	(1.9)	(19.0)	(1.1)	*(206.7)*	*(1.4)*	*(24.5)*	*(0.6)*
Herbs	30.4	45.7	33.6	46.3	34.3	45.7	25.6	46.3	35.1	42.1	16.0	42.0	*39.3*	*43.9*	*19.3*	*44.2*
	(22.2)	(1.1)	(40.9)	(0.7)	(40.8)	(1.1)	(36.8)	(1.1)	(54.6)	(1.5)	(29.7)	(6.9)	*(16.0)*	*(1.3)*	*(20.8)*	*(3.8)*
Cyperaceae	46.8	42.2	-	-	38.6	42.2	0.7	39.2	27.8	38.6	1.6	43.6	*37.8*	*40.4*	*5.5*	*43.6*
	(44.6)	(0.9)	-	-	(61.2)	(0.9)	(2.2)	(0.9)	(71.1)	(0.1)	(4.8)	(0.0)	*(29.9)*	*(0.5)*	*(5.3)*	*(0.0)*
Tree seedlings	13.7	44.2	7.2	47.4	11.6	44.2	6.1	47.4	9.6	44.5	4.7	44.0	*84.0*	*44.4*	*11.2*	*45.7*
	(30.6)	(0.0)	(16.1)	(0.0)	(27.6)	(0.0)	(12.4)	(0.0)	(24.6)	(1.7)	(8.1)	(1.9)	*(76.3)*	*(0.8)*	*(19.3)*	*(1.0)*
Subtotal live	571.3	41.3	46.9	46.2	935.6	41.1	44.2	45.9	1254.8	39.6	38.5	42.0	*624.3*	*41.0*	*80.6*	*43.6*
	(199.7)	(0.7)	(32.9)	(0.2)	(408.5)	(0.7)	(27.0)	(0.7)	(602.9)	(1.3)	(21.5)	(2.5)	*(166.5)*	*(1.0)*	*(21.6)*	*(1.3)*
Dead																
Leaves	13.5	44.9	-	-	36.8	44.9	1.1	44.2	56.5	42.2	1.8	35.7	*72.4*	*43.6*	*1.7*	*35.7*
	(30.1)	(0.0)	-	-	(54.0)	(0.0)	(3.1)	(0.0)	(73.2)	(2.6)	(5.0)	(0.0)	*(36.5)*	*(1.3)*	*(1.7)*	*(0.0)*
Litter	50.6	40.7	5.6	46.4	110.8	40.7	16.0	46.4	147.3	35.1	23.1	40.7	*167.6*	*37.9*	*33.0*	*43.6*
	(25.8)	(2.7)	(8.5)	(12.8)	(84.5)	(2.7)	(22.5)	(2.7)	(123.4)	(4.3)	(32.1)	(0.0)	*(57.1)*	*(3.5)*	*(20.4)*	*(6.4)*
Subtotal dead	64.0	41.6	5.6	46.4	147.6	41.8	17.1	46.3	203.8	37.1	24.9	40.3	*240.0*	*39.6*	*34.7*	*43.2*
	(26.7)	(1.3)	(8.5)	(12.8)	(76.9)	(1.3)	(21.3)	(1.4)	(109.5)	(3.4)	(30.1)	(0.0)	*(50.9)*	*(2.3)*	*(19.5)*	*(3.5)*
Total Fine Fuels	635.3	41.3	52.4	46.3	1083.2	41.2	61.3	46.0	1458.7	39.3	63.4	41.4	*864.3*	*40.6*	*115.3*	*43.5*
	(182.3)	(1.0)	(30.3)	(6.5)	(363.3)	(1.0)	(25.4)	(1.1)	(534.0)	(2.3)	(24.9)	(1.3)	*(134.4)*	*(1.7)*	*(20.9)*	*(2.4)*
TREES AND SHRUBS																
Live																
Leaves	3.6	45.0	3.4	45.0	57.9	45.5	53.6	45.5	109.1	45.2	103.6	45.2	244.9	44.5	233.4	44.5
	-	(3.6)	-	(3.6)	-	(3.5)	-	(3.5)	-	(4.6)	-	(4.6)	-	(4.8)	-	(4.8)
Wood	35.0	44.8	35.0	44.8	538.2	45.1	538.2	45.1	907.5	43.7	907.4	43.7	3079.3	43.4	3079.2	43.4
	-	(2.5)	-	(2.5)	-	(2.7)	-	(2.7)	-	(2.7)	-	(2.7)	-	(2.8)	-	(2.8)
Subtotal live	38.6	44.8	38.4	44.8	596.2	45.1	591.8	45.1	1016.6	43.9	1011.0	43.9	3324.2	43.5	3312.5	43.5
	(3.6)	(3.0)	(3.6)	(3.0)	(93.6)	(3.1)	(93.6)	(3.1)	(36.8)	(3.6)	(36.8)	(3.6)	(110.1)	(3.8)	(110.1)	(3.8)
Dead																
Standing wood	1.5	49.9	1.5	49.9	7.5	46.3	7.4	46.3	28.0	47.0	27.1	47.0	197.0	44.7	190.7	44.7
	(0.1)	(1.5)	(0.1)	(1.5)	(0.8)	(1.0)	(0.8)	(1.0)	(1.5)	(1.6)	(1.5)	(1.6)	(32.6)	(1.4)	(32.6)	(1.4)
Fallen wood	-	-	-	-	36.4	47.1	29.7	47.1	13.8	46.8	9.4	46.8	14.7	45.8	10.0	45.8
	-	-	-	-	(7.7)	(2.0)	(7.7)	(2.0)	(0.6)	(2.2)	(0.6)	(2.2)	(1.4)	(1.8)	(1.4)	(1.8)
Subtotal dead	1.5	49.9	1.5	49.9	43.9	46.9	37.0	46.9	41.8	46.9	36.5	46.9	211.7	44.8	200.7	44.8
	(0.0)	(1.5)	(0.0)	(1.5)	(7.6)	(1.5)	(7.6)	(1.5)	(1.6)	(1.9)	(1.6)	(1.9)	(32.6)	(1.6)	(32.6)	(1.6)
Total Trees and Shrubs	40.1	45.0	39.9	45.0	640.1	45.2	628.8	45.2	1058.4	44.0	1047.6	44.0	3535.9	43.6	3513.3	43.6
	(3.5)	(2.2)	(3.5)	(2.2)	(87.7)	(2.3)	(88.6)	(2.3)	(35.4)	(2.8)	(35.6)	(2.8)	(105.5)	(2.7)	(105.7)	(2.7)
TOTAL Steppe-like savanna	675.4	41.6	92.3	45.7	1723.2	42.7	690.1	45.3	2517.0	41.3	1110.9	43.8	4400.2	43.0	3628.6	43.6
	(171.7)	(1.6)	(18.7)	(4.4)	(261.0)	(1.7)	(82.9)	(1.7)	(324.4)	(2.6)	(35.0)	(2.0)	(111.2)	(2.2)	(103.0)	(2.5)
ASHES-PARTICULATES	-	-	20.9	17.1	-	-	55.4	17.1	-	-	75.7	14.4	-	-	*74.4*	*15.7*
	-	-	(6.8)	(2.8)	-	-	(48.6)	(2.8)	-	-	(76.3)	(2.9)	-	-	*(7.3)*	*(2.8)*

(1) numbers in italics represent estimated values, as specified in the text.

Table 7 - Stock and release of pre-burn carbon in the post-burn phase (fate of carbon).

Fate	kg $C.ha^{-1}$	%	kg $C.ha^{-1}$	%	kg $C.ha^{-1}$	%	kg $C.ha^{-1}$	%
"Savanna" Group	Sg CF		Sg DF		Sp		Sa	
Live Biomass	190.3	15.9	291.9	23.5	1760.6	51.4	4465.0	85.6
Dead Biomass	58.7	4.9	58.7	4.7	132.0	3.9	56.4	1.1
Ashes-Particulates	95.6	8.0	36.3	2.9	56.7	1.7	82.1	1.6
Presumed Release	849.7	71.2	853.8	68.8	1474.3	43.1	613.6	11.8
"Steppe-like Savanna" Group	Tg CF		Tg DF		Tp		Ta	
Live Biomass	85.3	12.6	636.0	36.9	1049.5	41.7	3393.1	77.1
Dead Biomass	7.0	1.0	54.1	3.1	61.4	2.4	235.5	5.4
Ashes-Particulates	20.9	3.1	55.4	3.2	75.7	3.0	74.4	1.7
Presumed Release	562.2	83.2	977.7	56.7	1330.3	52.9	697.2	15.8

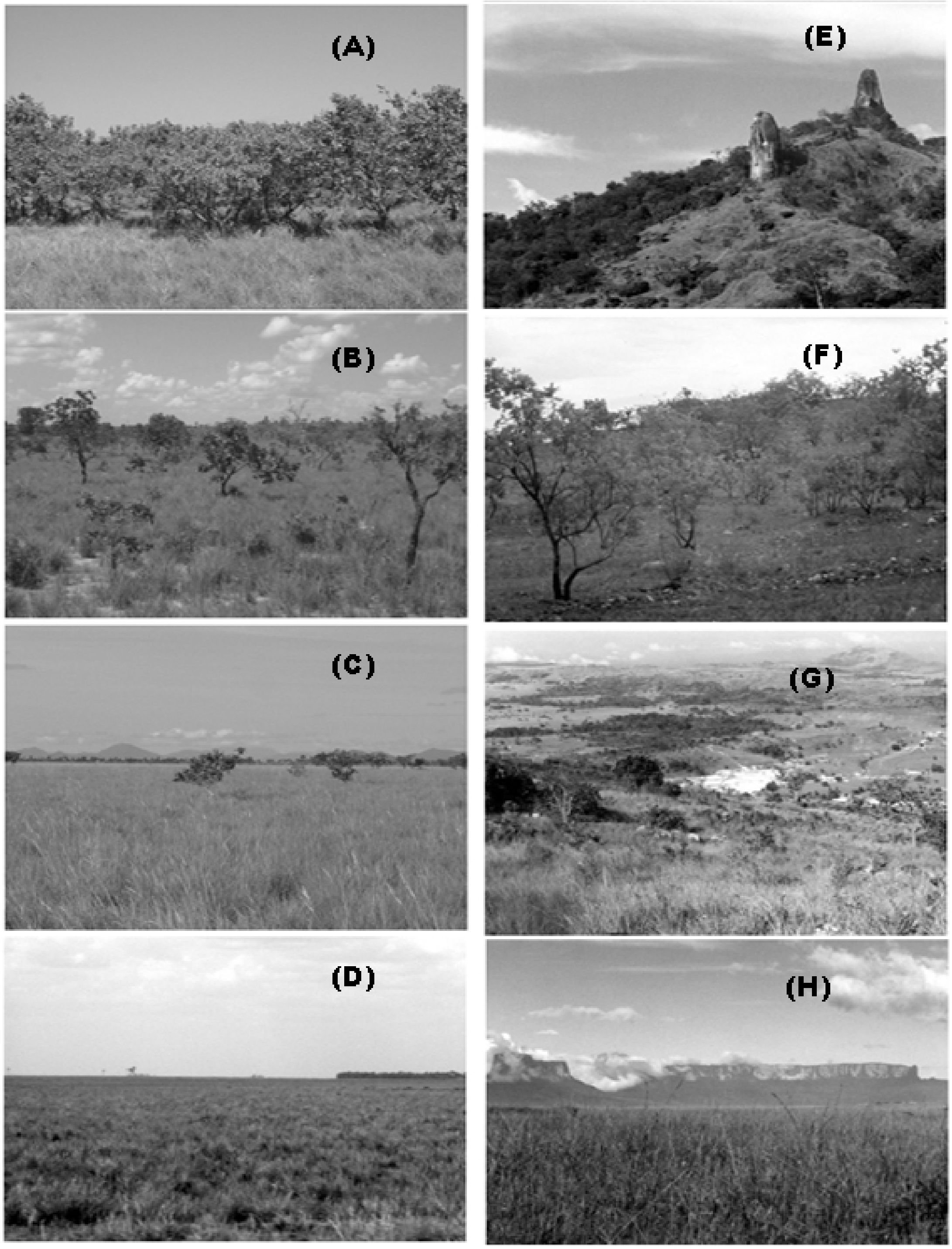

Figure 1 - Eight savanna types studied in Roraima: “Savannas” / “Steppe-like savannas” – (A / E) open woodland, (B / F) parkland, (C / G) grassland (dirty field) and (D / H) grassland (clean field).