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Biomass Burning in Brazil's Amazonian "Arc of Deforestation": Burning efficiency and charcoal formation in a fire after mechanized clearing at Feliz Natal, Mato Grosso.

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Abstract

Estimates of greenhouse-gas emissions from deforestation are highly uncertain because of high variability in key parameters and because of the limited number of studies providing field measurements of these parameters. One such parameter is burning efficiency, which determines how much of the original forest's aboveground carbon stock will be released in the burn, as well as how much will later be released by decay and how much will remain as charcoal. In this paper we examined the fate of biomass from a semideciduous tropical forest in the "arc of deforestation," where clearing activity is concentrated along the southern edge of the Amazon forest. We estimated carbon content, charcoal formation and burning efficiency by direct measurements (cutting and weighing) and by line-intersect sampling (LIS) done along the axis of each plot before and after burning of felled vegetation. The total aboveground dry biomass found here (219.3 Mg ha^{-1}) is lower than the values found in studies that have been done in other parts of the Amazon region. Values for burning efficiency (65%) and charcoal formation (6.0%, or 5.98 MgC ha^{-1}) were much higher than those found in past studies in tropical areas. The percentage of trunk biomass lost in burning (49%) was substantially higher than has been found in previous studies. This difference may be explained by the concentration of more stems in the smaller diameter classes and the low humidity of the fuel (the dry season was unusually long in 2007, the year of the burn). This study provides the first measurements of forest burning parameters for a group of forest types that is now undergoing rapid deforestation. The burning parameters estimated here indicate substantially higher burning efficiency than has been found in other Amazonian forest types. Quantification of burning efficiency is critical to estimates of trace-gas emissions from deforestation.

Keywords: Burning; Biomass; Carbon; Deforestation; Fire; Global warming; Greenhouse-gas emissions; Rainforest

1. Introduction

CO_2 emission estimates due to land-use change in tropical areas vary widely (Prentice et al., 2001). Tropical forests, in particular the Amazon forest, contain a great quantity of biomass and are one of the last agricultural frontiers. Deforestation in Brazilian Amazonia is concentrated in the "arc of deforestation,"a crescent-shaped band along the eastern and southern edges of the forest, including the state of Mato Grosso. As compared to forests in the remainder of Amazonia, those in the arc of deforestation have lower biomass (and smaller-diameter trees), and a drier climate. These characteristics facilitate fires with high burning efficiency when the forests are cleared in preparation for agriculture and ranching.

The greenhouse effect is a complex problem mainly due to its large number of sources and their dispersion in the world. It results from the total emissions of myriad small, medium and large sources of CO_2. Global carbon emissions due to land-use change in the 1990s range from +1.4 to +3.0 GtC yr^{-1} (Houghton, 2003). The large uncertainties in carbon balance estimates are due to uncertainty in estimates of tropical deforestation rates and in estimates of forest biomass (Houghton et al., 2001; DeFries et al., 2002). Uncertainty concerning carbon stocks in tropical forests leads to a wide range of possible carbon emissions due to deforestation and degradation. Doubts concerning biomass and deforestation estimates for the tropics have approximately equal weight in the final emission uncertainties (Houghton, 2005). In the Brazilian Amazon, uncertainties in biomass determinations were responsible for 60% of the variation in the estimated net carbon flux for the region (Houghton et al., 2000). In addition to uncertainties concerning biomass and deforestation, uncertainties regarding burning efficiency have an important effect on emission of trace gases, and thus on the global-warming impact of deforestation.

Measurements of burning coefficients in Amazon forests are few in the literature as these studies are time consuming, expensive and very labor intensive. The few attempts that have been made show high variability in time and space (Araújo et al., 1999; Carvalho et al., 1995, 1998, 2001; Fearnside et al., 1993, 1999; Graça et al., 1999; Guild et al., 1998; Kauffman et al., 1995; Soares Neto et al., 2009). This applies both to measurements of burning efficiency (the percentage of above-ground carbon lost from the site as a result of the burn) and of biomass consumption (percentage loss of dry-weight biomass, irrespective of carbon content). This study evaluated the fate of carbon when forest is felled and burned for a semideciduous tropical forest biomass at Feliz Natal, in Brazil's state of Mato Grosso (Figure 1).

[Figure 1 here]

Recently Feliz Natal has experienced a soybean "boom" and thus an acceleration of deforestation (Fearnside, 2001). At present the state of Mato Grosso is responsible for about half of the total deforestation in Brazil's nine-state Legal Amazon region. Feliz Natal is located in the northeastern portion of Mato Grosso, where most of the deforestation in the state is taking place. Feliz Natal is one of the top ten municipalities (counties) in Amazonia as ranked for deforestation and biomass burning (Agência Brasil, 2009).

Our goal was to quantify these parameters in a kind of vegetation that has, until now, lacked field measurements on burning effects. This information is needed to reduce uncertainties in greenhouse-gas emission estimates from tropical deforestation and forest biomass burning.

2. Materials and methods

2.1. Site description

The study area is located at 12°32’38.3”S, 54°52’40.5 W at Feliz Natal, Mato Grosso, Brazil.

The study area belongs to Mr. José Sebastião da Silva and is located about 20 km from the city of Feliz Natal. The forest is classified as seasonal semideciduous forest, a kind of forest in which the trees lose from 20 to 50% of their leaves during the dry period (Brazil, IBGE and IBDF, 1988). This is a typical transitional forest between rainfoest (ombrophylous forest) and seasonal forest (IBGE map code = ON; RADAMBRASIL map code = Fse3, or seasonal semideciduous submontane forest). The most common timber trees found in the region are: cedrinho (*Erisma* sp.), itaúba (*Mezilaurus itauba*), champangne (*Dipeterix* sp.), garapeira (*Apuleia* sp.), angelim pedra (*Dinisia excelsa*), amescla (*Trattinickia rhoifolia*), cupiúba (*Goupia glabra*), canela (*Ocotea* sp.), jatobá (*Hymenaea* sp.), guanandi (*Calophyllum* sp.), cambará (*Vochysia divergens*), cedro rosa (*Cedrela fissilis*) and cedro amazonas (*Cedrelinga* sp.). The topography is a quite uniformly flat, smoothly undulating plateau and the area is about 384 m above mean sea level. The soil is a red-yellow Latosol in the Brazilian classification, an Oxisol in the U.S. classification and an orthic Ferralsol in the UNESCO/FAO classification.

The climate is classified as *Am* under the Köppen-Geiger classification with minimum air temperature not lower than 18ºC and with annual rainfall exceeding evapotranspiration (Nimer, 1979). The rains start in early November and continue through the end of April (6 months). The rainiest months are January, February and March and the driest are June, July and August. Average annual rainfall in Feliz Natal is approximately 1850 mm. Mean air temperatures is 24 to 26°C and the annual temperature range (difference between the maximum and minimum reported for a year) is up to 3°C. In winter, the region can receive cold fronts from the polar Atlantic air mass. These are responsible for the phenomenon of cold-snaps or “*friagens*”, which are sudden drops in temperature by as much as 10°C.The burning season occurs in the dry period and extends to the beginning of the rains. The success of a burn is highly dependent to the period that the woody material is left to dry in the field and on the weather during this period (Fearnside, 1989).

The forest conversion in Feliz Natal was typical of the deforestation occurring at the agriculture expansion frontier in the arc deforestation. These forests generally have undergone some degree of degradation, such as that due to selective logging of high-value timber or due to incidental fires originated from burns in neighboring pastures in or regrowth vegetation. The study area had been subjected to selective logging at least seven years previous to our study. Rotten stumps present in the area indicate removal of 1-2 individuals of 40-50 cm DBH per hectare, or at most 20 m^3 of logs per hectare.

The forest was felled in June 2007 at the beginning of the dry season by using a pair of bulldozers attached to each other by a heavy chain. The clearing was approximately 100 ha in area. Farmers are opening new areas for pasture or agriculture in these relatively low-biomass forests; higher-biomass forests in other parts of Amazonia are felled with chainsaws rather than the "large chain" (*correntão*) method. The biomass burn was done at an unusual time of year in the beginning of December of the same year as the felling, after the rainy season had started. This year was considered atypical with regard to the rainfall regime because the dry period extended until the middle of November rather than ending in October. The delay in the farmer's decision to burn was due to the extension of a legal prohibition of burning in the state of Mato Grosso. Although the dry season in 2007 was longer than usual (as reflected in ground fires in substantial areas of forest in northern Mato Grosso and southern Pará), more severe droughts do occur, as in 2005 (Marengo et al., 2008). Severe drought events like the one in 2005 are expected to become much more frequent in the coming decades (Cox et al., 2008).

The felled vegetation is shown in Figure 2. The trees were broken off near ground level, rather than being uprooted. The predominance of small-diameter stems is evident. A single burn was used rather than piling unburned material into either heaps (*coivaras*) or windrows (*leiras*) for a second burning prior to planting.

[Figure 2 here]

2.2. Experiment layout

The sample plots were set up in the clearings during the interval between the felling of the trees and the time of the burn. The experiment started in early September 2007 with the setting up of the plots in the field and ended in late December 2007, after the burn and collection of charcoal. A star sampling design was used that has been adopted in a number of pervious studies (Fearnside et al., 1999; Graça et al., 1999) (Figure 3). This sample design for the felled vegetation consisted of six 2 × 30 m plots in the form of the rays of a star. The initial point (center) was located by throwing an iron rod backwards over the thrower's shoulder. Starting from this common starting point, six rays were laid out by using a measuring tape; rays are separated by angles of 60°, each ray beginning at a distance of 10 m from the central point. Each ray was sub-divided into three segments of 2 × 10 m, each segment representing a repetition. The center and the end of the rays were marked with iron reinforcing rods in order to resist the flames during the burn. The star design is intended to 1. avoid heavily sampling areas with many or few trees, as often happens when using conventional rectangles in forests; *2.* randomize the distribution of blocks to minimize angular bias from trees often being felled roughly parallel to each other, and; *iii.* be simple to use (Fearnside et al., 1999).

[Figure 3 here]

A total of five stars were laid out in the trial area. Stars were placed far away from each other in order to obtain a better sampling of the field. Three of the stars were used for biomass estimates (pre- and post-burn phases) by the destructive method and direct weighing for the thin material (small twigs, vines, litter and leaves). In all five stars the line-intersect sampling (LIS) method (described below) was used to determine wood volume of pieces >10 cm in diameter in both phases. Wood in this diameter class represents the largest part of the biomass in a forest. The indirect method has greater accuracy than the destructive method in determining burning efficiency for wood >10 cm in diameter is mainly due to the LIS method permitting that the same pieces (which were tagged) be measured before and after the burn. In contrast, the direct method uses alternate rays in the pre- and post-burn measurements.

The stars were denominated by letters from A to E and each star was considered to be a sampling point. The rays were numbered from one to six in each star and were identified by the letter of the star and the number of the ray. All biomass present in the odd rays (each 2 × 30 m) was cut and weighed in the pre-burn phase, except for wood pieces >10 cm in diameter. After weighing and taking samples, all material was returned to the plots in order to minimize the effect of piling of cut material that had been discharged from the balance. The even-numbered rays were evaluated in the post-burn phase.

2.3. Biomass classes

In the pre-burn and post-burn phases the plant material was separated into seven classes: 1. wood pieces >10 cm in diameter (estimated only by LIS in the post-burn rays); 2. thin wood pieces <5 cm in diameter; 3. thick wood pieces 5-10 cm in diameter; 4. leaves, litter and small plant fragments (flowers, fruits, etc.); 5. vines <5 cm in diameter; 6. vines 5-10 cm in diameter, and 7. charcoal (clinging to the plant material and present on the soil surface after the burn). No vines were found with diameter >10 cm. With the exception of wood >10 cm in diameter, which was estimated by LIS, all of the other classes of material were weighed in the field and sampled for correction to a dry-weight basis. The biomass and samples were separated for each class and 2 ×10 m ray segment. The pre-burn destructive sampling, therefore, totaled 9 rays of 60 m^2, or 540 m^2. Wood pieces >10 cm in diameter were measured in 15 rays totaling 900 m^2. Roots were not included in the aboveground biomass as these are rarely found above the soil in the plots and represent an insignificant portion of the aboveground biomass.

2.4. Balances

A heavy electronic crane scale was used for field measurements: Pesola® brand, model OCS-M with 300-kg capacity and 0.1-kg precision. For smaller loads and samples weighed in the field a set of precision spring balances was used: Pesola® brand, models 80005, 80010, 80020 (Macro-Line) with 5-kg capacity (accurate to 50 g), 10-kg capacity (accurate to 100 g) and 20-kg capacity (accurate to 200 g) and models 40600, 41000 and 42500 (Medio-Line) with 600-g capacity (accurate to 5 g), 1000-g capacity (accurate to 10 g) and 2500-g capacity (accurate to 20 g). In the laboratory samples were weighed on an electronic balance: Gehaka brand, model BG-400 accurate to 0.001 g. Wood-density determination by the hydrostatic method used a different electronic balance: Bel Engineering brand, model Mark-4100 accurate to 0.01 g.

2.5. Biomass collection and weighing

Before cutting and separating the plant material into the aforementioned classes, the plots were outlined with nylon twine stretched between the corner stakes. The boundaries were then cut, depending on the diameter class, using either a chainsaw (trunks and thick branches) or machetes (vines and thin branches). The part of the material that extended outside of plot was disregarded. All plant material, excepting trunks >10 cm in diameter, which were measured with the LIS method, was cut into small fractions to allow placement on a tray suspended from the electronic crane scale (300-kg capacity). This gave us the wet weight, or field dry mass, for each biomass class.

After weighing the biomass, for each biomass class and sub-plot (2 × 10 m) a representative sample was randomly taken and weighed in the field using the small spring balances. The balance used for weighing each sample was chosen according to the sample's weight and the balance capacity. After weighing, the samples were placed in plastic bags and tagged with information on biomass class, ray segment, ray and star letter. In the case of the biomass class for wood >10 cm in diameter, a disk was cut from each piece. Wood pieces were directly marked using a felt-tipped marker.

All samples were dried in a forced-air oven at 70°C until they reached constant weight. These wet (obtained in the field) and dry (obtained in the laboratory) weights were used to convert biomass measurements made in the field to a dry-mass basis. Thus, moisture content of each sample was calculated by the difference between wet and dry weights divided by the dry weight. Determination of the moisture content for each biomass class and sub-plot was necessary because of its natural variation among different biomass classes and because of differences in the sizes of the samples, which result in differences in the drying of the material. Also there are differences in the way vegetation falls, which can created micro-sites with specific conditions.

The total dry mass estimate was obtained by summing the means of each class and ray segment (2 × 10-m sub-plot). For the biomass class for wood >10 cm in diameter, the dry biomasses were obtained by volume estimates (LIS – see description of this methodology below) in the pre-burn rays (measured before burning) and from the wood basic density.

2.6. Wood basic density determination

"Wood density" refers to "basic specific gravity", which means oven-dry weight divided by wet volume (Fearnside, 1997a). Wood density is an important factor in converting volumes (mainly trunks) to biomass and is a source of many biases in biomass estimates. The wide variation in wood-density determination is responsible for about half of the uncertainty in forest biomass estimates in Brazilian Amazonia. Data and discussion of wood density can be found in Fearnside (1997a) and Nogueira et al. (2007).

The basic wood density (dry mass divided by saturated volume) was determined by the hydrostatic method, by means of immersion into water of saturated wood as described by Vital (1984) and Truguilho et al. (1990). The method is based on the Archimedes principle, where the apparent loss of weight of a body immersed in a liquid is equal to the weight of the liquid displaced (the density of water in g cm^{-3} is assumed to be unity). All wood-disk samples from the biomass class of wood >10 cm in diameter were submerged in a drum filled with water where they were left until they were completely saturated. The saturated wood pieces were then weighed on a specially adapted balance. The pieces were maintained underwater and hung one-by-one by a hook attached to a string that passed through a hole in the table to the bottom of the balance. The pieces were left to stabilize and the immersed weight was obtained (W_i).

The same piece was then weighed out of the water, giving the saturated weight (*Ws*). The pieces were than dried in a forced-air oven at 80°C to constant weight (*Wd*). The wood basic density was then attained by expression (1):

$$Db = \frac{Wd}{Ws - Wi} \qquad (1)$$

Where *Db* is basic density and *Ws–Wi* is wood volume.

2.7. Line-intersect sampling (LIS) method

Line-intersect sampling (LIS) was used to estimate the wood volume of pieces >10 cm in diameter before and after the burn. This was done in order to reduce weighing and speed the measurement in the field, as we avoided cutting, carrying and weighing large pieces of trunks and branches. This sampling method was first developed by Van Wagner (1968) to estimate log volume in slashed forest areas. The method has been adapted to estimate charcoal formation after the burn (Graça et al., 1999). The LIS method makes it possible to calculate the percentage of biomass burned for this vegetation class.

This method is based on the theory that a sample line of a given length (L) crosses an area containing many horizontal cylinders of diverse lengths, diameters and orientations. The sample line that crosses the trunks at different angles generates a series of elliptical vertical sections that can be added, and the required volume can be estimated. The wood volume can be acquired by the expression of Van Wagner (1968) (2):

$$V = \frac{\pi^2 \times \sum d^2}{8 \times L} \qquad (2)$$

Where *V* is wood volume per area when all factors are expressed in the same units; *d* is trunk diameter and; *L* is the length of the sample line.

The sample line was stretched in the middle of the post-burn rays along their full length in all five stars. We followed the decision rules proposed by Van Wagner (1968) for the inclusion of the pieces intercepted by the sample line. The wood pieces >10 cm in diameter were tagged using sequentially numbered aluminum plates that were nailed to the pieces. These markings allowed us to measure the diameter of the pieces at the same position on the piece before and after the burn, reducing to a minimum the effect of spatial variation in biomass. Trunk circumference was measured directly using a measuring tape (graduated in millimeters). This measurement was done at 90° to the trunk axis of each piece. The individual numbering of trunks was useful in order to follow individual trees through the transformation caused by the burning and to provide field orientation. The estimated volumes were then converted to weights by using densities from the samples taken in the field. The volume of this stock was estimated for each sub-plot (2 × 10 m) and the total volume of the wood stock was estimated from the sum of the means of the ray segments.

Aluminum plates proved to be too fragile for burning experiments as many of them melted during the burn. Aluminum has a melting point of 660°C, which means that the temperatures at many points were higher than this. All of the pieces could be identified as they were tagged sequentially, and almost all the nails remained attached to the pieces; aluminum drops were easily seen because they contrast with the dark charcoal background. We believe that iron plates (1538°C melting point) would be cheaper and better.

The percentage of wood burned (or biomass consumption by fire) was calculated by comparing pre- and post-burn volumetric data (LIS).

2.8. Charcoal data set

In the post-burn rays we proceeded in the same way as in the pre-burn rays, separating the plant material into the same classes. A reinforced tarp was extended on the ground and all the charcoal present in the sub-plot was scraped onto the tarp from the pieces in each biomass class by using machetes and knives. The limit between charcoal and un-burned biomass was based on visual appearance (blackness). The un-burned material and charcoal was then collected and weighed separately using the appropriate spring balances. Charcoal present on the soil surface was gathered manually by picking up the coarse pieces and by using a brush and a dustpan for the small ones. The charcoal present on the soil surface comes from completely carbonized material and from charcoal that falls off the pieces during and after burn. A small quantity of charcoal remained on the soil surface, as it is very hard to separate this powdered charcoal from the soil particles which could be a source of larger errors than those incurred by not collecting it. In addition, samples were taken from the charcoal from each biomass class, which were wrapped in plastic bags, tagged and brought to the laboratory. Samples were oven dried and the dry weight was determined in the same way as for other classes of material.

Charcoal formation on pieces >10 cm in diameter was measured in the post-burn rays around the circumference of the trunks where the LIS was marked (the point of the identification plates). The thickness of charcoal was measured using a knife and a plastic ruler (graduated in millimeters) at ten points on each tagged trunk distributed all around its circumference. Small incisions were opened with a knife at the measurement points to a depth where there was no charcoal and the knife was inserted. The depth of charcoal was then measured using the graduated plastic ruler. Because the burning, and thus the charcoal formation, is neither random nor homogeneous around the circumference of a fallen log, the distribution of the ten measurement points was intended to produce an estimate of an average value. The thickness of charcoal formation on trunks that were partially buried in the soil was considered to be zero. Whenever possible, the trunks were raised for examination and measurement. The volumes of charcoal adhering to the trunks and branches (>10 cm in diameter) were calculated by subtracting the wood volume without charcoal (not burned, for which the radius was obtained by subtracting the mean charcoal depth around the trunk) from the diameter of the piece. Charcoal mass was then estimated by using the mean density of the charcoal (0.43 g cm^{-3}) found in the literature for Amazonian forests in similar experiments (Graça et al., 1999).

2.9. Carbon content of biomass

Carbon contents of biomass samples were determined by the ‘dry' method using a LECO model CR-412 carbon analyzer (furnace at 1350°C in pure oxygen). The values produced for carbon content of charcoal by this method refer to the total content of carbon (not just elemental carbon) in the sample. What appears visually as charcoal contains, in fact, some carbon in organic form, which can be expected to decay at a more rapid rate than the elemental (‘black') carbon. Kuhlbusch and Crutzen (1995) have estimated that 52–63% of the carbon contained in charcoal is in the elemental form, assuming that carbon that resists oxidation at temperatures up to 340°C is elemental carbon. However, the amount of carbon remaining unoxidized is highly sensitive to temperature: if 300°C were used as the standard instead of 340°C, the amount classified as elemental carbon would approximately double (Kuhlbusch and Crutzen, 1995).

Carbon content in different biomass classes was analyzed only in the pre-burn phase and, of course, the carbon content for charcoal in the post-burn phase. As was found in another study (Graça et al., 1999), carbon content does not differ significantly from the pre- to the post-burn phase. The slight differences observed by the authors are likely to be due to contamination, as it is impossible to remove all of the charcoal that exists around the pieces.

2.10. Biomass estimate and consumption by the fire

The total pre-burn biomass was estimated from the mean of each biomass class (direct weight) added to the results obtained from volumetric data (LIS) converted to dry mass (by wood density). The biomass stocks in the post-burn phase for pieces >10 cm in diameter were estimated from the percentage consumed by the fire. The percentage of biomass consumed by the fire was calculated considering the stock of biomass in each class before and after the burn.

3. Results

3.1. Wood water content

The humidities of the biomass subjected to fire were 16.3% for wood <5 cm in diameter, 20.7% for wood 5-10 cm in diameter; 29.9% for wood >10 cm in diameter; 35.7% for vines <5 cm in diameter; 26.6% for vines 5-10 cm in diameter and only 14.4% for litter and leaves.

3.2. Wood basic density

The wood basic density found in this study was 0.63 ± 0.12 g cm^{-3}, based on a total of 121 samples of wood >10 cm in diameter. This density was used to calculate the aboveground biomass derived from volume stocks calculated by LIS.

332. Aboveground biomass

The pre- and post-burn aboveground biomass results are summarized in Table 1. The total pre-burn aboveground biomass obtained in the felled area was 219.3 Mg ha^{-1}. As expected, wood pieces >10 cm in diameter (trunks and twigs, estimated by the LIS method) with 128.7 ± 120.3 Mg ha^{-1} accounted for the largest part (58.7%) of the total aboveground biomass, followed by wood pieces <5 cm with 17.6% (38.5 ± 19.4 Mg ha^{-1}). Wood volume calculated by LIS for pieces >10 cm in diameter was 204.1 ± 190.7 m^3 ha^{-1}. Litter and leaves (including small twigs that had fallen off the felled trees) and wood pieces 5-10 cm in diameter accounted for 11.7% (25.6 ± 7.7 Mg ha^{-1}) and 11.1% (24.4 ± 12.7 Mg ha^{-1}), respectively, while vines of both classes contributed only about 1% (vines <5 cm = 1.1 ± 1.8 Mg ha^{-1} and vines 5-10 cm = 1.0 ± 4.5 Mg ha^{-1}).

[Table 1 here]

The mean stock of total aboveground biomass remaining after the burn was 64.4 Mg ha^{-1}, which represents only 29% of the initial aboveground biomass. Note that this percentage is not the burning efficiency, as it is necessary to compute charcoal formation in terms of carbon content. About 92% (59.1 ± 48.8 Mg ha^{-1}) of the remaining aboveground biomass after the burn came from wood pieces >10 cm in diameter. After the burn the volume of this material had been significantly reduced to 93.7 ± 77.4 m^3 ha^{-1}, or a reduction of 54%; this category represented the largest remaining stock of material in terms of mass. Wood 5-10 cm in diameter contributed 6.1% (3.9 ± 3.3 Mg ha^{-1}) and wood <5 cm in diameter contributed 1.9% (1.2 ± 1.2 Mg ha^{-1}). Litter and leaves had almost disappeared, the remaining material representing only 0.20% or 0.1 ± 0.3 Mg ha^{-1}.

3.4. Charcoal formation

The total stock of charcoal formed in the burn was 8.7 Mg ha^{-1}, which represents about 12% of the total stock of biomass material left on the ground after the burn in terms of mass or about 6% of the pre-burn carbon stock. About two thirds of this charcoal (62.6% or 3.7 Mg ha^{-1}) was still clinging to the unburned biomass, while 37.4% (2.2 Mg ha^{-1}) was lying on the ground coming from different biomass classes. This last compartment is referred to in Table 1 as "other," as it is not possible to identify its origin; this class represented 2.1% of the original carbon stock in the pre-burn phase. It was not possible to identify charcoal that comes from the vines and litter-leaves classes due to the high flammability and small size of the material (if present). Charcoal clinging to wood in the class >10 cm in diameter contributed more than half (54.4%, or 3.3 ± 2.3 Mg ha^{-1}) of the total charcoal formation, or 5% of its own original biomass on a carbon mass basis, and it is probably the largest source of the charcoal lying on the soil surface. This last charcoal compartment was estimated by LIS. The other compartments were measured directly by scraping the wood pieces with machetes. Wood <5 cm in diameter contributed only 1.8% of the total charcoal formation (0.1 ± 0.1 Mg ha^{-1}) or 1% of the original biomass, while wood 5-10 in diameter supplied 6.5% (0.4 ± 0.2 Mg ha^{-1}) or 3% of the original biomass.

It was not possible to quantify ashes after the burn because the rainy season had already started just before the last step of the experiment. Carbon concentration in ashes is low (6.6% according to Graça et al., 1999). Ash formation is restricted to 2% of the original biomass, so its contribution to total remaining stock is very low.

3.5. Carbon concentration

The mean carbon concentration was 48.6% for all biomass classes together (Table 2). The carbon concentrations were quite similar in all classes ranging from

48.3% for wood 5-10 cm in diameter to 49.8% for litter-leaves (a difference of 1.5%). The concentration of carbon in charcoal (69.0%) was higher, as expected.

[Table 2 here]

3.6. Carbon stock in biomass and burning efficiency

Aboveground biomasses in different classes were converted to carbon stocks before and after the burn (Table 3) by using the carbon concentration determined previously (Table 2). Total carbon stock in biomass before the burn was 106.0 Mg C ha^{-1}, which was reduced to 36.9 Mg C ha^{-1} (post-burn biomass added to charcoal). This implies a presumed instantaneous emission to the atmosphere of 69.1 Mg C ha^{-1}.

[Table 3 here]

The burning of fine material was so complete that only 1% (0.1 ± 0.1 Mg ha^{-1}) of litter and leaves and 3% (0.6 ± 0.6 Mg ha^{-1}) of wood <5 cm in diameter remained intact after the burn while vines had completely disappeared. Left on the soil surface was 16% (1.9 ± 1.6 Mg ha^{-1}) of the wood 5-10 cm in diameter and 46% (28.4 ± 23.4 Mg ha^{-1}) of the wood >10 cm in diameter. The fraction present in each biomass class (in terms of biomass) remained almost the same as there are only small differences in carbon concentration among the different classes.

In terms of mass, total charcoal formation represented 6% of the original carbon present in the pre-burn phase. Because fire affects biomass classes differently, we could note that only 1% of the carbon in wood <5 cm in diameter becomes charcoal (long-term carbon pool) while this percentage was 3% for wood 5-10 cm and 5% for wood >10 cm in diameter. The "other" class (2.2 ± 0.7 Mg ha^{-1}) represented 2.1% of the total.

The water content of each biomass class was 16.3% for wood <5 cm in diameter; 20.7% for wood 5-10 cm in diameter; 29.9% for wood >10 cm in diameter; 35.7% for vines <5 cm in diameter; 26.6% for vines 5-10 cm in diameter and 14.4% for litter and leaves.

Burning efficiency is presented in Figure 4 for each individual biomass class (considering carbon in the biomass and charcoal that remained). The overall burning efficiency was 65.2%.

[Figure 4 here]

4. Discussion

4.1. Wood basic density

Wood density is well known as an indicator of successional stage for tropical trees, with pioneer tree species being lighter than mature forest species (Denslow, 1980). Wood densities in Amazon forests are higher than those found in tropical forests in Southeast Asia (Whitmore and Silva, 1990). The average basic wood density for wood pieces >10 cm in diameter found in this study (0.63 ± 0.12 g cm^{-3}) is quite close to the results of similar studies in the Amazon region. Nogueira et al. (2007) found a basic wood density of 0.64 g cm^{-3} for the Amazon region as a whole, while a value of 0.59 g cm^{-3} applies to the southern and southwestern portions of the Brazilian Amazon. Our result is 8.7% lower than the average previously used for the Brazilian Amazon (0.69 g cm^{-3}) (Fearnside, 1997a). Meanwhile, Chudnoff (1980) reported an average of 0.61 g cm^{-3} for the species of tropical America as a whole.

Such a reduction has a great impact on greenhouse-gas emission calculations because these are the types of forests that are now under high human pressure (Nogueira et al., 2007). Basic wood density determination is of great importance as it is a large source of errors in biomass estimates. Even small differences in per-hectare biomass in Amazonia translate into large amounts of annual emissions of greenhouse gases.

4.2. Aboveground biomass

The total aboveground biomass found in this study (219.3 Mg ha^{-1}) is lower than that found in other studies of burning in Amazonia (Table 4). The biomass at our site was also somewhat lower than at other sites where biomass has been estimated in semideciduous forests of northern Mato Grosso. Graça (2004) estimated an aboveground biomass of 238.4 Mg ha^{-1} in an undisturbed semideciduous forest (without either selective logging or accidental fire) in Cláudia, Mato Grosso. Monteiro et al. (2004), also at a location near Claudia, estimated an aboveground biomass of 326 Mg ha^{-1} for an undisturbed forest. The same authors report a biomass of 232 Mg ha^{-1} in highly degraded and burned areas. The forest in Claudia has IBGE code ON and RADAMBRASIL code Fse3 (transitional forest, with predominance of seasonal semideciduous submontane forest).

[Table 4 here]

Biomass determined at single points, such as the present study and those associated with the burning studies listed above, are not sufficient for the region-wide estimates used in estimating emissions from deforestation in Amazonia. To represent variation across the region, these large-scale estimates require use of a much larger number of sites, such as the approximately 3000 1-ha plots of the RADAMBRASIL project (Brazil, Projeto RADAMBRASIL, 1973-1983; see Fearnside, 1997b). The semideciduous vegetation type at Feliz Natal site where we found 219.3 Mg ha^{-1} of total aboveground biomass has a mean aboveground biomass of 252.5 Mg ha^{-1} in 33 RADAMBRASIL plots considering the conversions derived by Nogueira et al. (2007, 2008). The RADAMBRASIL surveys were done before these forests were subjected to significant disturbance from logging.

The biomass found in this study is lower than it would have been in “pristine” forest because of selective logging in the preceding years. The maximum removal of approximate 20 m^3 ha^{-1} we inferred is lower than that in higher-biomass forests, such as 35 m^3 ha^{-1} observed in forest in Claudia, Mato Grosso in transitional forest, with predominance of semideciduous forests (Graça, 2004). Logging increases burning efficiency (and therefore trace-gas emissions per ton of biomass cleared) by removing large-diameter logs that would burn poorly if present at the time of the fire (Fearnside, 1995). The effect that the logging at our site in Feliz Natal had on burning efficiency can be calculated as follows. The 20 m^3 ha^{-1} of log removal represents 12.6 Mg ha^{-1} of biomass dry-weight at the 0.63 g cm^{-3} mean wood density, or 6.05 Mg ha^{-1} of carbon at he 47.98% carbon content of material in this diameter class. At the 49% burning efficiency for material > 10 cm in diameter, 2.96 Mg C ha^{-1} would have been consumed had these logs been present in the burn, lowering the overall burning efficiency to 64.3% (a reduction of 1.4% relative to the 65.2% burning efficiency we found).

The type of forest in this study differs in biomass class composition from the forests examined in studies of burning in other forest types in Amazonia (Table 4). This kind of forest (semideciduous forest or seasonal forest-rainforest transition) has a greater quantity of small and medium branches than forests where burning has been studied. . Also litter and leaves represented a relatively large quantity of the total biomass (12.1%) as compared to other locations (Table 4). These characteristics increase burning efficiency because small-diameter material burns more completely and requires less time to dry in the period preceding the burn.

The number of boles and their volume distribution over different diameter classes had a very special pattern in Feliz Natal when compared to other destructive studies in tropical forest using the same methodology in Altamira, Pará (Fearnside et al., 1999); Ariquemes, Rondônia (Graça et al., 1999) and Manaus, Amazonas (Fearnside et al., 2001). The mean diameter of trunks in the >10-cm diameter class found in Feliz Natal (17 cm) was significantly smaller (*t*-test, $p < 0.01$) than other sites: 21.3 cm in Altamira, 24.8 cm in Ariquemes and 20.6 in Manaus. Figure 5 shows the distribution of the number of boles (*a*) and their volumes (*b*) by diameter class. When all four studies are included, a clear decrease in the number of boles as diameter increases (Figure 5*a*) is apparent, similar to a negative exponential (or reverse "J") curve. In addition, Feliz Natal had the largest percentage of boles (78%) in the two smallest diameter classes. Also at this location, these two diameter classes (10-14.9 and 15-19.9 cm) represented a great quantity of wood (Figure 5*b*) with about 44% of the total volume. This is much more in these small-diameter classes than has been found in other studies: Altamira had about 19%; Ariquemes 14% and Manaus 24%. One may consider the volume presented here as a percentage of the total as being equivalent to biomass because wood density is a constant multiplier for each location. In spite of this, a direct biomass comparison cannot be made between the data at the Feliz Natal study and those at each of the other locations. In Feliz Natal the LIS line crossed only one tree >50 cm in diameter, although this tree alone represented about 10.5% of the total volume. In the other three locations the wood present in this class contributed higher percentages of the total volume: 25% in Altamira, 20.5% in Ariquemes and 17% in Manaus.

[Figure 5 here]

After the burn a very small quantity of biomass (36.9 Mg ha^{-1}) was left on the ground if compared to 130 Mg ha^{-1} left in Manaus (Fearnside et al., 2001) or 92.1 Mg ha^{-1} left in Ariquemes (Graça et al., 1999). After the burn, trunks that had represented 58.3% of the total initial aboveground biomass were reduced to only 26.8% of the total initial aboveground biomass, while in other studies this percentage was almost unchanged due to the low burning coefficient of the trunks.

Burnng efficiency is influenced by a variety of factors. In a study of 274 burns in clearings for slash-and-burn agriculture in the Transamazon Highway colonization area near Altamira, Pará, burn quality could be predicted in 74% of cases from meteorological parameters (precipitation, evaporation and insolation) between the dates of felling and burning and from precipitation in the 15 days prior to the burn (Fearnside, 1986, 1989). Similar meteorological factors affect fire susceptibility of intact Amazonian forest (Ray et al., 2005). Cumulative precipitation, evaporation and insolation between felling and burning are related to the length of time between felling and burning (the "curing" time), which affects burning (Carvalho et al., 2001; see Table 4). Burning completeness can be reduced in small clearings (≤ 4 ha) (Carvalho et al., 2001; see Table 4), but the 100-ha clearing burned in the present study is well beyond the range of this effect.

4.3. Charcoal formation

Charcoal formation is important as it represents the carbon that is transferred to long-term pools in the form of black carbon; this accumulates over geological time scales (Kuhlbusch, 1998; Canut et al., 1996). There have been rare attempts to measure charcoal formation in Amazonian forest burns, and few papers report explicitly the quantity of charcoal formed. The charcoal formation in terms of carbon percentage and mass reported here (6.0% and 5.98 MgC ha^{-1}, respectively: Table 3) is much higher than others reported in tropical areas. Fearnside et al. (1993) reported that 2.7% (3.5 MgC ha^{-1}) of original carbon was converted to charcoal in a burn near Manaus, Amazonas. These same authors (Fearnside et al., 1999) found 1.3% (1.6 MgC ha^{-1}) in Altamira, Pará, while Graça et al. (1999) reported 2.9% (4.1 MgC ha^{-1}) in Ariquemes, Rondônia.

The high charcoal formation at Feliz Natal, which is about double the highest value that has been reported until now in primary forests, is probably due to the high burning percentage for trunks (49%). Trunks are probably the largest source of the remaining charcoal lying on the soil because the smaller-diameter biomass classes are known for their high burning coefficients. About half (54%) of the charcoal found was clinging to the trunks.

Because charcoal clinging to trunks (wood >10 cm) was measured indirectly by LIS, this could be a source of some deviation. "Brown" wood forms around the burned trunk just below the charcoal layer, and the limit between the black and brown layers is difficult to identify. This may reduce the charcoal estimate a little. However, charcoal lying on the soil represented about 40% of total charcoal formation or 2% of the original carbon in pre-burn biomass. This pool alone is equal to the charcoal formation reported in previous field studies in Amazonia. It should be emphasized that Fearnside et al. (2001) and Graça et al. (1999) did not find a significant difference between direct and indirect (LIS) measures of charcoal on wood >10 cm in diameter.

Charcoal has not been considered in several of the studies that have been done of Amazonian burns (Table 4). Omitting charcoal raises the perceived burning efficiency, since the higher carbon content of charcoal is not reflected in the post-burn carbon stocks, thereby increasing the inferred carbon losses from the site. For example, omitting charcoal from our study (and considering it to have the same carbon content as wood) would raise the computed burning efficiency to 66.9% (an increase of 2.6% relative to the 65.2% burning efficiency we found).

4.4. Carbon concentration

The mean carbon concentration found in this study (48.6%: Table 2) is very similar to other measurements of carbon concentration in the region. Fujisaka et al. (1998) found a carbon concentration of 48% in Amazonas. Araújo et al. (1999) report an average carbon content of 44.6% for trunks and branches, 50.4% for leaves, 39.3% for litter and 45.5% for vines in a study near Tomé-Açu, Pará. Graça et al. (1999) found 45.4% as a mean for all classes in Ariquemes, Rondônia, while Fearnside et al. (2001) found a mean carbon concentration of 49.3%. Graça et al. (1999) report a very similar carbon concentration for charcoal (64.4%). The carbon concentration in charcoal found in this study (69.0%) is slightly higher than this value but slightly lower than the concentration in charcoal manufactured from primary forest near Manaus (74.8%) (Corrêa, 1988).

4.5. Carbon stock in biomass and burning efficiency

Different classes of biomass make completely different contributions to fuel load and prompt emission of greenhouse gases from burning. Although the large-diameter wood class represents the largest part of pre-burn biomass, the comparatively small percentage of the biomass in these classes that actually burns reduces their relative importance. Fearnside et al. (2001) find that the relative contribution of different biomass classes to greenhouse-gas emissions will determine how these results can be of practical use in studies of different forest types.

Burning efficiency varies enormously, as well as forest biomass, even over short distances. This efficiency discrepancy has many sources, such as weather conditions, fuel load and arrangement in the field, time left to dry and management. The variability of rain and other meteorological events produces high variability in burn quality.

The burning efficiency found in this study (65.2%) is higher than has been found in other studies of burning in felled primary forests the Amazon region, which report efficiencies ranging from 27.6 to 56.1% (Table 4). A number of additional studies report only biomass consumption (the percentage of biomass dry weight loss), which are invariably higher than burning efficiency (% carbon lost) because biomass consumption ignores the differences in carbon content of the various biomass fractions, especially the higher carbon content of the charcoal present after the burn. The current study's biomass consumption (66.7%) is higher any of the 19 other estimates of this measure summarized in Table 4. It is important to remember that these studies were done in types of forest different from the one studied here, and that most of these studies were done in dense lowland forests.

Fearnside et al. (2001) demonstrated that differences in burning efficiency can depend on the methodology adopted. Estimates using the LIS method produced numbers that were intermediate among the three methods evaluated. This probably reduces errors in determining burning efficiency for trunks (wood >10 cm in diameter), because the LIS method allows re-measurement of the same pieces at the same precise point. In addition, our number is consistently higher than those based on other studies using identical methodology (LIS), e.g. Fearnside et al. (1993); Fearnside et al. (1999) and Graça et al. (1999).

A large part of the aboveground biomass (about 42% of the total aboveground biomass) was fine material that had very high burning efficiency (see *Aboveground*

Biomass discussion above). The burning efficiency reported here is also much larger for individual biomass classes. In addition to all fine material having burned almost completely (litter and leaves, wood <5 cm in diameter and vines) wood 5-10 cm in diameter also burned very well, with a burning efficiency of 81% (Figure 3). The largest discrepancy was found in trunks (wood >10 cm in diameter) with a coefficient of 49%. Fearnside et al. (1993) reported burning efficiencies for these two classes of 49.1% and 20.9%, respectively, and Graça et al. (1999) found 17.6% for wood >10 cm in diameter. Additionally, as presented earlier, there was a smaller percentage of biomass in trunks (>10 cm in diameter) than at other sites (Altamira, Ariquemes and Manaus) and most of this (44% by volume) was in the smallest diameter classes.

The very low water content of the biomass may provide an additional explanation for such high burning efficiency. The humidities of the different diameter classes at Feliz Natal were much lower than those reported at other sites in the literature (Table 4).. It is important to point out that no palms were found at this site. The contribution of palms to total aboveground biomass can be very low (0.7% in Fearnside et al., 2001) or more significant such as the 6.9% found by Graça et al. (1999), but palms normally contain plenty of water (192% on a dry basis as the average from Fearnside et al., 2001), and they have very low burning efficiency.

Although the burn occurred after the initiation of the rainy season (late November, early December) woody material had the opportunity to become drier than usual because water was not able to penetrate the pieces and re-hydrate them. The water on the surface was probably evaporated very quickly by the high solar radiation.

4.6. Greenhouse-gas emissions

Almost all of the carbon in the original forest biomass is released by the end of the first decade, and the remaining carbon left from the first burn is almost completely released over the course of the succeeding decades by decay and re-burns (Barbosa and Fearnside, 1996). It is only a matter of time before the great majority of the carbon held in the aboveground biomass is released to the atmosphere. However, burning efficiency affects both the amount of this release that occurs at the outset and the forms that it will take, influencing the relative amounts released as CO_2 or as trace-gases such as CH_4 and N_2O (e.g., Fearnside, 2000). The large share (≈ 80%) of Brazil's Amazonian deforestation and burning that takes place in the arc of deforestation, especially in Mato Grosso, makes better quantification of burning efficiency an important part of efforts to reduce the uncertainty surrounding greenhouse-gas emissions from this area (Fearnside et al., 2009).

5. Conclusions

This study on burning of forests cleared in the "arc of deforestation," where deforestation is concentrated, found a burning efficiency of 65%, which is much higher than what has been found in the dense closed forests that predominate in other parts of Amazonia. The differences in forest structure and biomass allocation within different classes and their low water content explain the high burning efficiency. The percentage of trunk biomass (in higher-biomass forest types) lost in the burn (49%) was substantially higher than has been found in existing studies. The concentration of more stems in lower diameter classes within the > 10-cm diameter class, together with the low humidity of the fuel at the time of the burn, may explain this difference. High burning efficiency increases trace-gas release and contribution to greenhouse-gas emission from land-use change. Meanwhile, the high variability of tropical forests adds substantial uncertainty in any calculation.

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References

Agência Brasil, 2009. Município de Feliz Natal é incluído na lista dos que mais desmatam em MT. Agência de Notícias Primeira Hora, 24 March 2009. http://www.primeirahora.com.br/noticia.php?intNotID=9954 (Accessed 15 Aug. 2009).

Araújo, T.M., Carvalho Jr., J.A., Higuchi, N., Brasil Jr. A.C.P., Mesquita, A.L.A.A, 1999. A tropical rainforest clearing experiment by biomass burning in the state of Pará, Brazil. Atmospheric Environment 33, 1991-1998.

Barbosa, R.I., Fearnside, P.M., 1996. Pasture burning in Amazonia: dynamics of residual biomass and the storage and release of aboveground carbon. Journal of Geophysical Research (Atmospheres) 101(D20), 25,847-25,857.

Brazil, IBGE & IBDF (Instituto Brasileiro de Geografia e Estatística & Instituto Brasileiro de Desenvolvimento Florestal), 1988. Mapa de Vegetação do Brasil. Scale 1:5,000,000. IBGE, Rio de Janeiro, Brazil.

Brazil, Projeto RADAMBRASIL, 1973-1983. Levantamento de Recursos Naturais, Ministério das Minas e Energia, Departamento Nacional de Produção Mineral (DNPM), Rio de Janeiro, Brazil. Vols. 1-23.

Canut, P.L., Andreae, M.O., Harris, G.W., Wienhold, F.G., Zenker, T., 1996. Airborne studies of emissions from savanna fires in Southern Africa. 1. Aerosol emissions measured with a laser optical particle counter. Journal of Geophysical Research (Atmospheres) 101(D10), 23615-23630.

Carvalho Jr., J.A., Santos, J.M., Santos, J.C., Leitão, M.M., Higuchi, N., 1995. A tropical rainforest clearing experiment by biomass burning in the Manaus region. Atmospheric Environment 29(17), 2301-2309.

Carvalho, J.A., Higuchi, N., Araújo, T.M., Santos, J.C., 1998. Combustion completeness in a rainforest clearing experiment in Manaus, Brazil. Journal of Geophysical Research 103 (D11), 13195–13200.

Carvalho, J.A., Costa, F.S., Veras, C.A.G., Sandberg, D.V., Alvarado, E.C., Gielow, R., Serra, A.M., Santos, J.C., 2001. Biomass fire consumption and carbon release rates of rainforest-clearing experiments conducted in Northern Mato Grosso, Brazil. Journal of Geophysical Research 106 (D16), 17877–17887.

Chudnoff, M., 1980. Tropical Timbers of the World. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. Madison, Wisconsin, U.S.A., 831 pp.

Corrêa, A.A., 1988. Conversão química de madeiras da Amazônia – carvão e briquettes de carvão vegetal. Acta Amazonica 18, 93-108.

Cox, P.M., Harris, P.P., Huntingford, C., Betts, R.A., Collins, M., Jones, C.D., Jupp, T.E., Marengo, J.A., Nobre, C.A., 2008. Increasing risk of Amazonian drought due to decreasing aerosol pollution**.** Nature 453, 212-215.

DeFries, R.S., Houghton, R.A., Hansen, M.C., Field, C.B., Skole, D., Townsend, J., 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980’s and 90’s. Proceedings of the National Academy of Sciences 99, 14,256-14,261.

Denslow, J.S., 1980. Gap partitioning among tropical rainforest trees. Biotropica 12 (suppl.), 23-30.

Fearnside, P.M., 1986. Human carrying capacity of the Brazilian rainforest. Columbia University Press. New York, NY, U.S.A., 293 pp.

Fearnside, P.M., 1989. Burn quality prediction for simulation of the agricultural system of Brazil’s Transamazon Highway colonists. Turrialba 39, 229-235.

Fearnside, P.M., 1995. Global warming response options in Brazil's forest sector: Comparison of project-level costs and benefits. Biomass and Bioenergy 8, 309-322.

Fearnside, P.M., 1997a. Wood density for estimating forest biomass in Brazilian Amazonia. Forest Ecology and Management 90, 59-87.

Fearnside, P.M., 1997b. Greenhouse gases from deforestation in Brazilian Amazonia: Net committed emissions. Climatic Change 35, 321-360.

Fearnside, P.M., 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. Climatic Change 46, 115-158.

Fearnside, P.M., 2001. Soybean cultivation as a threat to the environment in Brazil. Environmental Conservation 28, 23-38.

Fearnside, P.M., Graça, P.M.L.A., Rodrigues, F.J.A., 2001. Burning of Amazonian rainforests: burning efficiency and charcoal formation in forest cleared for cattle pasture near Manaus, Brazil. Forest Ecology and Management 146, 115-128.

Fearnside, P.M., Leal Filho, N., Fernandes, F.M., 1993. Rainforest burning and the global carbon budget: biomass combustion efficiency and charcoal formation in the Brazilian Amazon. Journal of Geophysical Research (Atmospheres) 98 (D9), 16733-16743.

Fearnside, P.M., Graça, P.M.L.A., Leal Filho, N., Rodrigues, F.J.A., Robinson, J.M., 1999. Tropical forest burning in Brazilian Amazonia: measurement of biomass loading, burning efficiency and charcoal formation at Altamira, Pará. Forest Ecology and Management 123, 65-79.

Fearnside, P.M., Righi, C.A., Graça, P.M.L.A., Keizer, E.W.H., Cerri, C.C.. Nogueira, E.M. Barbosa, R.I., 2009. Biomass and greenhouse-gas emissions from land-use change in Brazil's Amazonian "arc of deforestation": The states of Mato Grosso and Rondônia. *Forest Ecology and Management*. Published online 22 Aug.2009. DOI: 10.1016/j.foreco.2009.07.042.

Fujisaka, S., Castilha, C., Escobar, G., Rodrigues, V., Veneklaas, E.J., Thomas, R., Fisher, M., 1998. The effects of Forest conversion on annual crops and pastures: estimates of carbon emissions and plant species loss in a Brazilian Amazon colony. Agriculture, Ecosystems and Environment 69, 17-26.

Graça, P.M.L.A., 2004. Monitoramento e caracterização de áreas submetidas à exploração florestal na Amazônia por técnicas de detecção de mudanças. Ph.D. Dissertation. Instituto Nacional de Pesquisas Espaciais- INPE, São José dos Campos, São Paulo, Brazil. CD-ROM. INPE-13644-TDI/1046.

Graça, P.M.L.A., Fearnside, P.M., Cerri, C.C., 1999. Burning of Amazonian forest in Ariquemes, Rondônia, Brazil: biomass, charcoal formation and burning efficiency. Forest Ecology and Management 120, 179-19.

Guild, L.S., Kauffman, J.B., Ellingston, L.J., Cummings, D.L., Castro, E.A., 1998. Dynamics associated with total above-ground biomass, C, nutrient pools and biomass burning of primary forest and pasture in Rondônia, Brazil, during SCAR-B. Journal of Geophysical Research (Atmospheres) 103(D24), 32091-32100.

Houghton, R.A., 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus 55B, 378-390.

Houghton, R.A., 2005. Aboveground forest biomass and the global carbon balance. Global Change Biology 11, 945-958.

Houghton, R.A., Lawrence, K.T., Hackler, J.L., Brown, S., 2001. The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. Global Change Biology 7, 731-746.

Houghton, R.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., Chomentowski, W.H., 2000. Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. Nature 403, 301-304.

Kauffman, J.B., Cummings, D.L., Ward, D.E., Babbitt, R., 1995. Fire in the Brazilian Amazon. 1. Biomass, nutrient pools, and losses in slashed primary forests. Oecologia 104, 397-408.

Kuhlbusch, T.A.J., 1998. Black carbon and the carbon cycle. Science 280, 1903-1904.

Kuhlbusch, T.A.J., Crutzen, P.J., 1995. Toward a global estimate of black carbon in residues of vegetation fires representing a sink of atmospheric CO_2 and a source of O_2. Global Biogeochemical Cycles 9, 491–501.

Marengo, J.A.,. Nobre, C.A., Tomasella, J.,. Oyama, M.D., Sampaio de Oliveira, G., de Oliveira, R., Camargo, H., Alves, L.M., Brown, I.F.. 2008. The drought of Amazonia in 2005. Journal of Climate 21, 495–516.

Monteiro, A.L.S., Souza Jr, C.M., Barreto, P.G., Pantoja, F.L.S, Gerwin, J.J., 2004. Impactos da exploração madeireira e de fogo em florestas de transição da Amazônia Legal. Scientia Forestalis 65, 11-21.

Nimer, E., 1979. Climatologia do Brasil. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, Brazil. 422 pp.

Nogueira, E.M., Fearnside, P.M., Nelson, B.W., Barbosa, R.I., Keizer, E.W.H., 2008. Estimates of forest biomass in the Brazilian Amazon: New allometric equations and adjustments to biomass from wood-volume inventories. Forest Ecology and Management 256, 1853-1857.

Nogueira, E.M., Fearnside, P.M., Nelson, B.W., França, M.B., 2007. Wood density in forests of Brazil's 'arc of deforestation': implications for biomass and flux of carbon from land-use change in Amazonia. Forest Ecology and Management 248, 119–135.

Prentice, I.C., and 62 others., 2001. The carbon cycle and atmospheric carbon dioxide. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van de Linden, P.J., Dai, X., Maskel, K., Johnson, C.A. (Eds.). Climate Change: The Scientific Basis. Cambridge University Press, Cambridge, U.K., pp. 188-237.

Ray, D, Nepstad, D., Moutinho, P., 2005. Micrometeorological and canopy controls of fire susceptibility in a forested Amazon landscape. Ecological Applications 15, 1664-1678.

Soares Neto, T.G., Carvalho, Jr., J.A., Veras, C.A.G., Alvarado, E.C., Gielowe, R., Lincoln, E.N., Christian, T.J., Yokelson, R.J., Santos, J.C., 2009. Biomass consumption and CO_2, CO and main hydrocarbon gás emissions in an Amazonian forest clearing fire. Atmospheric Environment 43, 438–446.

Truguilho, P.F., da Silva, D.A., Frazão, F.J.L., de Matos, J.L.M., 1990. Comparação de métodos de determinação de densidade básica em madeira. Acta Amazonica 20, 307–319.

Van Wagner, C.E., 1968. The line intersect method for forest fuel sampling. Forest Science 14(1), 20-26.

Vital, B.R., 1984. Métodos de determinação da densidade da madeira. Sociedade de Investigações Florestais. (Boletim Técnico, 1), Viçosa, Minas Geraus, Brazil. 21 pp.

Whitmore, J.C., Silva, J.N.M., 1990. Brazil rain forest timbers are mostly very dense. Commonwealth Forestry Review 69(1), 87-90.

Figure legends

Figure 1. Location of the study area in the municipality of Feliz Natal, Mato Grosso state, in Brazil's Legal Amazon region.

Figure 2._ Clearing at Feliz Natal: the predominance of small-diameter stems is apparent. Wood pieces >10 cm in diameter are being tagged with sequentially numbered aluminum plates that were nailed to the pieces.

Figure 3. Layout of plots at each sampling point (star) used for biomass estimates in Feliz Natal, Mato Grosso, Brazil. The rays were 2 m in width by 30 m in length (3 repetitions of 10 m each). The evaluation of pieces >10 cm in diameter was done by line-intersect sampling (LIS) in the middle of the post-burn plots (even rays) before and after the burn.

Figure 4. Burning efficiency fraction based on carbon content for each biomass class in a semideciduous forest in eastern Amazonia at Feliz Natal, Mato Grosso, Brazil.

Figure 5. Distribution of the number of boles ***(a)*** and their volumes ***(b)*** in a semideciduous forest in eastern Amazonia at Feliz Natal, Mato Grosso, Brazil. Both are given as percentages of the total, by diameter class for wood >10 cm in diameter.